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THERMOPHYSICAL PROPERTIES OF SODIUM

by

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NOMENCLATURE

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Symbol	Definition
C	Sonic velocity; ft/sec
C_p	Specific heat at constant pressure; Btu/lb-°F
C_v	Specific heat at constant volume; Btu/lb-°F
E	Internal energy; Btu/lb, Btu/lb mole
F	Free energy; Btu/lb, Btu/lb mole
H	Enthalpy; Btu/lb, Btu/lb mole
K	$R'/R = 2.72131$ Btu/atmos-ft^3
k	Thermal conductivity; Btu/hr-ft-°F, cal/sec-cm-°C
M	Molecular weight ($M_1 \equiv 22.991$)
N	Mole fraction
P	Pressure; atmos abs
Pr	Prandtl number $\eta C_p/k$
R	Gas constant; 0.730229 atmos-ft^3/lb-mole-°R
R'	Gas constant; 1.98718 Btu/lb-mole-°R
S	Entropy; Btu/lb-°R, Btu/lb-mole-°R
T	Absolute temperature; °R(≡ °F + 459.7), °K(≡ °C + 273.15)
t	Temperature; °F, °C
V	Specific volume; ft^3/lb
v	Specific volume; ft^3/lb-mole monomer, cm^3/gm
X	Weight fraction
α	Thermal diffusivity; $k/\rho_\ell C_p$; ft^2/hr
α_P	Thermal expansion coefficients; 1/°F
β_T	Isothermal compressibility; atmos^{-1}
β_S	Adiabatic compressibility; atmos^{-1}
γ_ν	Thermal pressure coefficient; atmos/°F
η	Dynamic viscosity; lb$_m$/hr-ft
ρ	Vapor density; lb/ft^3, lb-mole monomer/ft^3
ρ_ℓ	Liquid density; lb/ft^3, lb-mole monomer/ft^3
ρ_e	Electrical resistivity; $\mu\Omega$-cm
σ	Surface tension; lb$_f$/ft

Subscripts

f	Formation
s	Saturation
v	Vaporization
D	Dimerization
T	Tetramerization
0	Absolute zero
1	Monomer
2	Dimer
4	Tetramer

Superscripts

0	Standard state
ℓ	Liquid phase
g	Gaseous phase
s	Solid phase

SUMMARY

The literature about sodium properties through 1966 has been reviewed as a basis for recommending current best values for such properties. Consideration has been given to the liquid density, vapor pressure, thermodynamic and P-V-T properties, transport properties, electrical resistivity, and surface tension, as well as the thermal expansion coefficient, compressibility, and sonic velocity of the liquid. A FORTRAN subroutine has been written to compute the enthalpy and entropy of sodium in a given state, and also the composition, mean molecular weight, specific volume, and compressibility factor of the corresponding vapor. Tabular results for the saturated liquid and vapor are presented in an Appendix for the range 500-2500°F, in 10° increments. Also given are derived H-S and T-S diagrams. The transport properties are the viscosity and thermal conductivity of the saturated liquid and vapor; these are also presented in tabular form for the range 210-2500°F, in 10° increments.

SUMMARY OF PROPERTIES EQUATIONS

The equations used to generate property values recommended in this report are summarized by number and page as follows:

	Property	Equation Number	Page
1.	Liquid density	2.1	13
2.	Vapor pressure: $t \leq 1600°F$	3.2	19
	$t > 1600°F$	3.1	16
3.	Vapor equation of state	4.6+	24
		4.29+	29
		4.26-4.28+	29
		4.19 and 4.20	28
4.	Saturated liquid enthalpy	4.37	32
5.	Saturated liquid entropy	4.38	33
6.	Heat of vaporization	4.40	34
7.	Vapor enthalpy	4.43	37
8.	Vapor entropy	4.44	37
9.	Vapor specific heat	4.47	38
10.	Liquid specific heat (constant pressure)	5.4	40
11.	Liquid thermal conductivity	5.9	43
12.	Vapor thermal conductivity	5.12	46
13.	Liquid viscosity	5.19a	50
14.	Vapor viscosity	5.20	51
15.	Liquid electrical resistivity	6.2a	54
16.	Surface tension	7.9a	62
17.	Thermal expansion coefficient	8.1	63
18.	Isothermal compressibility coefficient	8.5	64
19.	Thermal pressure coefficient	8.7	65
20.	Sonic velocity	Ref. (116)	-
21.	Adiabatic compressibility coefficient	8.6 and 2.1	64 & 13
22.	Liquid specific heat (constant volume)	8.4	64

THERMOPHYSICAL PROPERTIES OF SODIUM

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I. INTRODUCTION

Interest in sodium as a heat transfer fluid and as a working fluid for power cycles has resulted in a number of studies of its related properties in recent years. The Liquid Metals Handbook in its three editions (1950, 1952, and 1955) contains the earliest extensive critical compilations of such properties.[1-3] Subsequent compilations are reported by Thomson and Garelis[4] in 1956, Meisl and Shapiro[5] and Dunning[6] in 1960, Weatherford et al.,[7] in 1961, Burdi[8] in 1964, and Spiller[9] in 1965. The compilation of Burdi is based largely upon the earlier work of Weatherford et al. Similarly, many of the property values recommended by Spiller are taken from the earlier work of Thomson and Garelis and of Dunning. The large amount of information that has become available since 1960, however, suggests the necessity of an updated compilation.

A specific stimulus for such an updating is the work underway at the Naval Research Laboratory. A group there rather recently published P-V-T and related measurements for saturated and superheated sodium vapor.[10] From a thermodynamic analysis of their data they concluded that the vapor contains not only the monomer and dimer, but also species of higher molecular weight, probably the tetramer. Using their results, they computed the thermodynamic properties of saturated and superheated sodium for the range 1600-2500°F, essentially the range of their measurements. There is, however, great interest in such values at temperatures well below 1600°F, where precise P-V-T measurements have not been made.

Following is a compilation of sodium properties, updated wherever possible through 1966. Included in the compilation are the following:

1. liquid density
2. vapor pressure
3. thermodynamic (including P-V-T) properties
4. transport properties (including electrical resistivity)
5. surface tension
6. thermal expansion coefficient, compressibility, and sonic velocity for the liquid phase.

In each case, the results of different investigators are compared and a recommendation is made. To facilitate the use of the results in engineering applications, recommended values are presented in tabular form as appendixes. Thermodynamic charts (H-S and T-S) are also given in appendixes. Specific recommendations are made for further experimental work in the third of the above areas.

The critical parameters (temperature, pressure, and specific volume) are not included in the compilation because considerable uncertainty exists regarding reported values, and no experimental basis is available for making a "best" choice.

II. DENSITY OF LIQUID SODIUM

Stone *et al.*, give the following cubic equation for the density of liquid sodium:[10]

$$\rho_\ell(\mathrm{lb/ft^3}) = 59.566 - 7.9504 \times 10^{-3}t - 0.2872 \times 10^{-6}t^2 + 0.06035 \times 10^{-9}t^3;$$

$$208 \le t \le 2500°\mathrm{F}. \qquad (2.1)$$

They derived this equation from the data of Hagen[11] and of Ewing *et al.*,[12] at lower temperatures, of Jackson *et al.*,[13] Novikov *et al.*,[14] Rinck,[15] and Nishibayashi[16] at intermediate temperatures, and their own work at higher temperatures (1577-2491°F). Table II.1 indicates the methods and ranges of measurement used by the foregoing investigators as well as the average agreement between each of their sets of data and the above equation. Equation (2.1) is plotted in Fig. 2.1.

The data of references 12, 15, and 11 were correlated earlier by Thomson and Garelis,[4] who reported the following equation:

$$\rho_\ell(\mathrm{gm/cm^3}) = 0.9490 - 2.23 \times 10^{-4}\left(\frac{t-32}{1.8}\right) - 1.75 \times 10^{-8}\left(\frac{t-32}{1.8}\right)^2;$$

$$208.1 \le t \le 1184°\mathrm{F}.$$

TABLE II.1. Summary of Density Measurements for Liquid Sodium[10]

Investigator	Method	Temp Range (°F)	% Average Deviation; $\frac{\text{Obs.} - (\text{Eq. 2.1})}{(\text{Eq. 2.1})}$
NRL[12]	Dilatometric	mp to 503	±0.08
Jackson[13]	Buoyancy	937 to 1314	-0.74
Rinck[15]	Buoyancy	804 to 1183	+0.15
Hagen[11]	Dilatometric	mp to 336	±0.05
NRL[10]	Dilatometric (Pycnometers)	1577 to 2491	±0.17
Novikov[14] (A)[a]	Buoyancy	248 to 505	-0.14
(B)[b]	Buoyancy	275 to 1324	+0.71
Nishibayashi[16]	Buoyancy	486 to 1580	±1.09

[a] (A) with steel sinker.

[b] (B) with tungsten sinker.

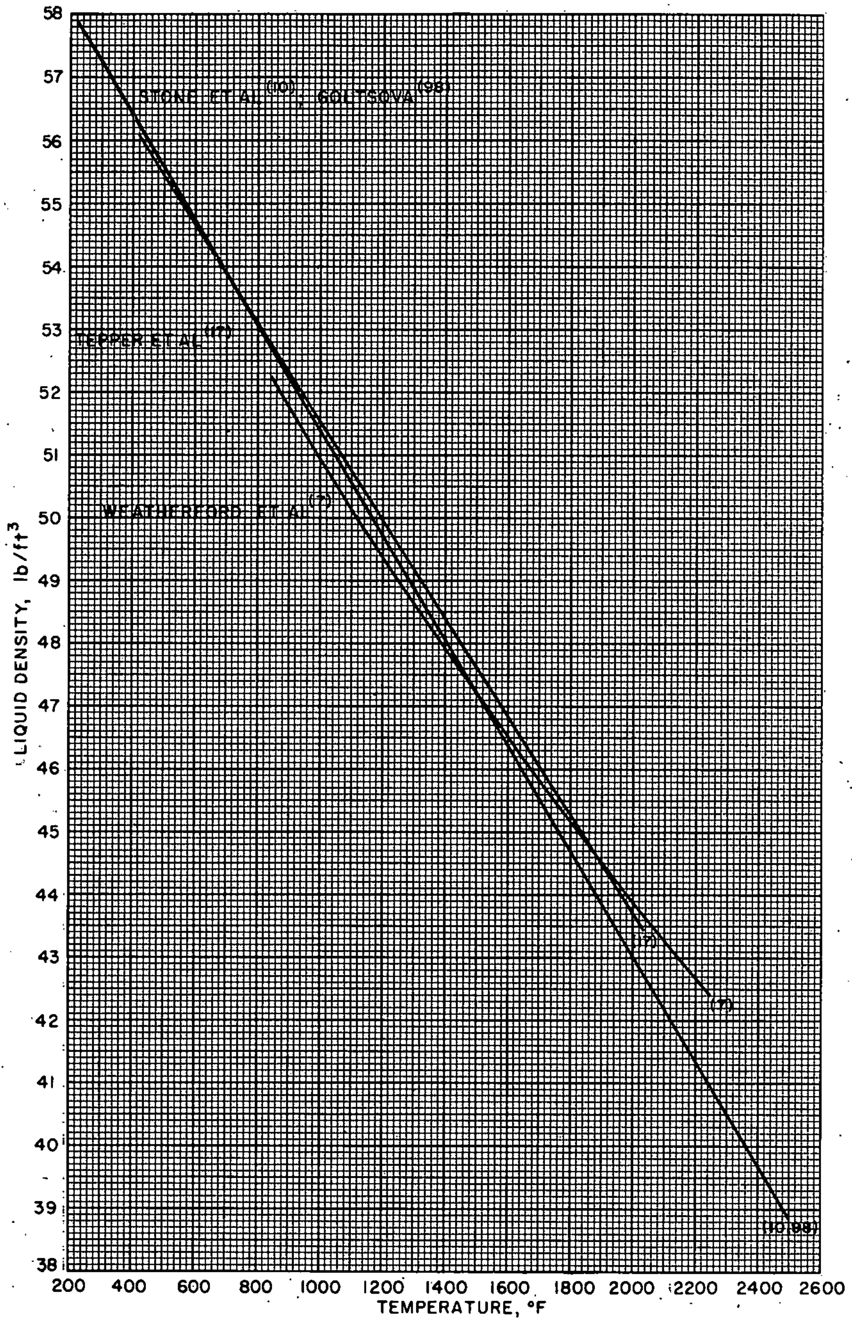

Fig. 2.1. Density of Liquid Sodium

In the applicable temperature range, the above equation agrees with that of Stone et al., to within 0.1%.

Tepper et al.,[17] give the following linear equation for the density of liquid sodium:

$$\rho_{\ell}(\text{lb/ft}^3) = (0.9493 - 0.12485 \times 10^{-3}\,t)(62.43); \qquad 411 \le t \le 2030°\text{F}. \qquad (2.2)$$

This equation is based entirely on density determinations made by the above investigators using a dilatometric technique. The standard deviation quoted for Eq. (2.2) is 0.0013 gm/cm^3. This equation is also plotted in Fig. 2.1. The maximum deviation between Eqs. (2.1) and (2.2) over their common range of applicability occurs at 2030°F, and equals 1.6%.

Goltsova[98] determined the density of sodium over the approximate range 100-1450°C (212-2642°F) using a molybdenum pycnometer. Based upon this work he recommends the equation

$$\rho_{\ell}(\mathrm{gm/cm^3}) = 0.927 - 0.238 \times 10^{-3}[t(^\circ\mathrm{C}) - 100]. \tag{2.3}$$

He states that the average scatter of the experimental points relative to the above equation is ±0.5%. Equation (2.3) agrees very well with that of Stone et al., over the range 212-2500°F; the deviation between them at the latter temperature is 0.39%.

Also shown in Fig. 2.1 are the values of Weatherford,[7] based on Meisl and Shapiro[5] for the source of graphical data. Meisl and Shapiro used reference 2, which cites reference 12 as its source. In the experimental work reported in this last reference, the density of sodium was determined by a dilatometric technique over the range 225-503°F. It thus appears that Miller[2] extrapolated the data of reference 12 to 1292°F, and Meisl and Shapiro further extrapolated the original data to 2240°F.

On the basis of the close agreement of the work of Thomson and Garelis, Goltsova, and Stone et al., we take Eq. (2.1) to represent the density of saturated liquid sodium over the range 212-2500°F.

III. SATURATION VAPOR PRESSURE OF SODIUM

A comparison of various vapor pressure equations for sodium is complicated by the fact that some of these equations are fits to specific sets of experimental data, while others are "pooled" results. It appears most meaningful to discuss these two classes of equations separately.

Stone et al.,[10] measured the saturation vapor pressure of sodium via a static capsule technique. This work was done in connection with P-V-T measurements (see Sect. IV) and also in a separate apparatus. A least-squares fit of data taken in the range 1624-2539°F resulted in the following Kirchhoff-type equation:

$$\log P_s(\text{atmos}) = 6.83770 - \frac{9980.94}{T(^\circ R)} - 0.61344 \log T(^\circ R). \qquad (3.1)$$

This equation gives a normal boiling point of 1618.6°F. The average deviation of all the experimental data from corresponding values computed from the above equation is reported to be ±0.37%. These investigators also made an independent "third law check," demonstrating the internal consistency of their vapor pressure data (ibid.).

The results of related investigations since 1955 are summarized in Table III.1. The derived equations above are not "pooled" equations, but are based upon the data of the specific investigators as given in the references. Three of the seven equations give normal boiling points that agree to within 0.5°F with that given by Stone's equation.

TABLE III.1. Results of Investigations of Sodium Vapor Pressure since 1955

Investigator	Method	Temp Range (°F)	Derived Equation	Derived Normal Boiling Point (°F)
Bowles and Rosenblum[18]	Static capsule	1470-3417	$\log P_s(\text{atmos}) = 4.51961 - \frac{9363.82}{T(^\circ R)}$	1612.1
Sowa[19]	Evaporation from crucible at fixed pressure	1651-2533	$\log P_s = 4.56719 - \frac{9491.55^a}{T}$	1618.5
Kirillov and Grachev[20]	Static capsule	1616-2372	Authors' smoothed data[b]	-
Makansi et al.[21]	Refluxing capsule	1148-2075	$\log P_s = 4.521 - \frac{9396^c}{T}$	1618.6
Achener and Jouthas[22]	Flash boiler	1129-1752	$\log P_s = 4.71924 - \frac{9770.25}{T}$	1610.6
Fischer[23]	Quasistatic variation	971-1484	$\log P_s = 4.6279 - \frac{9616.14}{T}$	1618.2
Vinogradov and Volyak[97]	Elastic membrane-sealed static capsule	1096-1628	Authors' smoothed data[d]	1621.1

[a] Equation derived from least-squares fit to data published by Sowa.
[b] Table 1, reference 20.
[c] Fit of equation of Kirchhoff type tried and found to be no better than two-term fit (reference 24).
[d] Table 3, reference 97.

The equations and cited smoothed data of Table III.1 are compared in Fig. 3.1, which shows the percent deviation of a given equation or set of data from that of Stone et al.,[10] taken as reference, as a function of temperature (this figure does not agree with Fig. 3 of reference 10 with regard to the Sowa and the Kirillov and Grachev data). Five of the seven equations agree with Stone's equation to within 6% in the range 1270-2530°F. Makansi's equation agrees with Stone's equation within 1% in the range 1370-2210°F, and within 2½% in the range 1210-2500°F.

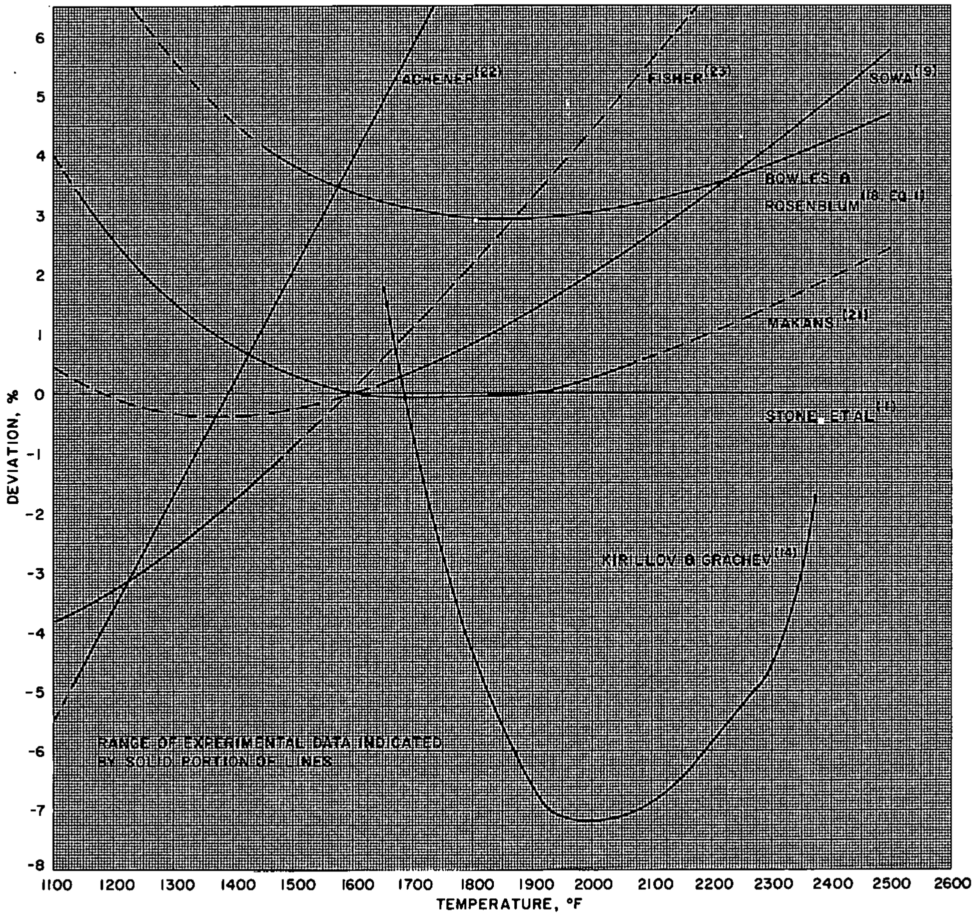

Fig. 3.1. Deviation of Equations for Sodium Vapor Pressure from That of Stone et al.

Figure 3.2 shows a plot of several "pooled equation" results in relation to the equation of Stone et al.[10] The values shown cover a wide range of temperature, and thus in certain situations represent wide extrapolations from intended intervals. Table III.2 summarizes the range of applicability of the vapor pressure correlations, the equations, and the predicted normal boiling point.

Ditchburn and Gilmour obtained their equation by analysis of the data of Heycock and Lamplough[28] at 1621.1°F, Haber and Zisch[29] (883-1049°F), Rodebush and DeVries[30] (358-1106°F), Edmondson and Egerton[31] (431-568°F), Weiler[32] (475-604°F), Ladenburg and Thiele[33] (431-1621°F), Rodebush and Walters[34] (1204-1553°F), Rodebush and Henry[35] (505-746°F), Lewis[36] (674-914°F), Thiele[37] (647-929°F), Ladenburg and Minkowski,[38] and Rowe.[39] The Ditchburn and Gilmour equation in general represents values well below the normal boiling point.

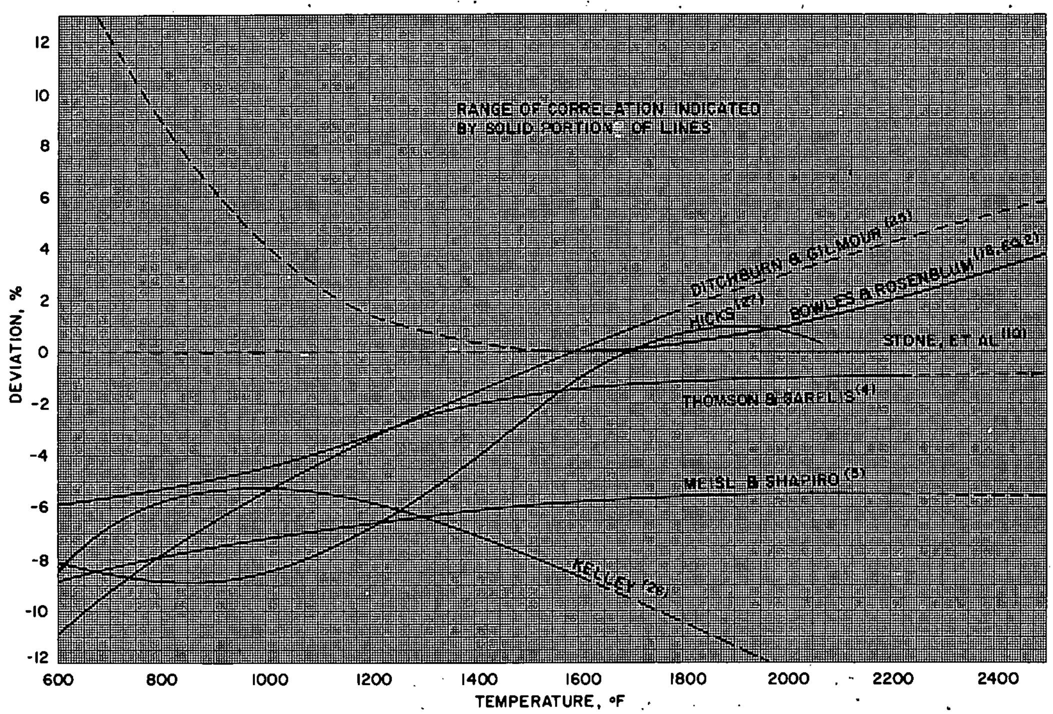

Fig. 3.2. Deviation of Pooled Correlations of Sodium Vapor Pressure from That of Stone et al.[10]

TABLE III.2. Pooled Correlations of Sodium Vapor Pressure

Investigator	Temp Range (°F)	Equation(s): log P_s =	Normal Boiling Point (°F)
Ditchburn and Gilmour[25]	mp-1790	$-\frac{10020.6}{T} - 0.5 \log T + 6.4818$	1617.5
Bowles and Rosenblum[18]	1149-3418[b]	$4.54025 - \frac{9435.8}{T}$	1618.4
Thomson and Garelis[4]	260-1250	$4.57791 - \frac{9448.38}{T - 14.65}$	
	1250-2240	$4.36383 - \frac{8718.3}{T - 83.16}$	1621.3
Meisl and Shapiro[5]	240-1040	$-\frac{10050}{T} - 0.698 \log T + 8.286$	
Weatherford et al.[7]	1040-2240	$-\frac{10104}{T} - 0.723 \log T + 8.402$	1630.3
Kelley[26]	357[a]-1620[a]	$-\frac{10395}{T} - 1.274 \log T + 9.1882$	1637.3
Stone et al.[10]	1624-2539	$-\frac{9980.94}{T} - 0.61344 \log T + 6.8377$	1618.6
Hicks[27]	mp-2070	See reference 23	1620.9

[a] Either lowest or highest temperature of data used to form correlation.

[b] Regression equation was found in this interval.

Bowles and Rosenblum[18] pooled their own measurements over the range 1470-3418°F with the measurements of Makansi et al.[21] (1149-2075°F), Ewing et al.[45] (1433-2539°F), and Sowa[19] (1652-2494°F) to obtain the equation given in Table III.2.

Thomson and Garelis analyzed critically the data of Rodebush and DeVries,[30] Edmondson and Egerton,[31] Rodebush and Walters,[34] Rodebush and Henry,[35] Thiele,[37] Makansi et al.,[21] and Heycock and Lamplough[28] to obtain the correlation given in Table III.2.

The correlations of Meisl and Shapiro[5] (which were used by Weatherford et al.[7]) were derived by an iteration process described in Sect. IV. The apparently anomalous value of the normal boiling point predicted by this process is noteworthy.

Kelley obtained his vapor pressure correlation from the data of Edmondson and Egerton,[31] Gebhardt[40] (716-1058°F), Haber and Zisch,[29] Hackspill[41] (662-746°F), Hansen[42] at 1367.3°F, Heycock and Lamplough,[28] Ladenburg and Thiele,[33] Lewis,[36] Rodebush and DeVries,[30] Rodebush and Henry,[35] Rodebush and Walters,[34] Ruff and Johannsen[43] (1612.1°F), Thiele,[37] Von Wartenburg[44] (823.7°F), and Weiler.[32]

Hicks[27] correlated the data of Makansi et al.,[21] Rodebush and Walters,[34] Haber and Zisch,[29] Heycock and Lamplough,[28] and Thiele.[37] He presented his results in tabular form.

Figure 3.2 shows that most of the "pooled" correlations differ rather uniformly from the equation of Stone et al.[10] below about 1600°F. On the basis of this and the close agreement between the equations of Stone et al.[10] and Makansi et al., above 1600°F, we choose the equation of Ditchburn and Gilmour:[25]

$$\log P_s(\text{atmos}) = 6.4818 - \frac{10020.6}{T(°R)} - 0.5 \log T(°R) \qquad (3.2)$$

for temperatures ≤1600°F and the equation of Stone et al. for higher temperatures. A similar choice was made earlier by Makansi, Selke, and Bonilla.[24]

IV. THERMODYNAMIC AND P-V-T PROPERTIES

Sodium vapor is composed of the monomer, dimer, and possibly the tetramer, the fraction of each species depending both upon temperature and pressure.[10] The saturated vapor contains about 10 mole percent dimer at 1500°F and 18 mole percent dimer at 2500°F. With ideal monomeric gas as a base, deviations from ideality in the vapor are due to the effect of species of higher molecular weight upon the mean molecular weight of the vapor and nonideal compressibility and mixing effects of the individual species. Before P-V-T measurements became available for sodium vapor, its mass specific volume at moderate pressures was computed from ideal-gas thermodynamic properties, generally neglecting the compressibility and mixing effects.

An outline of the thermodynamics of sodium provides a basis for discussing techniques that have been used to analyze pertinent experimental data. It is initially assumed that the vapor is saturated, consists only of the monomer and dimer, and these are ideal gases. For the dimerization reaction

$$2\mathrm{Na(g)} = \mathrm{Na_2(g)},$$

$$\Delta F_2^0 = RT \ln k_2, \qquad (4.1)$$

where

$$k_2 = \frac{P_{Na_2}}{P_{Na}^2} = \frac{N_2}{P_s N_1^2} = \frac{N_2}{P_s(1 - N_2)^2}. \qquad (4.2)$$

Dividing through Eq. (4.1) by T and rearranging,

$$-R \ln k_2 = \frac{\Delta F_2^0}{T} = \left(\frac{F^0 - H_0^0}{T}\right)_2 - 2\left(\frac{F^0 - H_0^0}{T}\right)_1 + \frac{(\Delta H_0^0)_D}{T}. \qquad (4.3)$$

As a convenience, denote

$$(\Delta H_0^0)_D = \Delta D_0^0,$$

the heat of dimerization of the ideal gas at absolute zero.

The thermodynamic properties of ideal gaseous Na and Na_2 have been computed from spectroscopic data via statistical-mechanical techniques. The computations of Benton and Inatomi[46] cover the range 180-4680°R for both species, those of Evans _et al_.[47] cover the range 0-4500°R for the monomer and 0-2700°R for the dimer, those of Stull and Sinke[48] the range 536-5400°R for the monomer and 536-2700°R for the dimer, and those of the JANAF Tables[96] the range 0-10800°R for both species. The values of the free energy functions $\left(\frac{F^0 - H_0^0}{T}\right)_1$ and $\left(\frac{F^0 - H_0^0}{T}\right)_2$ reported by all four of these groups are in excellent agreement. Thus, it may be assumed that Eq. (4.3) involves the three quantities P_s, N_2, and ΔD_0^0; i.e., only P_s and ΔD_0^0 are required to determine the ideal composition of the saturated vapor.

The status of work on the vapor pressure is discussed in the preceding section. The value of ΔD_0^0 has been determined experimentally by a number of investigators, as discussed in detail by Thomson and Garelis.[4] The values presented range from -8400 ± 100 to -9300 ± 500 cal/gm-atom Na. The vapor composition is extremely sensitive to the value of ΔD_0^0, however, as shown in Table IV.1, taken from Thomson and Garelis.[4]

TABLE IV.1. Effect of Change in ΔD_0^0 of Dimerization on Amount of Na_2 (Ref. 4)

$-\Delta D_0^0$ of Dimerization (cal/gm-atom Na)	Mole percent Na_2 at temperature (°K) shown			
	600	800	1000	1200
8000	0.4	2.2	5.2	8.8
8500	1.0	3.9	8.1	12.3
9000	2.3	6.9	12.2	16.8
9500	4.9	11.6	17.7	22.3

For vaporization to the ideal monomer:

$$Na(\ell) = Na(g),$$

$$\Delta F_v^0 = -RT \ln P_{Na}. \tag{4.4}$$

Thus,

$$(\Delta H_0^0)_v = -RT \ln P_{Na} - T\left[\left(\frac{F^0 - H_0^0}{T}\right)_i - \left(\frac{F^0 - H_0^0}{T}\right)_\ell\right], \tag{4.5}$$

where $(\Delta H_0^0)_v$ is the heat of vaporization to the ideal monomer at absolute zero.

Ginnings, Douglas, and Ball measured the heat capacity of condensed-phase sodium to a high order of precision in the range 547-2106°R.[49] From this work they derived empirical equations for the enthalpy, specific heat, and entropy of condensed-phase sodium from 492-2111°R. Stone <u>et al</u>. recently reported specific heat measurements for the range 1060-2610°R; they used their results as a basis for extrapolating the Ginnings' correlations to 2610°R,[10] as shown in Fig. 4.1. Also shown is a specific heat curve derived from an equation given by Shpilrain et al.[77] for the enthalpy of liquid sodium.[77] The latter equation is based upon data taken in the range 1032-2292°R; the scatter of the experimental points is reported to be within ±2%. Lacking further precise high-temperature data here, we arbitrarily take the work of Ginnings et al., as extended by Stone et al., as definitive.

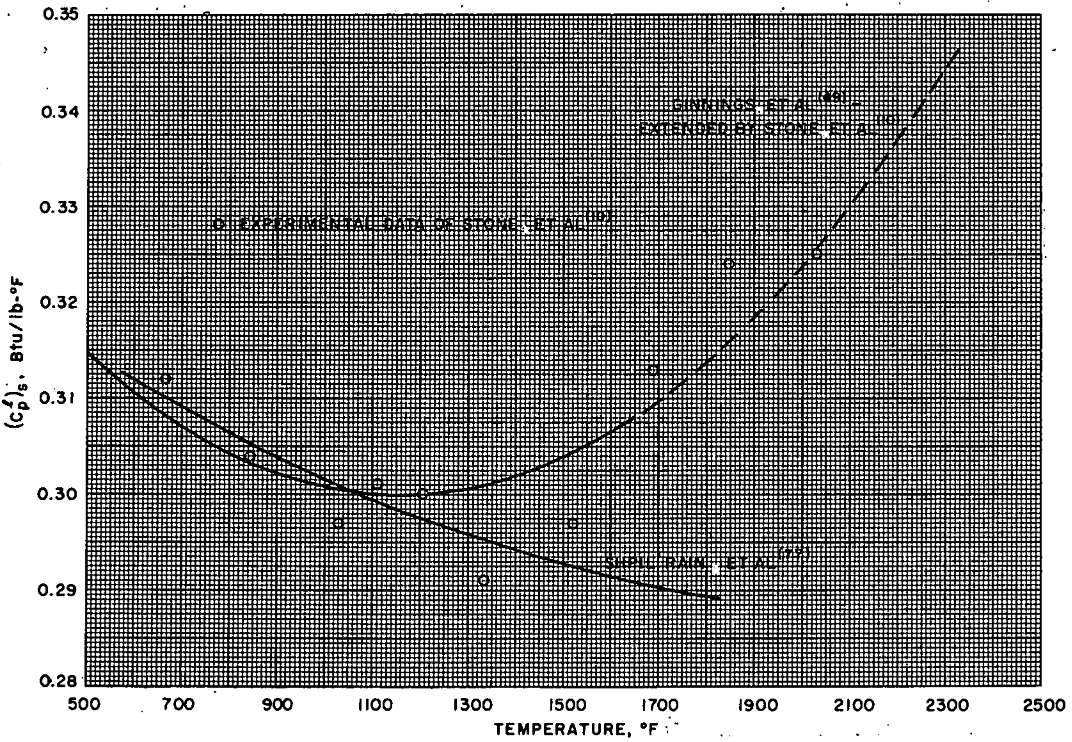

Fig. 4.1. Specific Heat of Saturated Liquid Sodium

Since the foregoing work permits the calculation of $\left(\frac{F^0 - H_0^0}{T}\right)_\ell$ to at least 2100°R, it may be assumed that Eq. (4.5) involves the three parameters P_S, N_2, and $(\Delta H_0^0)_v$. Thus, Eqs. (4.3) and (4.5) constitute two relationships involving the four parameters P_S, N_2, ΔD_0^0, and $(\Delta H_0^0)_v$. Fixing any two of these parameters should completely characterize the ideal system. Given a vapor pressure relationship and an assumed value of ΔD_0^0, the vapor composition can be computed from Eq. (4.3); the derived value of P_{Na} can then be used to evaluate $(\Delta H_0^0)_v$. If $(\Delta H_0^0)_v$ is found to be invariant over the temperature range for a given vapor pressure relationship and assumed value of ΔD_0^0, there is obtained the so-called "third-law check" of the internal consistency of the vapor pressure data (see Sect. III).

Thomson and Garelis[4] analyzed the data for sodium vapor pressure available in 1955, using the condensed-phase data of Ginnings, Douglas, and Ball,[49] and the free energy functions of Benton and Inatomi[46] for the ideal monomeric and dimeric gases. They found systematic discrepancies between the various sets of data that were considerably greater than the experimental scatter within the sets, and they discussed three alternate approaches as attempts to reconcile these discrepancies. On the basis of the available evidence, they took $\Delta D_0^0 = -9100$ cal/gm-atom Na, and obtained a "best" value of $(\Delta H_0^0)_v = 26289$ cal/gm-atom Na. Using these values, they prepared the self-consistent thermodynamic tables of reference 4. These tables include free energy functions for vaporization to the ideal monomeric gas, corresponding functions for the dimerization, the proportion of the dimer in the equilibrium vapor, the total and partial vapor pressures, enthalpies of the various states, and heats of vaporization to these states. The temperature range of the tables is 25-1125°C (77-2057°F), except for the vapor pressure table, which is for 97.83-1125°C (208-2057°F). The quoted normal boiling point in this work is 1621.3°F.

Evans et al.[47] took $\Delta D_0^0 = -8765$ and $(\Delta H_0^0)_v = 25920$ cal/gm-atom Na. Using their data we calculated a normal boiling point of 1637.7°F. We also calculated values of ΔD_0^0 and $(\Delta H_0^0)_v$ from the tables of Stull and Sinke,[48] using Eqs. (4.3) and (4.5), respectively. At 298°K, $\Delta D_0^0 = -8761$ and $(\Delta H_0^0)_v = 25946$ cal/gm-atom Na. At 1000°K the corresponding values are -8765 and 25951 cal/gm-atom Na. Their quoted normal boiling point is 1634°F. We repeated these calculations for the 1000°K data of the JANAF tables[96] and obtained $\Delta D_0^0 = -9082$ and $(\Delta H_0^0)_v = 25818$ cal/gm-atom Na. Here the quoted normal boiling point is 1621°F.

Makansi, Selke, and Bonilla[24] assumed that the vapor pressure could be described by the Ditchburn equation (see Sect. III) in the range 720-2160°R and by the Makansi equation (ibid.) in the range 1440-2520°R, with both equations used in the region of overlap. They used these relationships together with the condensed-phase data of Ginnings, Douglas, and Ball, and ideal gaseous monomer and dimer properties of Benton and Inatomi to determine the most self-consistent value of ΔD_0^0. To do this, they derived a function based upon the assumptions that the liquid specific volume is negligible compared to that of the vapor, and that the vapor species behave ideally (they also took the atomic weight of sodium to be 22.997). They pointed out that ideally this function should equal zero at all temperatures for the correct value of ΔD_0^0, but, because of the assumptions made in its derivation, this would not occur. These investigators described in detail the techniques used to obtain a "best" value of ΔD_0^0 from this function, which gave $\Delta D_0^0 = -8420$ cal/gm-atom Na.

They then computed the thermodynamic properties of sodium along the saturation curve and also in the superheated region of the vapor. The saturation properties included the vapor pressure, weight fraction dimer in the vapor, specific volume of the vapor, and enthalpy and entropy of the liquid and vapor, all for the range 768-3341°R. The superheat properties (the enthalpy, entropy, and specific volume of the vapor) were computed for a series of pressures from 10^{-8} to 50 atmos. at temperatures from saturation to 4680°R. A temperature-entropy chart was also presented.

In preparing the foregoing tables and chart, Makansi, Selke, and Bonilla took $\Delta D_0^0 = -8420$ cal/gm-atom Na, Ditchburn's equation at saturation pressures up to 0.05 atm, Makansi's equation at higher pressures, the condensed-phase data of Ginnings, Douglas, and Ball, and the ideal monomeric and dimeric gas properties of Benton and Inatomi. They computed the specific volume of the vapor on the assumption that the monomer and dimer components behave ideally, i.e.,

$$V = RT/\overline{M}P, \tag{4.6}$$

where

$$\overline{M} = M_1N_1 + M_2N_2 = M_1(1 + N_2). \tag{4.7}$$

They computed N_2 by means of Eq. (4.3) for a given total pressure, used Ginnings' data to calculate the enthalpy and entropy of the saturated liquid, and computed the heat of vaporization using the Ditchburn equation together with the approximate form of the Clausius-Clapeyron equation ($V^g - V^\ell \approx V^g$). They then calculated the enthalpy and entropy of the saturated vapor from the corresponding saturated liquid properties and the heat of vaporization. They computed the enthalpy of the superheated vapor by integrating the effective specific heat of the equilibrium vapor at constant pressure with respect to temperature, the lower limit corresponding to the saturation state, and obtained the entropy of the superheated vapor in a similar manner, integrating the effective specific heat divided by the temperature.

They obtained a normal boiling point of 1618.6°F from the Makansi equation. We computed $(\Delta H_0^0)_V$ at 1000°K using their value of ΔD_0^0, Makansi's equation, the data of Benton and Inatomi for the free energy functions of the ideal monomer and dimer, and the data of Evans et al. for the free energy function of the condensed phase. We found $(\Delta H_0^0)_V = 25657$ cal/gm-atom Na.

Meisl and Shapiro[5] began by computing the enthalpy and entropy of the saturated liquid and then the corresponding properties of the saturated vapor, assuming the vapor pressure to follow Ditchburn's equation. They found a small discrepancy between $\Delta H_V/T$ and ΔS_V, which they removed by adjustment of the total vapor pressure. These investigators took their condensed-phase specific heat data from Thomson and Garelis (who took their data from Ginnings, Douglas, and Ball), and computed the enthalpy and entropy of the saturated liquid from the foregoing specific heat data, taking the enthalpy of the solid at 298°K, the fusion temperature, and the latent heat of fusion from Stull and Sinke. They computed a trial value of the vapor composition from Ditchburn's equation and the free energy functions of Stull and Sinke, and then calculated the enthalpy of the saturated vapor from

$$H_s^g = \frac{1}{\overline{M}} \sum_i N_i H_i^{0g}, \tag{4.8}$$

taking the enthalpy functions from Stull and Sinke, and $\overline{M}$ from Eq. (4.7). They calculated the entropy of the saturated vapor from

$$S_s^g = \frac{R}{\overline{M}} \left[\sum_i N_i \left(\frac{H_i^{0g} - F_i^{0g}}{RT} - \ell n\, N_i \right) - \ell n\, P \right], \tag{4.9}$$

using the same source of data. They then varied the total pressure to make

$$\frac{H_s^g - H_s^\ell}{T} = S_s^g - S_s^\ell. \tag{4.10}$$

Meisl and Shapiro presented their results in tabular and graphical form. The tables were for the temperature range 700-2700°R at 100° increments, and gave superheat properties up to 2700°R in 100° increments at each temperature. The saturation properties given were vapor pressure, liquid and vapor enthalpy, entropy, molecular weight and specific volume, equilibrium and frozen vapor sonic velocities and specific heats at constant pressure, and the frozen specific heat ratio. Corresponding properties were given for the superheated vapor.

Using their final vapor pressure relationships, we calculated a normal boiling point of 1630.3°F (2090.0°R). Also, we took their data at 1800°R to compute ΔD_0^0 and $(\Delta H_0^0)_v$ via Eqs. (4.3) and (4.5), respectively, using the free energy functions of Stull and Sinke. We calculated $\Delta D_0^0 = -8761$ and $(\Delta H_0^0)_v = 25928$ cal/gm-atom Na.

We employed the procedure of Meisl and Shapiro to compute the enthalpy and entropy of vaporization to the equilibrium vapor, using only data from the tables of Evans <u>et al</u>., that is, the partial pressures of the monomer and dimer, and hence their mole fractions, were derived directly from the tables. We found $\Delta H_v/T = 24.921$ eu and $\Delta S_v = 26.391$ eu at 1000°K. A repeat of these calculations using only the tables of Stull and Sinke gave $\Delta H_v/T = 24.981$ eu and $\Delta S_v = 26.459$ eu at 1000°K. We repeated these calculations for the JANAF tables and found $\Delta H_v/T = 25.168$ eu and $\Delta S_v = 27.197$ eu. In all three cases the inconsistency is considerable.

Weatherford, Tyler, and Ku gave tables and charts of thermodynamic properties of sodium.[7] They took their tables of enthalpy, entropy, and free energy functions for the liquid and for the ideal monomeric and ideal dimeric gases directly from Stull and Sinke.[48] They took their properties of the saturated phases directly from Meisl and Shapiro.[5]

Dunning[6] took the mole fractions of monomer and dimer in the saturated vapor from the work of Thomson and Garelis.[4] To compute the mole fractions in the superheated vapor, he started by computing k_2 in Eq. (4.2) from partial pressure data for the saturated vapor given by Thomson and Garelis. Since k_2 depends only upon temperature for the ideal system, the mole fraction of dimer could be computed for any pressure below the saturation value at a given temperature. [Note that his Eq. (14) is incorrect as written; the term on the left should be squared.] Given the mole fractions, he computed the mean molecular weight of the vapor via Eq. (4.7). Although he used the partial pressure data of Thomson and Garelis, Dunning computed the total saturation vapor pressure from the Ditchburn equation.

Dunning further computed the equilibrium vapor specific volume on a molar basis from the perfect gas law, applying a compressibility factor determined from generalized compressibility charts. To do this, the critical temperature was assumed to be 2273°K and the critical pressure to be 343 atmos. He then converted the specific volume to a mass basis by dividing the molar volume by the mean molecular weight above. This application of a compressibility as well as a molecular weight correction for the nonideal behavior of the vapor is unique in the literature dealing with sodium properties (excepting properties taken <u>from</u> Dunning, e.g., the paper of Spiller[9]).

Dunning calculated the enthalpy and entropy of the saturated liquid using the specific heat data of Thomson and Garelis for the range 97.81-1125°C (208-2057°F) and extrapolated values from 1125-1300°C (2057-2372°F). He obtained the molar heat of vaporization by substitution of Ditchburn's equation into the approximate form of Clausius-Clapeyron equation, and converted it to a mass basis by dividing the molar value by the mean molecular weight. He checked the resulting values by means of the equation

$$\Delta H_V \doteq \frac{N_1 \Delta H^0_{f1} + N_2 \Delta H^0_{f2}}{N_1 M_1 + N_2 M_2}, \qquad (4.11)$$

obtaining the heats of formation of the ideal monomeric and dimeric gases from Evans <u>et</u> <u>al</u>.,[47] but did not indicate the extent of agreement between the two approaches. Dunning used the resulting heat of vaporization together with the enthalpy and entropy of the saturated liquid to determine the corresponding properties of the saturated vapor. His method of computing the enthalpy of the superheated vapor is not clear, since his cited Eq. (23) does not appear to have any meaning. This is also true of the corresponding entropy.

Stone et al. were the first to report P-V-T measurements for sodium vapor.[10] They made 90 sets of measurements on the superheated vapor, covering the temperature range 1760-2590°F and pressure range 1.9-25.1 atmos. Nine sets of measurements of the specific volume of the saturated vapor in the temperature range 1750-2555°F were also obtained. In related work, they measured the saturation vapor pressure in the temperature range 1437-2538°F (0.34-23.8 atmos), the density of the liquid at an overpressure of one atmosphere in the range 1577-2491°F, and the specific heat of the saturated liquid in the range 600-2150°F. An extensive thermodynamic analysis of their data was also made.

Two different models can be set up to account for the nonideal behavior of sodium vapor. The first of these models is based upon a phenomenological approach, that is, the vapor is assumed to be made up entirely of the monomer, and the nonideal behavior is accounted for by means of a precise equation of state. The equation of state for a real gas can be expressed in one of the following "virial" forms:

$$\frac{Pv}{RT} = 1 + \frac{B}{v} + \frac{C}{v^2} + \frac{D}{v^3} + \ldots \qquad (4.12)$$

and

$$\frac{Pv}{RT} = 1 + B'P + C'P^2 + D'P^3 + \ldots, \qquad (4.13)$$

where the coefficients B, B', etc., are functions of temperature alone, and v is the volume per pound mole of the monomer. In general it has been found that for the same number of terms, Eq. (4.12) gives a better fit to experimental data than does Eq. (4.13).[50] Hence, in what follows T and v (or its reciprocal, ρ) are taken as independent variables, with P derived. Ewing et al. discussed methods for evaluating the virial coefficients of Eq. (4.12) from P-V-T data.[51,10] Stone et al. fitted Eq. (4.12), truncated to the number of terms shown, to their P-V-T data and obtained the following expressions for the coefficients:

$$B = -4.44734 \times 10^{-5}\, T\, e^{15554.65/T} \quad \text{ft}^3/\text{mole}; \qquad (4.14)$$

$$C = 0.243388\, e^{24958/T} \quad \text{ft}^6/\text{mole}^2; \qquad (4.15)$$

$$D = -0.811895\, e^{31175/T} \quad \text{ft}^9/\text{mole}^3. \qquad (4.16)$$

Their quoted average deviation of the equation from their data is ±0.26%.

The second (quasi-chemical) model for treating nonideality in sodium vapor starts with the basic assumptions that the vapor is made up of the monomer, dimer, and, say, tetramer, and that these are all perfect gases. For the reactions

$$2Na(g) = Na_2(g) \text{ and } 4Na(g) = Na_4(g),$$

we have

$$k_2 = N_2/N_1^2P \tag{4.17}$$

and

$$k_4 = N_4/N_1^4P^3, \tag{4.18}$$

where

$$\log k_2 = -A_2 + \frac{B_2}{T}, \tag{4.19}$$

$$\log k_4 = -A_4 + \frac{B_4}{T}, \tag{4.20}$$

and

$$N_1 + N_2 + N_4 = 1.$$

Ewing <u>et</u> <u>al</u>. also discussed techniques for evaluating the constants A_2, B_2, A_4, and B_4 from P-V-T data.[51,10] From their data Stone <u>et</u> <u>al</u>.[10] obtained

$$A_2 = 4.3249; \quad B_2 = 7204.2;$$

$$A_4 = 10.6798; \quad B_4 = 16325.$$

It was in connection with this part of their analysis that they deduced the presence of the tetramer in the vapor (which was consistent with the results of a parallel study made on potassium[51]).

Stone <u>et</u> <u>al</u>. then employed the equilibrium constants k_2 and k_4 to derive the mean molecular weight of the vapor at a given temperature and pressure. They computed the apparent dimerization constant k_2', with all association taken to be due to the dimer:

$$k_2' = \frac{N_2'}{N_1'^2P} = k_2 + 3k_4P^2 - 2k_2k_4P^3. \tag{4.22}$$

With $N_1' + N_2' = 1$, they solved the above equation for the apparent mole fraction of monomer, N_1', and dimer, N_2', and used these values to compute $\overline{M}$ from Eq. (4.7). Their quasi-chemical equation of state was Eq. (4.6) with $\overline{M}$ determined as above; they reported that it also fitted their data with an average deviation of ±0.26%.

The fact that the quasi-chemical approach gives a precise correlation of the experimental data should not be taken as complete substantiation of the physical model upon which it is based. To date, the presence of tetramer in the vapor has not been demonstrated by independent, i.e., mass-spectroscopic techniques. The departure from ideality ascribed to the presence of a higher molecular weight species may be due to another effect, such as nonideal compressibility of the monomer and/or dimer.

Given P, k_2, k_4, and $\overline{M}$, Stone et al. determined the vapor composition with a technique[51] based upon that of Ritter and Simons.[52] They solved the degenerate quartic equation

$$3\left(\frac{P\overline{M}}{M_1}\right)^3 k_4\,\alpha_1^4 + \left(\frac{P\overline{M}}{M_1}\right) k_2\,\alpha_1^2 = 1 - \frac{M_1}{\overline{M}} \qquad (4.23)$$

for α_1^2, where α_1 is the unassociated fraction of one initial mole of monomer, and then found the mole fractions of dimer and tetramer from

$$N_2 = \alpha_1^2\, P\left(\frac{\overline{M}}{M_1}\right)^2 k_2; \qquad (4.24)$$

$$N_4 = \alpha_1^4 P^3\left(\frac{\overline{M}}{M_1}\right)^4 k_4. \qquad (4.25)$$

We employed Eqs. (4.17) through (4.21) to obtain the mole fractions directly. Eliminating N_2 and N_4 from these equations results in

$$P^3k_4N_1^4 + Pk_2N_1^2 + N_1 - 1 = 0. \qquad (4.26)$$

We solved Eq. (4.26) numerically, and then computed

$$N_2 = k_2PN_1^2 \qquad (4.27)$$

and

$$N_4 = 1 - N_1 - N_2. \qquad (4.28)$$

Thus

$$\overline{M} = M_1(N_1 + 2N_2 + 4N_4). \qquad (4.29)$$

The two techniques gave results that agreed to five significant figures in the range 500-1600°F; at 2500°F Eq. (4.29) gave a value that is only 0.69% greater than that derived from Eq. (4.22).

Table IV.2 compares the vapor pressure, mole fraction of dimer, and vapor specific volume at saturation conditions as based upon the methods of the following workers:

a. Makansi, Selke, and Bonilla;[24]
b. Meisl and Shapiro;[5]
c. Dunning;[6] and
d. Stone et al.[10]

The agreement between the work of Makansi, Selke, and Bonilla and of Stone et al. above about 1300°F is noteworthy. The close correspondence of their experimental vapor pressure data was mentioned in Sect. III. The agreement between their values of N_2 and V at intermediate temperatures is striking because the former deduced a "best" value of ΔD_0^0 from available vapor pressure data and used it to compute N_2 and V, whereas the latter group deduced their N_2 values and hence ΔD_0^0 from their P-V-T measurements.

TABLE IV.2. Comparisons of Vapor Pressure, Mole Fraction of Dimer, and Specific Volume of Vapor at Saturation Conditions

	Makansi, Selke, and Bonilla[24]			Meisl and Shapiro[5]			Dunning[6]			Stone et al.[10]		
	ΔD_0^0 = -8,420 cal/mole Na			ΔD_0^0 = -8,760 cal/mole Na			ΔD_0^0 = -9,100 cal/mole Na			ΔD_0^0 = -8,500 cal/mole Na		
t, °F	P_S, atmos[a]	N_2	V_S, ft^3/lb[b]	P_S, atmos[c]	N_2[d]	V_S, ft^3/lb[e]	P_S, atmos[f]	N_2[g]	V_S, ft^3/lb[h]	P_S, atmos[i]	N_2[j]	V_S, ft^3/lb[k]
300	7.10×10^{-9}	0.0093	3.40×10^{9}	7.58×10^{-9}	0.00141	3.18×10^{9}	[f] 7.29×10^{-9}	0.00336	3.30×10^{9}	-	-	-
500	3.54×10^{-6}	0.0034	8.58×10^{6}	3.69×10^{-6}	0.00755	8.21×10^{6}	3.50×10^{-6}	0.0147	8.58×10^{6}	4.06×10^{-6}	0.00609	7.47×10^{6}
700	2.04×10^{-4}	0.0098	1.79×10^{5}	2.05×10^{-4}	0.0211	1.76×10^{5}	2.08×10^{-4}	0.0360	1.72×10^{5}	2.25×10^{-4}	0.0167	1.61×10^{5}
900	3.52×10^{-3}	0.0254	1.20×10^{4}	3.45×10^{-3}	0.0414	1.20×10^{4}	3.63×10^{-3}	0.0642	1.12×10^{4}	3.76×10^{-3}	0.0331	1.11×10^{4}
1100	3.13×10^{-2}	0.0504	1510	2.79×10^{-2}	0.0659	1670	2.91×10^{-2}	0.0954	1560	3.02×10^{-2}	0.0532	1560
1300	0.152	0.0736	342	0.139	0.0917	367	0.144	0.126	344	0.150	0.0752	347
1500	0.532	0.0957	107	0.498	0.117	112	0.536	0.154	100	0.531	0.0971	107
1700	1.48	0.117	41.5	1.27	0.140	47.3	1.50	0.179	38.6	1.48	0.118	41.2
1900	3.46	0.138	19.0	3.28	0.161	19.7	3.54	0.200	17.5	3.46	0.137	18.9
2100	7.08	0.157	9.92	6.65	0.179	10.4	7.30	0.217	8.80	7.04	0.153	9.79
2300	13.1	0.175	5.71	12.2	0.193	6.05	13.5	0.232	4.95	12.9	0.166	5.59
2500	22.2	0.191	3.56	-	-	-	-	-	-	21.7	0.176	3.44

[a] Obtained from point-by-point interpolation of reference data.
[b] $V = RT/\bar{M}P$, where $\bar{M} = 22.997(1 + N_2)$.
[c] Obtained from point-by-point interpolation of reference data using $\log P = A - (B/T)$.
[d] Interpolation of values of mole fraction of dimer as computed from reference tabulation of vapor molecular weights.
[e] $V = RT/\bar{M}P$, where $\bar{M} = 22.991(1 + N_2)$.
[f] Cited source is Ditchburn equation.
[g] Taken from Ref. (4) as cited source.
[h] Contains corrections both for dimerization and nonideal compressibility.
[i] Eq. (3.1).
[j] Eq. (4.27).
[k] $V = RT/\bar{M}P$ with $\bar{M}$ determined from Eq. (4.29).

To compute the thermodynamic properties of real saturated sodium one generally uses either the liquid or the ideal monomeric gas as a base. In the former approach, the properties of the saturated liquid are computed from known specific heat data, the heat of vaporization is deduced from either the Clausius-Clapeyron equation or the heats of formation and mole fractions of the individual gas-phase species, and the resulting values are used to compute the corresponding properties of the saturated vapor. This is known as the "liquid-base" approach; it was employed by Makansi, Selke, and Bonilla[24] and Dunning.[6] The other approach is to compute the properties of the ideal gas from spectroscopic data, add a correction based upon an equation of state or the computed dimerization, etc., to obtain the properties of the real gas, deduce the heat of vaporization as before, and then compute the corresponding properties of the saturated condensed phase. This is termed the "gas-base" approach; it was employed by Stone et al.[10] With either approach, the properties of the subcooled liquid and superheated vapor can be derived starting with the corresponding saturation property.

It has been shown that the molar enthalpy and entropy of a real gas are given by[50]

$$H^g(T,v) = E^g(T,v) + KPv = E^{0g}(T) + K\int_v^{\infty}\left[P - T\left(\frac{\partial P}{\partial T}\right)_v\right]dv + KPv \tag{4.30}$$

and

$$S^g(T,v) = S^{0g}(T) + R'\,\ell n\,\frac{v}{RT} + K\int_v^{\infty}\left[\frac{R}{v} - \left(\frac{\partial P}{\partial T}\right)_v\right]dv. \tag{4.31}$$

The above equations are readily evaluated by means of the virial Eq. (4.12), integrating to the following (where $\rho = 1/v$):

$$H^g(T,\rho) = H^{0g}(T) + R'T\rho\left[\left(B - T\frac{dB}{dT}\right) + \rho\left(C - \frac{T}{2}\frac{dC}{dT}\right) + \rho^2\left(D - \frac{T}{3}\frac{dD}{dT}\right)\right]. \tag{4.32}$$

and

$$S^g(T,\rho) = S^{0g}(T) - R'\,\ell n\,\rho RT - R'\rho\left[\left(B + T\frac{dB}{dT}\right) + \frac{\rho}{2}\left(C + T\frac{dC}{dT}\right) + \frac{\rho^2}{3}\left(D + T\frac{dD}{dT}\right)\right]. \tag{4.33}$$

The consistent value of ρ is evaluated from Eq. (4.12). The corresponding molar latent heat of vaporization is computed from the differential (exact) form of the Clausius-Clapeyron equation:

$$\Delta H_v = KT\left(\frac{1}{\rho} - \frac{1}{\rho_\ell}\right)\frac{dP_s}{dT}. \tag{4.34}$$

The molar gas-base virial properties are computed from Eqs. (4.32)-(4.34), with[10]

$$H^{0g} - (H_0^0)^s = 22.991\left(2005.15 + 0.21598T + 12172\,e^{-43830/T}\right) \tag{4.35}$$

and

$$S^{0g} = 22.991(0.23859 + 0.21598 \, \ell n \, T). \tag{4.36}$$

The gas-base enthalpy of the saturated real vapor computed from the virial equation is shown in the seventh column of Table IV. 3; the derived enthalpy of the saturated liquid is shown in the eighth column.

TABLE IV.3. Comparison of Saturated Liquid and Vapor Enthalpies (Btu/lb) Computed via Liquid- and Gas-base Approaches

T (°F)	Liquid-base: $H_s^\ell - \left(H_0^0\right)^{s}$ [(a)]	Virial: Clausius-Clapeyron ΔH_v [(b)]	Liquid-base Virial: $H_s^g - \left(H_0^0\right)^{s}$ [(c)]	Quasi-chemical: ΔH_v [(d)]	Quasi-chemical: $H_s^g - \left(H_0^0\right)^{s}$ [(e)]	Gas-base Virial: $H_s^g - \left(H_0^0\right)^{s}$ [(f)]	Gas-base Virial: $H_s^\ell - \left(H_0^0\right)^{s}$ [(g)]
500	303.8	1930.9	2234.7	1901.1	2204.8	2208.8	278.5
600	335.0	1921.1	2256.1	1885.5	2220.5	2226.9	306.9
700	365.9	1908.9	2274.8	1868.3	2234.1	2243.3	336.0
800	396.4	1893.9	2290.3	1849.3	2245.8	2257.7	366.0
900	426.7	1876.1	2302.8	1829.0	2255.7	2270.0	396.7
1000	456.9	1855.3	2312.2	1807.6	2264.4	2280.3	428.1
1100	486.9	1831.9	2318.8	1785.4	2272.3	2288.9	460.1
1200	516.9	1806.3	2323.2	1762.7	2279.6	2295.9	492.7
1300	546.9	1778.9	2325.8	1739.9	2286.7	2310.7	525.5
1400	577.0	1750.4	2327.4	1716.9	2293.9	2306.9	558.4
1500	607.2	1721.4	2328.6	1693.9	2301.1	2311.8	591.3
1600	637.7	1692.6	2330.3	1670.8	2308.5	2316.9	624.0
1700	668.5	1666.0	2334.5	1648.5	2317.0	2322.6	656.6
1800	699.6	1640.0	2339.7	1625.6	2325.2	2329.0	689.0
1900	731.2	1614.9	2346.2	1602.1	2333.4	2336.4	721.5
2000	763.4	1590.5	2353.8	1577.8	2341.2	2344.7	754.2
2100	796.0	1566.1	2362.2	1552.5	2348.6	2353.5	787.4
2200	829.4	1541.2	2370.5	1526.0	2355.3	2362.5	821.4
2300	863.3	1514.6	2378.0	1498.1	2361.5	2371.2	856.6
2400	898.1	1485.3	2383.5	1468.8	2366.9	2378.8	893.5
2500	933.8	1451.6	2385.4	1438.1	2371.9	2384.4	932.8

[(a)] Eq. (4.37).

[(b)] Eq. (4.34); ρ computed from Eq. (4.12); for $t \le 1600$°F, P_S computed from Ditchburn equation; for $t > 1600$°F, P_S computed from Stone equation.

[(c)] Sum of liquid-base $\left[H_s^\ell - \left(H_0^0\right)^s\right]$ and virial Clausius-Clapeyron ΔH_v.

[(d)] Eq. (4.40); for $t \le 1600$°F, P_S computed from Ditchburn equation; for $t > 1600$°F, P_S computed from Stone equation.

[(e)] Eq. (4.42).

[(f)] Eq. (4.32).

[(g)] Difference between virial values of gas-base $\left[H_s^g - \left(H_0^0\right)^s\right]$ and ΔH_v.

The liquid-base molar enthalpy and entropy of the saturated liquid are computed from[10]

$$H_s^\ell - (H_0^0)^s = 22.991(0.389352\,T - 0.552955 \times 10^{-4}\,T^2 + 0.113726 \times 10^{-7}\,T^3 - 29.023) \tag{4.37}$$

and

$$S_s^{\ell} = 22.991(0.896497 \log T - 1.10557 \times 10^{-4} T + 0.170408 \times 10^{-7} T^2 - 1.792026). \quad (4.38)$$

Liquid-base enthalpy values for the saturated liquid are shown in the second column of Table IV.3. Corresponding liquid-base virial values for the saturated vapor are shown in the fourth column. Over the range 1700-2500°F the mean deviation between the enthalpies of the saturated vapor computed from the gas- and liquid-base virial approaches is about 0.34%, and the maximum deviation is about 0.51% (the standard deviation Stone et al.[10] quoted for their virial equation is 0.28%). When the two approaches are used to calculate H_s^g values at temperatures below 1700°F, however, deviations of as much as 1.44% are observed, the mean deviation over the range 500-2500°F being about 0.78%.

From a third-law check of their vapor pressure data, Stone et al. took $(\Delta H_0^0)_v$ = 25,610 cal/mole Na. They employed Eqs. (4.19) and (4.20) in the van't Hoff equation to compute average values of the heats of dimerization and tetramerization for the range of their data, obtaining $\Delta H_2^0 = -18{,}304$ cal/mole Na_2 and $\Delta H_4^0 = -41{,}478$ cal/mole Na_4. They computed ΔD_0^0 by two methods. Using the foregoing value of ΔH_2^0 and the data of Evans et al.[47] in the identity

$$\Delta D_0^0 = \Delta H_2^0 - \Delta(H^0 - H_0^0)\Big|_{2Na}^{Na_2},$$

they obtained ΔD_0^0 = -8,500 cal/mole Na at 2250°F. Using Eq. (4.3) and the same sources of data, they obtained ΔD_0^0 = -8,400 cal/mole Na. Values of ΔD_0^0, $(\Delta H_0^0)_v$, and the normal boiling point (NBP) corresponding to the work of the various investigators are given in Table IV.4.

TABLE IV.4. Summary of Key Parameters Corresponding to Work of Various Investigators

Investigators	$-\Delta D_0^0$, cal/gm-atom Na	$(\Delta H_0^0)_v$, cal/gm-atom Na	P_s	NBP, °F
Thomson and Garelis[4]	9100	26289	derived	1621.3
Evans et al.[47]	8765	25920		1637.7[b]
Stull and Sinke[48]	8765[a]	25951[a]		1634
Makansi et al.[24]	8420	25657[a]	see text	1618.6
Meisl and Shapiro[5]	8761[a]	25928[a]	see text	1630.3
JANAF Tables[96]	9082	25818		1621
Stone et al[10]	8400-8500	25610	Stone equation	1618.6

[a] Computed from 1000°K data.

[b] Computed from reference data.

We computed a quasi-chemical heat of vaporization, starting with Eqs. (4.26)-(4.29), to determine N_1, N_2, N_4, and $\overline{M}$. The heat of formation of the monomer was computed from the saturated liquid by use of

$$\Delta H^0_{f1}(T) = T\left[\left(\frac{H^0 - H^0_0}{T}\right)_1 - \left(\frac{H^0 - H^0_0}{T}\right)_\ell\right] + (\Delta H^0_0)_v, \tag{4.39}$$

where

$$(\Delta H^0_0)_v = 25{,}610 \text{ cal/mole Na},$$

$$\left(\frac{H^0 - H^0_0}{T}\right)_1 = 4.9680 \text{ cal/mole Na °K},$$

and

$$\left(\frac{H^0 - H^0_0}{T}\right)_\ell = \left(8.95162 - 2.28834 \times 10^{-3}\,T + 8.47156 \times 10^{-7}\,T^2 - \frac{370.70}{T}\right) \text{cal/mole Na °K}.$$

Then for T in °R:

$$\Delta H^0_{f1}(T) = (25980.7 - 2.21312\,T + 7.06278 \times 10^{-4}\,T^2 - 1.4526 \times 10^{-7}\,T^3) \text{ cal/mole Na}.$$

As an approximation, we took

$$\Delta H^0_{f2}(T) = (2\Delta H^0_{f1} - 18304) \text{ cal/mole } Na_2$$

and

$$\Delta H^0_{f4}(T) = (4\Delta H^0_{f1} - 41478) \text{ cal/mole } Na_4.$$

Then

$$\Delta H_v = \frac{N_1\Delta H^0_{f1} + N_2\Delta H^0_{f2} + N_4\Delta H^0_{f4}}{\overline{M}} \text{ cal/gm}. \tag{4.40}$$

From the equation for computing the enthalpy of the saturated vapor from the liquid base:

$$H^g_s - (H^0_0)^s = H^\ell_s - (H^0_0)^s + \Delta H_v, \tag{4.41}$$

and ΔH_V defined by Eq. (4.40), it is readily shown that

$$H_s^g - (H_0^0)^s = H^{0g} - (H_0^0)^g + (\Delta H_0^0)_V + X_{2S}\Delta H_2^0 + X_{4S}\Delta H_4^0, \tag{4.42}$$

that is, the above procedure for computing H_s^g makes it in fact independent of the liquid properties, i.e., makes it a gas-base calculation. This implies that the difference between values of H_s^g computed via the gas-base virial and the above method is due mainly to the two different equations of state employed.

The heat of vaporization computed from Eq. (4.40) is shown in the fifth column of Table IV.3; the corresponding enthalpy of the saturated vapor computed from Eq. (4.42) is shown in the sixth column. In the range 1700-2500°F the mean deviation between H_s^g values calculated from the gas-base virial and quasi-chemical approaches is about 0.29%, and the maximum deviation is about 0.52%. At lower temperatures, however, this good agreement is maintained, the mean deviation over the range 500-2500°F being about 0.44%. Thus, these two methods for computing H_s^g agree to very nearly the quoted standard deviation for both equations of state, namely, 0.28%.

The heat of vaporization defined by Eq. (4.40) makes the entropy of the saturated vapor dependent upon liquid properties; it is thus necessary to compare S_s^g values computed by the virial and quasi-chemical methods. In the range 1700-2500°F the mean deviation is 0.11%, and the maximum deviation is 0.17%. Enthalpy and entropy values for the superheated vapor as computed by the two methods are compared in Table IV.5; again the excellent agreement is evident.

TABLE IV. 5. Enthalpy and Entropy of Superheated Vapor Computed via Virial and Quasi-chemical Approaches

T, °F	P, atmos	H^g(vir), Btu/lb	H^g(qc), Btu/lb	%, Deviation[a]	S^g(vir), Btu/lb °F	S^g(qc), Btu/lb °F	%, Deviation[a]
1800	2.0	2347.8	2342.2	0.24	1.7922	1.7900	0.12
	1.0	2416.2	2406.5	0.40	1.8776	1.8734	0.22
	0.2	2477.3	2473.3	0.16	2.0397	2.0376	0.10
2000	5.0	2344.9	2341.5	0.15	1.7215	1.7208	0.04
	1.0	2491.8	2484.8	0.28	1.9097	1.9074	0.12
	0.2	2527.3	2525.3	0.08	2.0609	2.0603	0.03
2200	9.0	2372.7	2366.7	0.25	1.6891	1.6879	0.07
	5.0	2450.8	2445.8	0.20	1.7630	1.7622	0.05
	1.0	2551.6	2547.3	0.17	1.9331	1.9323	0.04
	0.2	2573.9	2572.9	0.04	2.0791	2.0794	-0.02
2500	20.0	2399.9	2388.6	0.47	1.6414	1.6391	0.14
	15.0	2448.2	2441.8	0.26	1.6785	1.6777	0.05
	10.0	2504.1	2500.1	0.16	1.7281	1.7281	0.00
	5.0	2569.8	2565.3	0.18	1.8055	1.8054	0.01
	1.0	2628.8	2626.8	0.08	1.9606	1.9612	-0.03
	0.2	2641.3	2640.9	0.01	2.1031	2.1042	-0.06

[a] $\frac{\text{vir} - \text{qc}}{\text{qc}} \times 100.$

The heat of vaporization computed by the virial and quasi-chemical methods [Eqs. (4.34) and (4.40), respectively] are shown in Fig. 4.2. Over the range 1700-2500°F the mean deviation between values computed by the two methods is 0.95%, and the maximum deviation is 1.12%. The deviation increases with decreasing temperature, however, and equals 1.5% at 500°F, the lower limit of extrapolation of the methods. Also shown in Fig. 4.2 are values taken from the tabulations of Meisl and Shapiro,[5] Makansi, Selke, and Bonilla,[24] and the recent experimental work of Achener and Jouthas.[22] The latter recommend the relationship

$$\Delta H_V = 2023 - 0.2129\,t\ (\text{Btu/lb}), \quad 1100 < t < 1700°\text{F}.$$

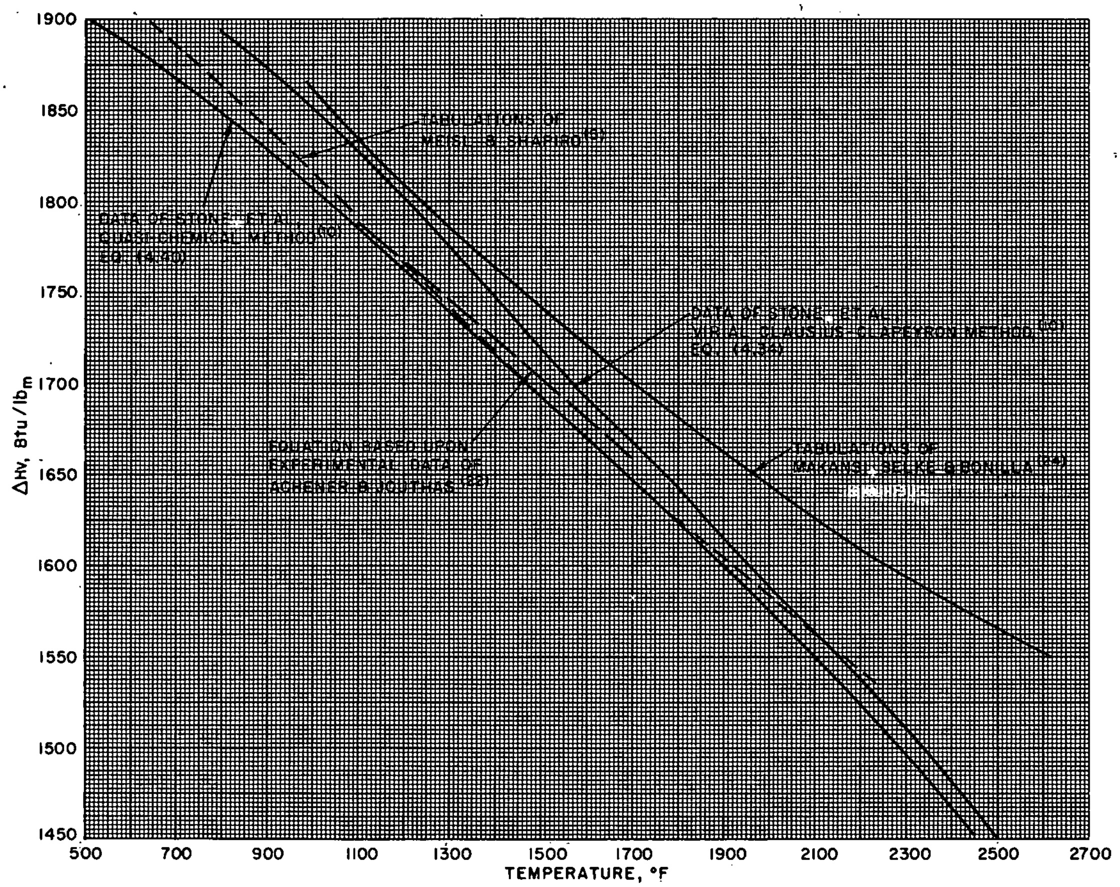

Fig. 4.2. Heat of Vaporization of Sodium

It is seen that at temperatures below about 1600°F the quasi-chemical curve agrees more closely with that of Achener and Jouthas than does the virial curve. Because of this and the close agreement between the virial and quasi-chemical methods at temperatures above 1600°F, we choose Eq. (4.40) to compute the heat of vaporization.

We have written a FORTRAN subroutine based upon the quasi-chemical approach for computing the thermodynamic properties of sodium in the range 500-2500°F. It is based upon the work of Ditchburn and Gilmour,[25] Ginnings, Douglas, and Ball,[49] Evans et al.,[47] and Stone et al.[10] For a given temperature and pressure the subroutine determines the state (i.e., subcooled liquid, saturated liquid and vapor, or superheated vapor) and computes the properties. For temperatures $\leq 1600°F$, the vapor pressure is computed from Ditchburn's equation; at higher temperatures, Stone's Eq. (3.1) is used. The enthalpy and entropy of the saturated liquid are computed from Eqs. (4.37) and (4.38), respectively, i.e., the liquid-base approach is used here. The corresponding properties of the saturated vapor are computed from the saturated liquid properties and the quasi-chemical heat of vaporization as given in Eq. (4.40); as indicated earlier, this is actually a gas-base calculation. The vapor composition is found by solving Eqs. (4.17)-(4.21) and (4.26)-(4.28), and the mean molecular weight from Eq. (4.29). This latter is used in Eq. (4.6) to compute the mass specific volume of the vapor.

Given the temperature and pressure of superheated vapor, we computed its composition, mean molecular weight, and specific volume as above. Ewing et al.[51] give the following equations for the enthalpy and entropy of the vapor in state i:

$$H_i^g(T,P) = H^{0g}(T) + X_2\Delta H_2^0 + X_4\Delta H_4^0 \qquad (4.43)$$

and

$$S_i^g(T,P) = S^{0g}(T) + \frac{X_2\Delta H_2^0}{T} + \frac{X_4\Delta H_4^0}{T} - \frac{R}{\overline{M}}\ln P + \frac{RX_2}{2M_1}\ln k_2 + \frac{RX_4}{4M_1}\ln k_4 - \frac{R(N_1\ln N_1 + N_2\ln N_2 + N_4\ln N_4)}{\overline{M}}. \qquad (4.44)$$

[Note the equivalence of Eqs. (4.42) and (4.43).] We used these equations to compute the change in enthalpy and entropy along the following path:

Saturated vapor at T and P_s $\xrightarrow[T]{\text{constant}}$ Very low P; all dimer and tetramer converted to monomer (ideal monomeric gas) $\xrightarrow[T]{\text{constant}}$ $P < P_s$; partial conversion of monomer to dimer and tetramer (superheated vapor)

This gives the enthalpy and entropy of the superheated vapor.

We computed the enthalpy and entropy of the subcooled liquid starting with the corresponding properties of the saturated liquid. The enthalpy change is given by

$$dH_T = \frac{K}{\rho_\ell}\left[1 + \frac{T}{\rho_\ell}\left(\frac{\partial \rho_\ell}{\partial T}\right)_P\right] dp \qquad (4.45)$$

and the entropy change by

$$dS_T = \frac{K}{\rho_\ell^2}\left(\frac{\partial \rho_\ell}{\partial T}\right)_P dp. \tag{4.46}$$

As an approximation, we computed $\left(\frac{\partial \rho_\ell}{\partial T}\right)_P$ from the density Eq. (2.1).

A listing of the subroutine is given in Appendix A. It can be used in any compatible computer program calling for the given properties, or as the core of a table-making program. A tabulation of the thermodynamic and related properties of the saturated liquid and vapor as computed by the subroutine is given in Appendix B.

We used the subroutine to compute the specific heat of the vapor at constant pressure along the saturation curve, taking

$$\left(C_p^g\right)_s = H^g(T+1, P_s) - H_s^g(T). \tag{4.47}$$

Differences between the quasi-chemical and virial approaches are magnified when vapor specific heats computed by the two approaches are compared, because of the increased sensitivity of these derivatives to error. In the range 1600-2500°F, the maximum deviation between the two approaches is 8.9%, and the rms deviation is 6.2%. Because of this relatively large discrepancy, values of $\left(C_p^g\right)_s$ computed via the quasi-chemical approach are listed in a separate table, together with the related vapor Prandl number and thermal diffusivity (see Appendix D).

The foregoing general approach is tentative in that it is based directly on the best experimental data presently available. Given more high-quality experimental data, a different approach might be selected. In other words, precise P-V-T measurements to temperatures well below 1700°F might lead to the choice of gas-base calculations. On the other hand, extension of the precision measurements for saturated liquid specific heat to temperatures well above 1600°F would probably strengthen the choice of liquid-base calculations. Either or both of the foregoing types of experiments appear justifiable.

V. TRANSPORT PROPERTIES

In this chapter are reviewed the thermal conductivity and viscosity of both the saturated liquid and vapor phases. A summary of the recommended values of transport properties is given in Appendix C for the temperature range from 210 to 2500°F in 10° temperature intervals. Prandtl number (Pr), thermal diffusivity (α), specific heat at constant pressure, electrical resistivity, and surface tension data are also tabulated in Appendix C for the liquid phase. Appendix D contains provisional tabulations of specific heat, Prandtl number, and thermal diffusivity for the saturated equilibrium vapor. These tabulations were not incorporated into Appendix C but reported separately for reasons indicated in the last paragraphs of Chapter IV together with germane statements made throughout this chapter.

Further, it should be stressed that throughout this chapter and Chapters VI and VII an attempt was made to report referenced material in the form in which it appeared; the symbolism, however, was changed to conform to that shown in the Nomenclature listing. Some confusion may therefore arise because both the engineering and metric system of units are used, depending on the author referenced.

A.1. Thermal Conductivity of Liquid Sodium

The thermal conductivity of liquid sodium was measured by Evangelisti and Isacchini[54,55] over the temperature range 104-832°C (194-1530°F). The sodium was contained within a thermally stabilized and guarded Type 304 stainless steel capsule. The thermal conductivity at a particular temperature level was inferred from a steady-state temperature drop in the liquid sodium across a well-defined length and from a determination of the axial heat flux. Twenty experimental points were obtained. The results were presented in tabular, graphical, and equation form. The relationship between thermal conductivity and temperature was given by the linear equation

$$k(\mathrm{W/cm\text{-}^\circ C}) = 0.916 - 0.49 \times 10^{-3}\, t(^\circ\mathrm{C}). \qquad (5.1)$$

The average deviation of the experimental points about the linear fit was stated to be ±1.17% with a maximum deviation of +3.9%.

Thomson and Garelis,[4] drawing on the measurements of Hall[56] from 100 to 210°C, Ewing and Grand[57] from 181.7 to 512.5°C, and on unpublished data of the General Electric Company given in reference 2 from 100 to 350°C, recommend the following representative fit of the data:

$$k(\mathrm{cal/cm\text{-}sec\text{-}^\circ C}) = 0.2166 - 1.16 \times 10^{-4}\, t(^\circ\mathrm{C}), \qquad (5.2)$$

over the temperature range 97.8-550°C (208-1022°F). The difference between the observed source data and the calculated values using the above equation is stated to be less than 2%, and for the majority of the points the difference is stated to be less than 1%.

Miller and Epstein[3] in reviewing the work of Hall[56] and of Ewing and Grand[57] recommend the relationship

$$k(\mathrm{W/cm\text{-}°C}) = \frac{2.443 \times 10^{-2}\,(t + 273.16)}{6.8393 + 3.3873 \times 10^{-2}\,t + 1.7235 \times 10^{-5}\,t^2}, \tag{5.3}$$

where t is in degrees centigrade, over the temperature range 200-800°C (392-1472°F), and thus represents a 520°F extrapolation beyond the experimental data. The range of applicability was extended with the aid of the Wiedemann-Franz-Lorenz equation using a value of the Lorenz number equal to 2.35×10^{-8} W-ohm/°K^2 and resistivity values calculated from Eq. (6.7) in Table VI.1.

Novikov et al.,[58] experimentally determined the thermal diffusivity of liquid sodium over the temperature range 100-680°C (212-1256°F). Thermal conductivity values were calculated from the diffusivity results using the density data recommended in reference 2 together with the specific heat data of Ginnings et al.[49] (As was stated in Chapter IV we also recommend the use of the specific heat data of Ginnings et al.; in engineering units the Ginnings et al., relationship is given by

$$C_p(\mathrm{Btu/lb\ °F}) = 0.389352 - 1.10599 \times 10^{-4}\,T + 3.41178 \times 10^{-8}\,T^2, \tag{5.4}$$

where T is in degrees Rankine.) The conductivity results were presented in graphical form and were found to agree fairly well with the thermal conductivity relationship recommended in reference 2.

Rudnev et al.,[111] measured the thermal diffusivity of liquid sodium over the temperature interval 350-876°C. Twenty-four experimental points were obtained. The thermal diffusivity was expressed by

$$\alpha(\mathrm{cm^2/sec}) = 0.721 - 0.0174 \times 10^{-2}\,t\ (°C). \tag{5.5}$$

The average deviation of the experimental points from the above relationship was stated to be ±2.5%, while the maximum deviation was 7.8%. Using averaged values of density and specific heat taken from various sources, Rudnev et al., obtained the following expression for the thermal conductivity:

$$k(\mathrm{cal/cm\text{-}sec\text{-}°C}) = 0.224 - 0.159 \times 10^{-7}\,t^2, \tag{5.6}$$

where t is given in degrees centigrade. Since we were unable to check the specific heat and density values used by Rudnev, we calculated conductivity values using Eq. (5.5) together with our recommended density values given in Eq. (2.1) and specific heat values obtained from Eq. (5.4); see Fig. 5.1.

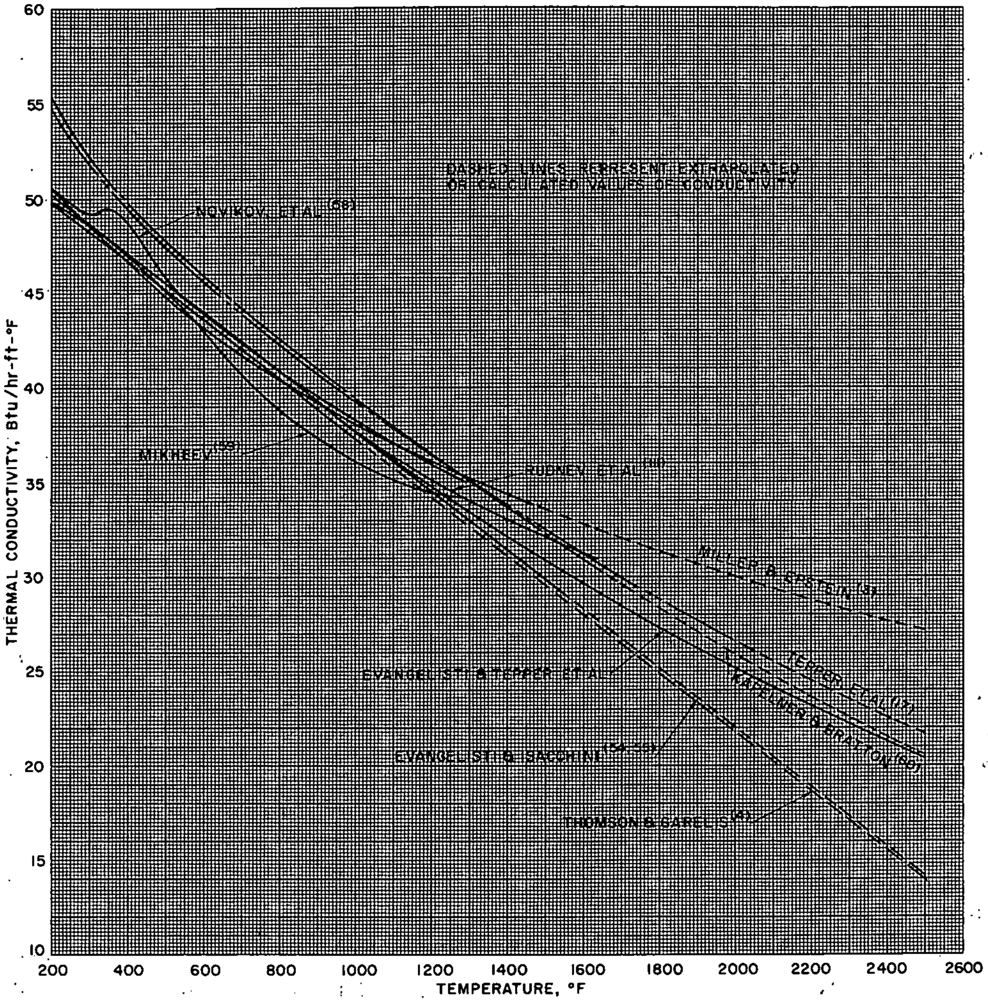

Fig. 5.1. Thermal Conductivity of Liquid Sodium (see text)

Mikheev[59] has reported smoothed values of thermal conductivity in tabular form obtained at ENIN (The Institute of Power Engineering). No functional relationship was presented or original work referenced.

Tepper et al.,[17] computed the following relationship for the thermal conductivity of liquid sodium from the melting point to 2000°F, employing the Wiedemann-Franz-Lorenz equation and a relationship derived from experimental resistivity data, Eq. (6.2):

$$k = 1.4298 - 6.1292 \times 10^{-4} t + 1.7127 \times 10^{-7} t^2 - 3.0633 \times 10^{-11} t^3, \tag{5.7}$$

where k and t are given in watts/in.-°F and degrees Fahrenheit, respectively. The Lorenz constant was assumed equal to 2.45×10^{-8} W-ohm/°K^2. It should be noted that the thermal conductivity values used in Fig. 5.1 were computed directly from the Wiedemann-Franz-Lorenz relationship and not from the above equation, which is a least-squares fit of the computed values.

Kapelner and Bratton[60] have also estimated the thermal conductivity of liquid sodium by means of the Wiedemann-Franz-Lorenz relationship and their experimental resistivity values from the melting point to 900°C (1625°F), see Fig. 6.1. With a Lorenz number of 2.45×10^{-8} W-ohm/°K^2 their relationship for the thermal conductivity is

$$k = \frac{1.4156 \times (t + 273.16)}{5.904 + 3.695 \times 10^{-2} t - 9.359 \times 10^{-7} t^2 + 2.291 \times 10^{-8} t^3}, \qquad (5.8)$$

where k and t are given in Btu/hr-ft-°F and degrees centigrade, respectively.

Figure 5.1 shows the various relationships for thermal conductivity plotted versus the temperature in degrees Fahrenheit. It is seen that there is good agreement between the experimentally obtained conductivity values as reported by the various sources below 1000°F. Thermal conductivity values estimated from electrical resistivity data represented by the results of Tepper et al., and Kapelner and Bratton are seen to be roughly 7% higher than the directly measured experimental values. This disparity could, of course, be minimized by using a reduced Lorenz constant or an appropriate temperature-dependent Lorenz number. Above 1000°F the various relationships begin to diverge from each other.

In order to estimate thermal conductivity values up to 2500°F for the purposes of this report, we arbitrarily decided to use the experimental values of Evangelisti and Isacchini, being in good agreement with values reported by other sources, from the melting point to 1200°F. Thermal conductivity values greater than 1200°F were computed from the Wiedemann-Franz-Lorenz law using the electrical resistivity values obtained from Eq. (6.2) and a Lorenz value of 2.34×10^{-8} V^2/°K^2.* By doing this it was possible to reduce the temperature coefficient of the Evangelisti and Isacchini relationship, thereby bringing it more in line with the temperature behavior of the data above 1200°F. Further, it appears that the Evangelisti and Isacchini relationship is not suitable without modification for sizable extrapolation, since the temperature at which the Evangelisti and Isacchini relationship reaches zero conductivity is approximately 3400°F (more exactly, 1869.3°C). This temperature should roughly indicate the critical temperature for sodium. Latest estimates, however, point to critical temperatures near 4600°F (2800°K).[78]

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*The Lorenz number was computed using thermal conductivity and electrical resistivity values obtained from Eqs. (5.1) and (6.2) evaluated at 1200°F.

To have one single relationship representing the thermal conductivity over the entire range from the melting point to 2500°F rather than the two proposed above, a smooth least-squares fit was obtained using values of the two relationships evaluated at 100°F temperature intervals from 200 to 2500°F. The result is

$$k = 54.306 - 1.878 \times 10^{-2} t + 2.0914 \times 10^{-6} t^2, \qquad (5.9)$$

where k and t are given by Btu/hr-ft-°F and degrees Fahrenheit, respectively. This relationship is also shown in Figs. 5.1 and 5.2 by the curves labeled Evangelisti and Tepper et al.

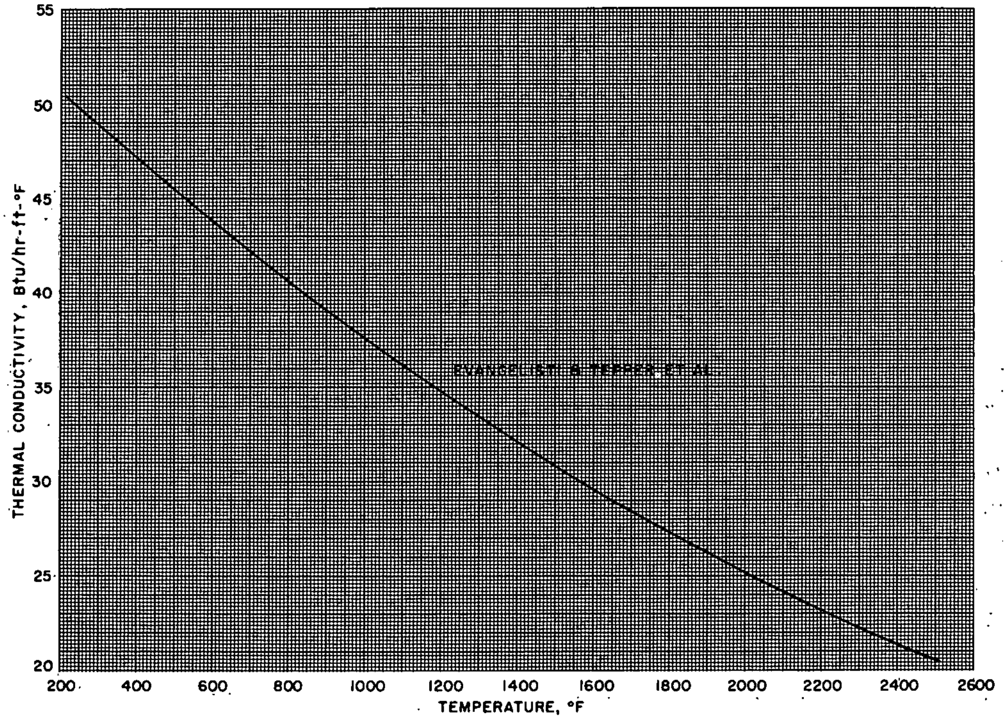

Fig. 5.2. Thermal Conductivity of Liquid Sodium (Recommended)

A.2. Thermal Conductivity of Sodium Vapor

To our knowledge the only experimental values of thermal conductivity published for sodium vapor are those of Stefanov et al.[99] The measurements were made with a dilatometer described in detail by Timrot and Totskii.[100] The conductivity results were reported in tabular form (apparently smoothed) and are given in Table V.1. The "average maximal error" of the experimental results was reported to be 20%. The experimental range was stated to include temperatures between 613-911°C and pressures between 0.034-0.69 kg/cm^2.

TABLE V.1. Thermal Conductivity of Sodium Vapor[99]

Thermal Conductivity (kcal/m-hr-deg) x 10^4

T, °K	Monatomic Vapor	Pressure, kg/cm² 0.01	0.05	0.1	0.5	1.0	On SAT Curve
800	218	-	-	-	-	-	417
900	246	308	-	-	-	-	469
1000	274	293	375	427	-	-	510
1100	303	310	339	370	524	-	540
1200	332	336	348	363	455	526	566
1300	361	363	369	377	429	478	-
1400	390	391	395	399	429	469	-
1500	421	421	423	426	444	465	-

An experimental effort is underway[61] to measure the vapor conductivity between 800 and 2000°F. No results to our knowledge have been reported.

Another experimental effort which covers all the alkali metal vapors is also underway.[101] The experimental method, that of Lee and Bonilla, consists of measuring the amplitude of the third harmonic IR drop across a fine wire surrounded by the vapor and correlating it with similar observations made with a standard gas. This method has been applied to gases at high temperatures.[102] A parallel theoretical effort is also involved; this has been found to check closely the experimental results for cesium and rubidium obtained thus far. Accordingly, the predicted values for sodium, though not yet verified experimentally, could be expected to be fairly reliable; they do not, however, agree with the data of Stefanov et al. The theoretical method as applied and extended by Lee and Bonilla was first suggested by Vanderslice et al.[67] The potential-energy functions for the triplet states of the alkali-metal vapors by Davies et al.,[68] were used for deriving potential-energy functions for the monomer-dimer and dimer-dimer interactions by a scaling procedure and a perfect pairing approximation. The contributions of rotational and vibrational energy and the contribution by the dissociation reaction in the dimer-monomer mixed vapor were accounted for. It is expected that the calculated values will be correct within approximately ±35%. The full calculated results in the form of isobars for equilibrium and for "frozen" sodium vapor will shortly be available.[103] The curve for the saturated vapor at thermodynamic equilibrium is shown in Fig. 5.3.

Dunning[6] estimated the vapor conductivity by a method recommended by Lindsay and Bromley.[62] Thermal conductivity values were calculated and reported in graphical and tabular form from the melting point up to 1300°C (2372°F). See Fig. 5.3 for a graphic representation of these values.

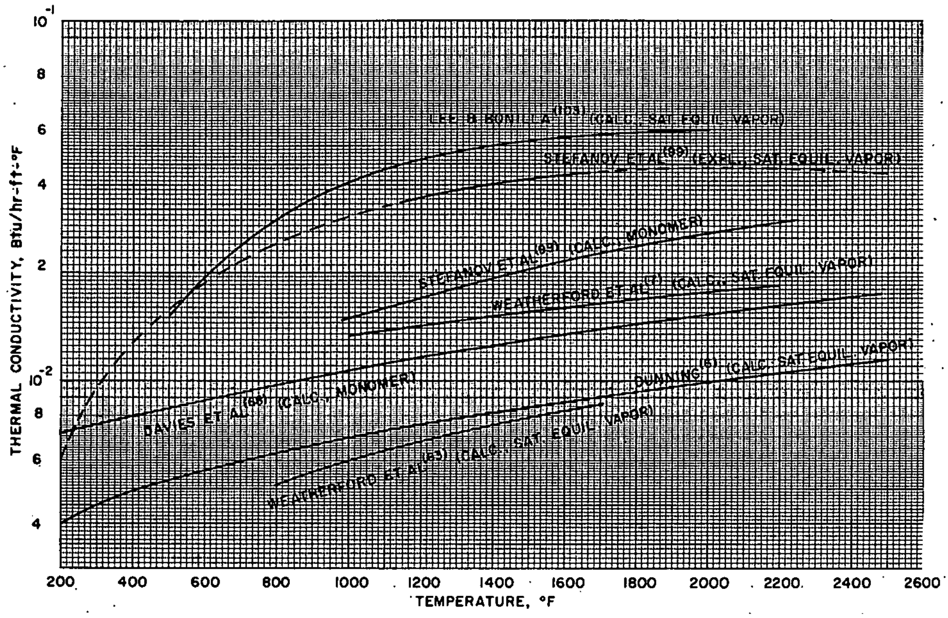

Fig. 5.3. Thermal Conductivity of Sodium Vapor

Weatherford et al.,[63] in an early report, now superseded, estimated vapor conductivity data over the temperature range 600-1700°F. It is not clear what method their original source used to obtain these results. The calculated values are shown in Fig. 5.3.

Weatherford et al.,[7] in the revised edition to that listed above presents somewhat higher calculated values. The conductivity values in this case were computed from estimated viscosity data* with a constant Prandtl number of 0.73 and a frozen specific heat of approximately 0.214 Btu/lb-°F.

We were able to estimate the vapor conductivity, as suggested by Miller,[66] by assuming the saturated vapor to be predominantly composed of ground-state sodium atoms. For temperatures up to 2500°F, thermal ionization of sodium atoms can be considered negligible and electronic excitation small. In Appendix B, however, it is indicated that the mole fraction of the higher molecular species in the saturated vapor is not entirely negligible, being of the order of 17.6% at 2500°F. It must therefore be assumed that the calculational method about to be described is only a first estimate.

For a single-component gas, the thermal conductivity can be estimated from the Chapman-Enskog kinetic-theory formulation as outlined by Vanderslice et al.,[67]

$$k(\text{mcal/cm-sec-°K}) = \frac{0.19891 T^{1/2}}{M^{1/2} \langle \Omega^{(2,2)} \rangle} , \tag{5.10}$$

---

*The method used to calculate the viscosity values was given at the 1961 Annual Meeting of the American Physical Society. Unfortunately, the calculational method was only outlined in the written proceedings. A modified and strengthened version of this method has been reported on by Weatherford.[65]

where M is the molecular weight, T is in degrees Kelvin, and $\langle \Omega^{(2,2)} \rangle$ is the weighted average collision integral. In evaluating the collision integral, it should be pointed out that two colliding sodium atoms do not follow a single interaction potential but rather two. Since each atom has one valence electron, the interaction between any two atoms involves parallel and antiparallel electron spins corresponding to repulsive and attractive potentials, respectively. Further, the weighted average collision integral in Eq. (5.10) must be obtained by appropriately weighting the two interaction states. Davies *et al.*,[68] state that under the present state of the art, calculations which do not take into account the existence of two interaction potentials have no real physical basis. Davies and associates have obtained potential-energy curves for ground-state sodium atoms scaled from hydrogen curves on the assumption that the interaction between two sodium atoms is qualitatively similar to those between two hydrogen atoms. Davies has also calculated the weighted transport collision integrals for atomic sodium vapor over the temperature range 1000-10,000°K. We used these collision integral values to compute the vapor conductivity from 1000 to 5500°K and obtain the following least-squares fit of the computed data:

$$k = 0.6169 \times 10^{-2} + 0.4450 \times 10^{-5}\, t + 0.5584 \times 10^{-10}\, t^2, \tag{5.11}$$

where k and t are in units of Btu/hr-ft-°F and degrees Fahrenheit, respectively.

Figure 5.3 shows plots of the various predictions or experimental results. There seems to be little agreement between most of the sources which appear. It is noteworthy, however, that while the predictions of Lee and Bonilla and the experimental results of Stefanov *et al.*, are as much as 25% different, together they represent the best information available. Arbitrarily we recommend the data of Stefanov *et al.*, at least until the finalized work of Lee and Bonilla[103] becomes available. For the purposes of Appendixes C and D we obtained a second-degree polynomial fit of the tabulated conductivity values appearing in Table V.1. The result is

$$k = 0.1639 \times 10^{-2} + 0.3977 \times 10^{-4}\, t - 0.9697 \times 10^{-8}\, t^2, \tag{5.12}$$

where k and t are given in Btu/hr-ft-°F and degrees Fahrenheit, respectively.

B.1. Viscosity of Liquid Sodium

The viscosity of liquid sodium was measured by Chiong[69] over the temperature range 98-355°C using an oscillating sphere method developed by Andrade and Chiong. The sodium was enclosed in a glass sphere and its viscosity inferred from the oscillatory motion of the sphere. Thirteen sets of measurements were taken over the above temperature range and are reported in Table V.2. The sodium density data required in Chiong's calculations were taken from the work of Hagen.[70] The viscosity data were well correlated (except for the low-temperature values) with the equation

$$\eta v^{1/3} = 1.183 \times 10^{-3} e^{716.5/vT}, \tag{5.13}$$

where η is the viscosity in poise, v the specific volume in cm^3/gm, and T the temperature in degrees Kelvin.

TABLE V.2. Experimental Results for Liquid Viscosity (in centipoise)

Ewing *et al.*[72]		Ewing *et al.*[73]		Chiong[69]		Godfrey[71]		Novikov[74]		Shpilrain *et al*[77]		Achener[79]	
T(°C)	η	T(°C)	η	T(°C)	η	T(°C)	η	T(°C)	η	T(°C)	η	T(°C)	η
103.7	0.6863	143	0.565	98.0	0.7264	327	0.333	100	0.715	300	0.349	100	0.545
103.7	0.6858	145	0.549	99.6	0.7142	328	0.335	150	0.540	350	0.312	200	0.439
121.6	0.6232	196	0.459	102.4	0.6856	331	0.322	200	0.457	400	0.283	300	0.368
121.6	0.6180	198	0.453	120.4	0.6170	383	0.288	250	0.394	450	0.260	400	0.317
121.6	0.6178	245	0.406	154.5	0.5314	385	0.292	300	0.347	500	0.241	500	0.278
147.0	0.5477	250	0.388	155.0	0.5322	386	0.289	350	0.307	550	0.224	600	0.248
147.0	0.5477	292	0.354	159.1	0.5225	437	0.264	400	0.282	600	0.211	700	0.224
167.6	0.5038	368	0.306	173.7	0.4942	440	0.254	450	0.260	650	0.199	800	0.205
167.6	0.5035	371	0.308	183.4	0.4760	460	0.238	500	0.240	700	0.189	900	0.188
192.7	0.4603	447	0.268	206.7	0.4431	463	0.236	550	0.223	800	0.172	1000	0.174
		447	0.271	218.0	0.4239	488	0.244	600	0.208	900	0.159	1100	0.162
		506	0.243	289.0	0.3506	495	0.242	650	0.194	1000	0.148		
		506	0.238	355.0	0.3015	537	0.243	700	0.182				
		571	0.216			537	0.250	800	0.160				
		572	0.213			586	0.233						
		686	0.183			587	0.232						
						628	0.204						
						629	0.188						
						678	0.184						
						678	0.207						
						726	0.218						
						727	0.193						
						730	0.190						
						777	0.164						
						777	0.178						
						827	0.147						
						878	0.149						
						879	0.148						

Godfrey,[71] also using an oscillating-sphere method, obtained viscosity data over the temperature range 327-879°C. Twenty-eight sets of measurements were taken. The data show some scatter, as can be seen in Table V.2.

Ewing *et al.*,[72] used a modified Ostwald glass viscometer to determine the viscosity of sodium over the temperature range 103.7-192.7°C. Ten sets of measurements were taken over the interval, as shown in Table V.2. Liquid density values required for the determinations were taken from Ewing *et al.*[12] The results of the measurements were correlated by an Andrade-type equation

$$\eta v^{1/3} = 1.089 \times 10^{-3} e^{756.9/vT}, \tag{5.14}$$

where the units are the same as for Eq. (5.13).

Ewing et al.,[73] extended their viscosity work to include higher temperatures by using a nickel viscometer of the Ostwald type. Data were obtained over the temperature range 143-686°C; the sixteen sets of measurements are shown in Table V.2. When their viscosity data at low and high temperatures were combined, a least-squares fit gave the following Andrade-type equation:

$$\eta v^{1/3} = 1.142 \times 10^{-3} e^{739.8/vT}, \tag{5.15}$$

where again the units are the same as quoted for the Chiong equation. Density values were obtained from reference 12.

Novikov et al.,[74,75] used an oscillating, cylindrical-shaped capsule to determine the kinematic viscosity of liquid sodium. This method is mechanistically similar to the oscillating-sphere technique and is theoretically treated by Shvidkovsky.[76] The kinematic viscosity was determined over the temperature range from roughly 100 to 800°C with 20 sets of measurements. Their results are reported in smoothed graphical form[74] and in tabular form.[75] Table V.2 shows their results converted to absolute viscosity units through use of the recommended density relationship given by Eq. (2.1).

Recent values for the dynamic viscosity have been reported in smoothed equation form by Shpilrain et al.,[77] covering the temperature range 160-800°C. The oscillating-cylinder technique together with Shvidkovsky's analysis was used. The kinematic viscosities were converted to absolute units through use of the density data of Goltsova.[98] Their correlation is

$$\log_{10} \eta = -1.6814 - 0.4296 \log_{10} T + (234.65/T), \tag{5.16}$$

where η is in poise and T in degrees Kelvin. The maximum relative experimental error was stated to be ± 2.5%, and the data deviation from the above equation was stated not to exceed ± 1%.

Achener,[79] also using the oscillating-cylinder technique and the Shvidkovsky analysis, recently reported viscosity data over the temperature range from near the melting point up to 1050°C. The data were represented by the following least-square relationships:

$$\log_{10} \eta = 3.25538 - \frac{10.4126}{T} - 0.96843 \log_{10} T, \tag{5.17}$$

or

$$\eta v^{1/3} = 1.54222\, e^{576.151/vT}, \tag{5.18}$$

where η is in millipoise, T in degrees Kelvin, and v in cm^3/gm. The standard deviations for the above correlations were stated to be 0.02538 on $\log_{10} \eta$ and 0.07336 on $\log (\eta v^{1/3})$. The liquid density values of Stone et al.[10] were used to convert the experimentally obtained kinematic viscosity to absolute viscosity units.

Several viscosity compilations have appeared in the literature. A few of these are listed in Table V.3 together with their recommended relationship.

TABLE V.3. Compilations of Liquid Sodium Viscosity

Compilation Reference	Information Source	Suggested Relationship
2	Chiong[69] Ewing et al.[72] Ewing et al.[73]	Tabular values are presented which are taken from the sources cited
3	Chiong[69] Godfrey[71] Ewing et al.[72] Ewing et al.[73]	Uses Ewing et al.[73]
4	Chiong[69] Godfrey[71] Ewing et al.[72] Ewing et al.[73]	$\log \eta = -1.09127 + \frac{382}{t + 313}$ as a compromise relationship between sources cited, where η and t are in centipoise and degrees centigrade, respectively.
7	Ewing et al.[73] Novikov[74] Miller and Epstein[3]	Uses Miller and Epstein
6	Miller and Epstein[3]	Uses Miller and Epstein
8	Weatherford et al.[7]	Uses Weatherford et al.
9	Thomson and Garelis[4] Dunning[6]	Uses both sources; however, does not recommend one in particular.
80	Ewing et al.[73] Novikov[74]	Presented tabular values calculated from the equation $\eta = 1.194 \times 10^{-3} \rho^{1/3} e^{712.3 \rho/T}$, where η, ρ, and T are in centipoise, gm/cm^3, and degrees Kelvin, respectively. Results are essentially those of Ewing et al.[73]

The wide-range viscosity-temperature correlations were selected for comparison in Table V.4. It is seen that for the temperature interval between 100 and 900°C, the agreement between all of the correlations is reasonably good, the Achener data showing the widest disparity. The deviations between the correlations become larger beyond 1000°C, which is well into the regime of wide extrapolation for most of them.

TABLE V.4. Wide-range Viscosity Correlations

T(°C)	Viscosity (centipoise) Ewing et al. Eq. (5.15)	Thomson and Garelis Table V.3	Achener, Eq. (5.17)	Novikov, Table V.2	Shpilrain, Eq. (5.16)	Golden and Tokar Eq. (5.19)
100	0.699	0.682	0.545	0.715	0.696	0.685
200	0.453	0.450	0.439	0.457	0.463	0.457
300	0.340	0.340	0.368	0.347	0.349	0.345
400	0.277	0.278	0.317	0.282	0.283	0.279
500	0.238	0.239	0.279	0.240	0.241	0.236
600	0.210	0.212	0.248	0.208	0.211	0.207
700	0.191 ↓ Extrapolated	0.193	0.224	0.182	0.189	0.184
800	0.175	0.179	0.205	0.162	0.172	0.167
900	0.163	0.167	0.188		0.158	0.154
1000	0.154	0.158	0.174		0.148	0.143
1100	0.145	0.151	0.162		0.139	0.133
1200	0.138	0.145	0.151		0.131	0.126
1300	0.132	0.140	0.142		0.124	0.119
1400	0.127	0.135	0.134		0.119	0.114

In order to obtain a relationship for the liquid viscosity over a temperature interval ranging from the melting point to 2500°F, it was necessary to fair in a smooth curve for all the available data plotted together. This form of smoothing was used because some of the information was not available in the form of experimental data points. Equations of the forms:

$$\log_{10}\eta = A + \frac{B}{T};\quad \log_{10}(\eta v^{1/3}) = A + \frac{B}{vT};\quad \log_{10}\eta = A + \frac{B}{T} + C\log_{10}T$$

were used to obtain a fit to the faired results. The best fit was given by

$$\log_{10}\eta = 0.5108 + \frac{220.65}{T} - 0.4925\log_{10}T, \qquad (5.19)$$

where η and T are in centipoise and degrees Kelvin, respectively. In engineering units, Eq. (5.19) is given by

$$\log_{10}\eta = 1.0203 + \frac{397.17}{T} - 0.4925\log_{10}T, \qquad (5.19a)$$

where η and T are given as $\mathrm{lb_m/ft\text{-}hr}$ and degrees Rankine, respectively. A plot of the above equation is given in Fig. 5.4. Tabular values are given in Appendix C.

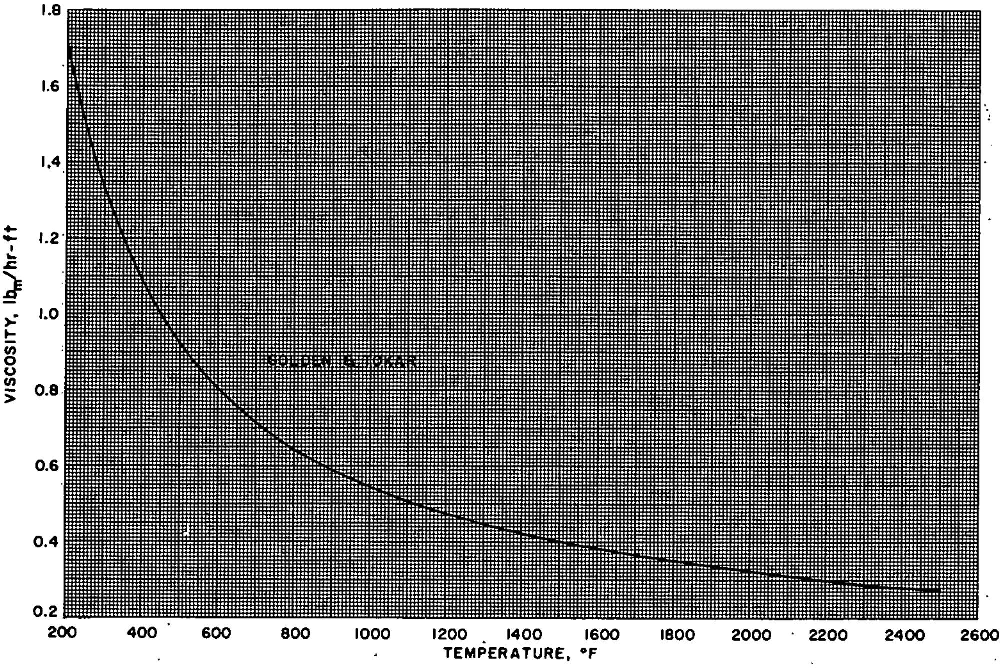

Fig. 5.4. Viscosity of Liquid Sodium (Recommended)

B.2. Viscosity of Sodium Vapor

Stefanov et al.,[99] have reported smoothed, tabulated results for vapor viscosity. Table V.5 has been transcribed from Stefanov's paper. The experimental range was stated to include temperatures between 686 and 870°C and pressures between 0.055 and 0.398 kg/cm^2. Details of the experimental apparatus and the calculational techniques were not given. The authors state that this information is to be published at a later date. We obtained a linear least-squares fit of the already-smoothed viscosity values in Table V.5 for the saturated equilibrium case:

$$\eta\,(\mathrm{lb_m/hr\text{-}ft}) = 0.03427 + 8.176 \times 10^{-6}\, t(°\mathrm{F}). \tag{5.20}$$

TABLE V.5. Viscosity of Sodium Vapor[99]

T, °K	Monatomic Vapor	Viscosity (g/cm-sec) x 10^7					
		Pressure, kg/cm^2					On SAT Curve
		0.001	0.01	0.1	1.0	5.0	
700	1784	-	-	-	-	-	1685
800	1920	1896	-	-	-	-	1751
900	2056	2048	1989	-	-	-	1810
1000	2192	2190	2166	1984	-	-	1868
1100	2328	2327	2316	2219	-	-	1926
1200	2464	2464	2458	2404	2074	-	1987
1300	2600	2600	2596	2562	2326	-	2050
1400	2736	2736	2733	2712	2544	2173	2117
1500	2872	2872	2856	2734	2408	2193	-

Lee and Bonilla have recently obtained experimental values for vapor viscosity in the atmospheric pressure range with about 100°F superheat. Additional experiments and full publication are expected shortly.[106] The experimental procedure for the results obtained with cesium[104] has been published recently. The results for sodium agree well with the data of Stefanov et al., at pressures below atmospheric.

Several theoretical estimates of the vapor viscosity have appeared in the literature. Dunning[6] estimated the saturated vapor viscosity from the formulation of Johnson et al.,[81] for both the monomer and dimer, and from an equation presented by Wilke[82] for the viscosity of two components.

Weatherford et al.,[63] in a now superseded report, reported estimated data for vapor viscosity over the temperature range from 600 to approximately 1630°F. As in the case of the thermal conductivity of the vapor, it is not clear what method the authors' original source used to obtain these results. Dunning felt that the agreement between his results and these was favorable enough to indicate that the same equations were used.

Weatherford et al.,[7] have reported much larger viscosity values. As mentioned in the section pertaining to the vapor thermal conductivity, the actual method used to obtain these values was given at an American Physical Society Annual Meeting.[64]

We calculated the vapor viscosity using the Chapman-Enskog kinetic-theory approach as outlined by Vanderslice[67] under the assumption that the saturated vapor is composed entirely of ground-state sodium atoms. The vapor viscosity can then be obtained from the following equation:

$$\eta = \frac{0.02669(MT)^{1/2}}{\left\langle \Omega^{(2,2)} \right\rangle}, \tag{5.21}$$

where η, M, T, and $\left\langle \Omega^{(2,2)} \right\rangle$ represent the absolute viscosity in millipoises, the molecular weight, the absolute temperature in degrees Kelvin, and the weighted average collision integral for the viscosity or thermal conductivity, respectively. Values for the collision integral have been tabulated by Davies et al.,[68] for the alkali metals and cover the temperature range from 1000 to 10,000°K. We used these tabulated values to compute the vapor viscosity and obtained the least-squares fit

$$\eta = 0.0190 + 0.1375 \times 10^{-4} t + 0.1709 \times 10^{-9} t^2, \tag{5.22}$$

where η and t are in units of lb_m/hr-ft and degrees Fahrenheit, respectively. The above correlation is shown plotted in Fig. 5.5 under the caption of Davies et al. Weatherford[65] has reported on calculated values for vapor viscosity of the monomer over the temperature range from 900 to 1500°K which agree very well with the results of Davies et al.

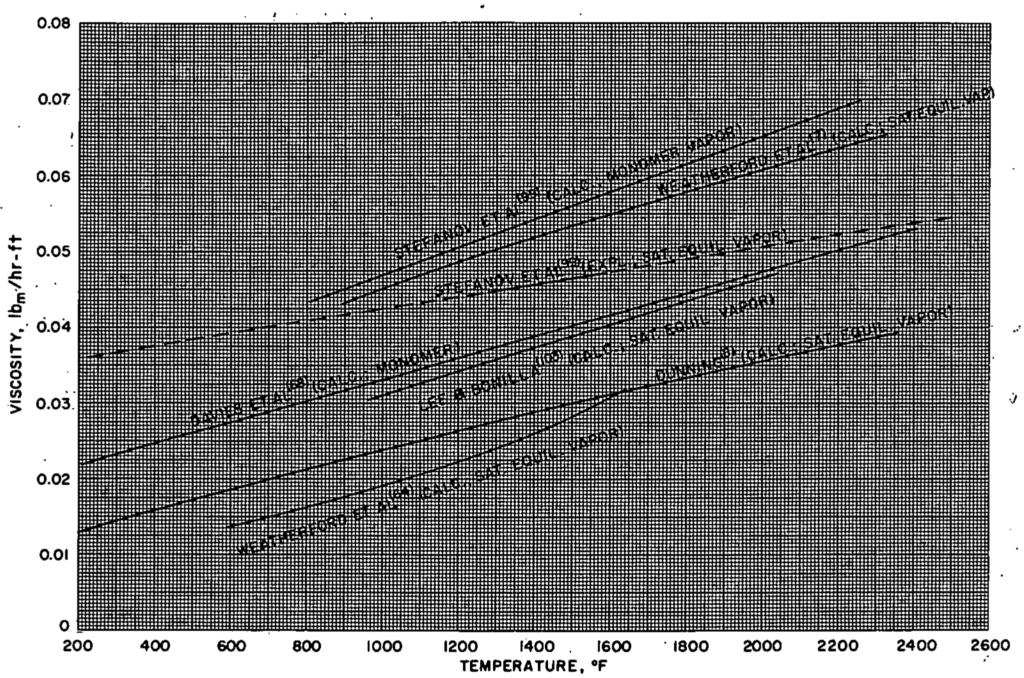

Fig. 5.5. Viscosity of Sodium Vapor

Figure 5.5 shows the various vapor-viscosity relationships plotted together. We recommend the use of the experimental data of Stefanov _et al._, linearly extrapolated to the melting point and to 2500°F. It should be noted that the majority of the Stefanov values shown in Table V.5 already show wide extrapolation, since the stated experimental temperature interval is 184°C whereas the tabulated values cover a 800°C interval. However, since there is moderate agreement between the Stefanov data with most of the recent theoretical predictions and with the preliminary experimental work of Lee and Bonilla as noted earlier, we believe that the Stefanov data should be used until such a time that more experimental information becomes available, hopefully upon publication of Lee and Bonilla's work.[106] Tabulated values for the vapor viscosity can be found in Appendix C.

VI. ELECTRICAL RESISTIVITY

Evangelisti and Isacchini[83,54] recently made measurements of the electrical resistivity of liquid sodium over the temperature range 100-1000°C (212-1832°F). Their experimental technique involved passing a known current through a calibrated, Type 316 stainless steel tube containing the sodium at a known uniform temperature and measuring the potential drop across a defined length of the tube. For a given system geometry, they calculated the resistance, and hence the resistivity of the sodium from the formula for parallel resistors. Their results were given by the following least-squares cubic relationship for 21 experimental points:

$$\rho_e = 6.56 + 2.868 \times 10^{-2}\, t + 1.868 \times 10^{-5}\, t^2 + 9.078 \times 10^{-9}\, t^3, \qquad (6.1)$$

where ρ_e and t are given in microhm-cm ($\mu\Omega$-cm) and degrees centigrade, respectively. The "average deviation" of the experimental points about the least-squares fit was stated to be ±0.45%. No tabular experimental results were reported.

Tepper et al.[17] measured the electrical resistivity of liquid sodium over the temperature range 272-1989°F, using the parallel-resistor technique. They took 36 data points over the above range, and reported their results in graphical, tabular, and equation form. A least-squares fit of their data was given as

$$\rho_e = 2.1729 + 7.6248 \times 10^{-3}\, t + 5.8313 \times 10^{-7}\, t^2 + 1.1260 \times 10^{-9}\, t^3, \qquad (6.2)$$

where ρ_e is in μohm-inch and t in °F. Unfortunately, Tepper et al. discuss their sodium results associatively with resistivity results obtained for other alkali metals. For this reason, we computed a least-squares fit of the 36 data points to obtain the standard deviation and maximum deviation. Our resulting fit to their data is

$$\rho_e = 2.1737 + 7.6254 \times 10^{-3}\, t + 5.8207 \times 10^{-7}\, t^2 + 1.1262 \times 10^{-9}\, t^3. \qquad (6.2a)$$

The standard deviation for the recomputed fit, which has slightly different coefficient values from that of Tepper's, is 0.02947 μohm-in. The maximum deviation, 0.07596 μohm-in., occurs at the experimental point taken at 1478°F; the largest percent deviation, 0.76%, occurs at 283°F.

Kapelner and Bratton[60] also determined the resistivity of liquid sodium by the parallel-resistor technique. Their measurements were from 98 to 852.8°C (208.4 to 1567°F), the range being covered by 10 data points. They gave a least-squares cubic fit of their data:

$$\rho_e = 5.904 + 3.695 \times 10^{-2}\, t - 9.359 \times 10^{-7}\, t^2 + 2.291 \times 10^{-8}\, t^3, \quad (6.3)$$

where ρ_e is in microhm-centimeters and t in degrees centigrade. The "mean deviation" for the 10 experimental points is stated to be ±0.40%, with a maximum deviation of 1.04% at 98°C.

Freedman and Robertson[84] reported measurements of liquid sodium resistivity over the temperature range 100-550°C (212-1022°F) using the parallel-resistor technique. They used a Type 304 stainless steel tube to contain the sodium. They reported their results both in graphical and tabular form. Unfortunately, the tabular values were not actual experimental points, but appear to represent smoothed values taken from a best-drawn fit to the data. We made a least-squares cubic fit to the tabular values and obtained

$$\rho_e = 6.3715 + 2.8728 \times 10^{-2}\, t + 1.8396 \times 10^{-5}\, t^2 + 5.1593 \times 10^{-9}\, t^3, \quad (6.3a)$$

where ρ_e and t are in microhm-centimeters and degrees centigrade, respectively. We made no statistical evaluation of the data for the reason given above.

Rahiser[85] determined the resistivity of liquid sodium over the temperature range 200-800°C (392-1472°F). This investigation was one of the earliest to use the parallel-resistor technique, i.e., using a conducting rather than a nonconducting sodium container; the container was constructed of Type 347 stainless steel. Smoothed graphical and tabular values were presented. We obtained the following second-degree least-squares relationship which adequately fits the smoothed data:

$$\rho_e = 7.6986 + 2.3705 \times 10^{-2}\, t + 3.0095 \times 10^{-5}\, t^2, \quad (6.4)$$

where ρ_e and t are in microhm-centimeters and degrees centigrade, respectively.

Semyachkin and Solovev[105] have reported smoothed tabular values of resistivity, presumably obtained from earlier work in which a parallel-resistor technique was employed. Tabulated values were reported in 50° intervals over the temperature range from 100 to 1000°C. We obtained a third-degree polynomial least-squares fit of these tabular values:

$$\rho_e = 6.4525 + 3.3775 \times 10^{-2}\, t + 9.127 \times 10^{-6}\, t^2 + 1.2515 \times 10^{-8}\, t^3, \quad (6.5)$$

where ρ_e and t are in microhm-centimeters and degrees centigrade, respectively.

Several widely used sources for values of sodium resistivity are presented in Table VI.1.

TABLE VI.1. Compilations of Electrical Resistivity

Compilation Reference	Basic Information Source	Suggested Relationship
2	Bornemann and von Rauschenplat, 98 to 350°C (See Ref. 4).	Same as source
4	Bornemann and von Rauschenplat, 98 to 350°C (See Ref. 4); Muller, P., 98 to 200°C (See Ref. 4); Northrup, E. F., 97.4 to 141.2°C (See Ref. 4).	$\rho_e(\mu\Omega\text{cm}) = 6.225 + 0.0345\ t\ (°\text{C})$ (6.6) (Melting point to 400°C); compromise of Bornemann and von Rauschenplat and of Northrup.
3	Thomson and Garelis[4]; Rahiser, Werner, and Jackson,[3] 300 to 800°C.	$\rho_e = 10.892 + 0.015272\ t + 3.6746 \times 10^{-5}\ t^2 - 379.26/t$ (6.7) (Melting point to 800°C), where ρ is in $\mu\Omega$cm and t in °C. The above is a fit of the two sources listed.
7	Thomson and Garelis[4]	Same as source
8	Stated Weatherford et al.[7] Actually Liquid Metals Handbook, 3rd Edition.[3]	Liquid Metals Handbook, 3rd Edition.

Figure 6.1 shows several resistivity relationships plotted versus the results of Tepper et al. The correlations of Kapelner and Bratton, Tepper et al., and Rahiser agree quite well over a wide temperature range. At low temperatures, the Evangelisti and Isacchini relationship deviates

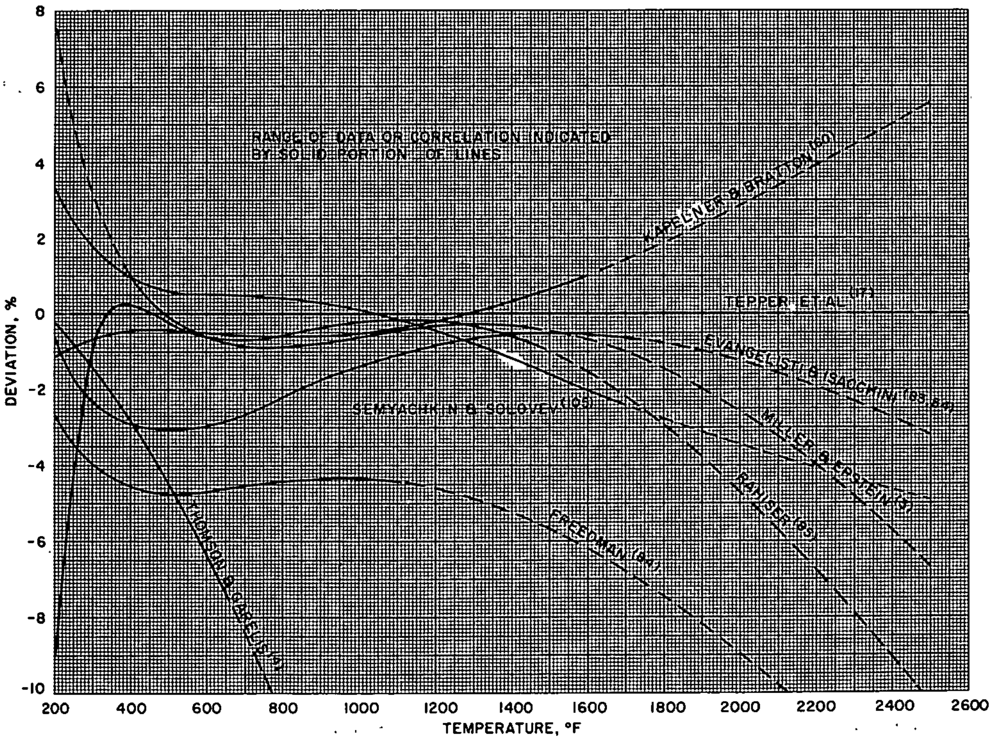

Fig. 6.1. Deviation of Electrical Resistivity Data from That of Tepper et al.[17]

slightly from the above three, whereas there is good agreement at higher temperatures. The Thomson and Garelis compilation and the Freedman results are obviously out of line with the others. The Miller and Epstein compilation, although in good agreement with the former group of four over most of the temperature range, deviates considerably at temperatures near the melting point; it should be remembered that this compilation is actually a fit of the results of Rahiser and the compilation of Thomson and Garelis. All the relationships deviate considerably from each other at high temperatures, where they are widely extrapolated. In summary, one could rationalize, although admittedly in an arbitrary manner, that the Tepper *et al.* results, although covering the widest experimental temperature range, also represent an average of the divergent extrapolated values. Having no other basis upon which to judge the reviewed work, it is recommended that the Tepper *et al.* relationship be used over the temperature range from the melting point up to 2500°F. Figure 6.2 shows the plot of the recommended electrical resistivity versus temperature. See Appendix C for tabular values ranging from 210 to 2500°F.

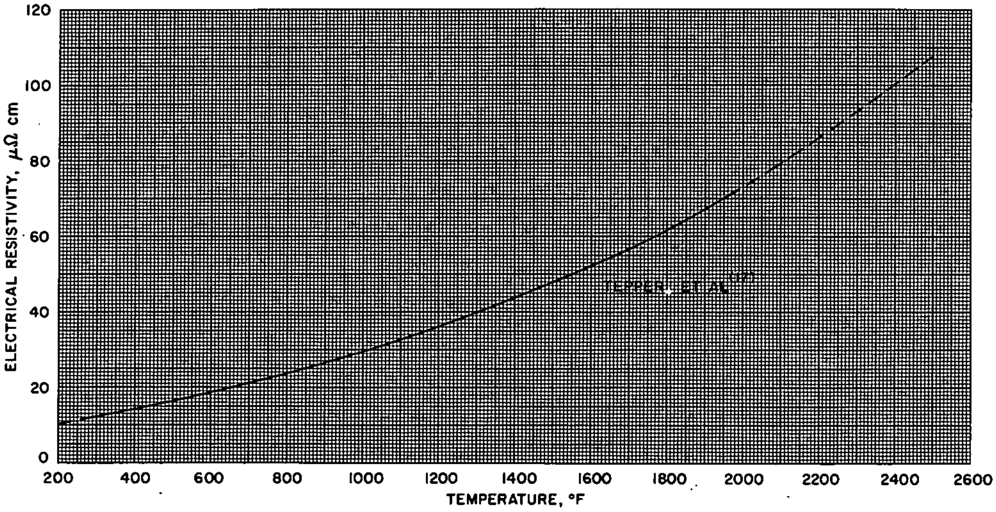

Fig. 6.2. Electrical Resistivity of Liquid Sodium (Recommended)

VII. SURFACE TENSION

Tepper et al.[86-88] determined the surface tension of liquid sodium by the maximum-bubble-pressure technique. The method involves measuring the pressure required to form and liberate an argon-filled bubble from a vertical capillary tube immersed in the liquid sodium. They made twenty-six sets of measurements in the temperature range 285-1817°F. The surface tension as a function of temperature was given as

$$\sigma(\text{dynes/cm}) = 202.15 - 0.0986\,t\ (°\text{C}). \tag{7.1}$$

The "standard deviation" for the 26 sets of data points was stated to be 3.3%.

Taylor reported earlier measurements of the surface tension of liquid sodium made with the maximum-bubble-pressure method.[89-91] He took measurements over the temperature range 110-450°C (230-842°F). The density of liquid sodium over the same temperature range was also measured in the surface tension apparatus.. His derived density-temperature relationship was in good agreement with literature values and thus provided an indirect check on the overall accuracy of the experimental measurements. A surface tension of 190.8 dyne/cm was obtained at the melting point, with a temperature coefficient of -0.1 dyne/cm-°C from a best straight-line fit of the experimental data. The surface tension as a function of temperature was given as

$$\sigma(\text{dyne/cm}) = 200.6 - 0.1\,t\ (°\text{C}). \tag{7.2}$$

Addison et al.[92] measured the surface tension over the temperature range 128-180°C (262.4-356°F), using a vertical-plate technique. They obtained a value of 195 dyne/cm at the melting point, with a temperature coefficient of -0.1 dyne/cm-°C from a linear fit of the data. The surface tension-temperature relationship was

$$\sigma(\text{dyne/cm}) = 204.8 - 0.10\,t\ (°\text{C}). \tag{7.3}$$

Poindexter and Kernaghan[93] determined the surface tension by a modified flat-drop technique over the temperature range 103-243°C (217.4-469.4°F). From the best mean straight line through the experimental points, they took the surface tension at 100 and 250°C as 206.4 and 199.5 dyne/cm, respectively. The relationship between surface tension and temperature obtained with these values is

$$\sigma(\text{dyne/cm}) = 211.0 - 0.046\,t\ (°\text{C}). \tag{7.4}$$

Addison et al.,[107] in an attempt to verify their earlier vertical-plate results, measured the surface tension of sodium over the temperature range 110-220°C using a drop-volume technique. Twenty-seven sets of measurements were made over the temperature interval. Apparently a best drawn

2

linear fit of the experimental data was made which yielded a temperature coefficient of -0.1 dyne/cm-°C and an extrapolated (98°C) surface tension value of 202 dyne/cm at the melting point. It was not possible for us to obtain a meaningful least-squares fit of the data since the experimental results were reported only in graphical form. The surface tension-temperature relationship obtained from the above values is

$$\sigma = 211.8 - 0.1\ t, \tag{7.5}$$

where σ and t are given in units of dyne/cm and degrees centigrade, respectively.

In summation of their entire effort, Addison et al.[108] concluded that the small disparity between their vertical-plate and drop-volume results was largely due to the presence of oxygen in the argon atmosphere used during the earlier vertical-plate experiments. This view was supported by an additional series of tests made with the drop-volume apparatus. At a temperature of 180°C the surface tension was found to decrease linearly with partial pressure of oxygen from an initial value of 194 to 186 dyne/cm. A minimum occurred at an oxygen partial pressure of 2×10^{-4} atmos, after which the tension increased to very high values. The minimum was related to the change from a soluble to an insoluble film of sodium oxide at the metal surface. On the basis of these results, Addison et al. argued that the vertical-plate measurements were subject to some doubt, since there was evidence of some slight oxide contamination of the sodium.

Jordan and Lane[109] used a vertical-plate balance to determine the surface tension of liquid sodium over the temperature range 130-245°C. A temperature coefficient of -0.11 ± 0.01 dyne/cm-°C was found over the indicated temperature interval. This value coupled with a carefully determined value of 189 dyne/cm obtained at 200°C yields an extrapolated surface tension value of 200.2 ± 0.6 dyne/cm at the melting point. The surface tension-temperature relationship is

$$\sigma = 210.96 - 0.11\ t, \tag{7.6}$$

where σ and t are given in dyne/cm and degrees centigrade, respectively.

Solovev and Makarova[110] obtained experimental values for surface tension by use of a vertical-plate balance. Altogether twenty-six experimental points were obtained over the temperature interval ranging from 194 to 932°C. The data were said to be well represented by the linear relationship

$$\sigma = 202 - 0.092\ (t - 98), \tag{7.7}$$

where σ and t are in dyne/cm and degrees centigrade, respectively. The "mean square" deviation of the points about the relationship was stated to be 1.4%. Using their reported tabular experimental values we obtained the following least-squares relationship:

$$\sigma = 209.47 - 0.08939\ t, \qquad (7.8)$$

where again σ and t are in dyne/cm and degrees centigrade, respectively. The mean deviation of the points about the least-squares line is 1.18%; the standard deviation is 2.17 dyne/cm.

Surface tension values for liquid sodium have appeared in many other sources; several of these are listed in Table VII.1.

TABLE VII.1. Compilations of Surface Tension

Compilation Reference	Information Source	Suggested Relationship
2	Poindexter and Kernaghan[93]	Same as source
3	Poindexter and Kernaghan[93] Taylor[89-91] Addison *et al.*[92]	σ(dyne/cm) = 200.12 - 9.833 x 10^{-2} t (°C) least-squares relation of Taylor's experimental results.
4	Poindexter and Kernaghan[93] Taylor[89-91] Addison *et al.*[92]	σ(dyne/cm) = 204.1 - 0.10 t (°C); compromise relationship between data of Taylor and Addison *et al.*
7	Miller and Epstein[3]	Same as source
6	Thomson and Garelis[4] Miller and Epstein[3]	Thomson and Garelis
8	Dunning[6]	Same as source
9	Dunning[6] Thomson and Garelis[4]	Thomson and Garelis Dunning

The various surface tension relationships are shown together in Fig. 7.1. Except for the data of Poindexter and Kernaghan there is moderately good agreement between all the correlations, both with respect to the temperature coefficient and the actual values of surface tension obtained near the melting point. This is perhaps more clearly indicated in Table VII.2.

Because of the moderately good agreement between most of the correlations, the task of choosing a "best" fit is difficult. Several of the referenced authors put forth various arguments as to why their data should be treated as being accurate and as to why results obtained from other investigations should be subject to some doubt. In our estimation most of these arguments were circumstantial and relied heavily on strings of deductions; therefore little credence was given to them. We arbitrarily decided to pool the various sources and average both their melting-point surface tension

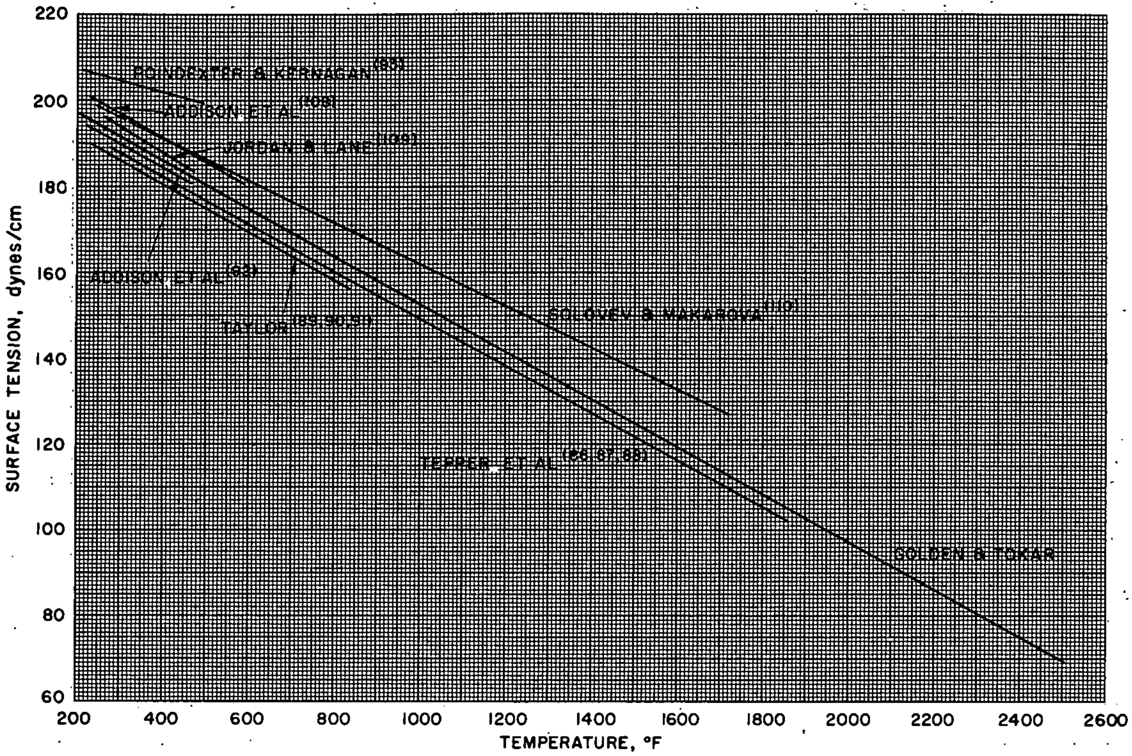

Fig. 7.1. Surface Tension of Sodium

TABLE VII.2. Values of Surface Tension Obtained from Correlations

Reference	Temperature Range (°C)	Melting Point (98°C) Value (dyne/cm)	Temperature Coefficient (dyne/cm-°C)
Addison <u>et</u> <u>al</u>.	128 to 180	195	-0.10
Addison <u>et</u> <u>al</u>.	110 to 220	202	-0.10
Jordan and Lane	130 to 245	200.2	-0.11 ± 0.01
Poindexter and Kernaghan	103 to 243	206.5	-0.046
Solovev and Makarova	194 to 932	200.7	-0.0894
Taylor	110 to 450	190.8	-0.10
Tepper <u>et</u> <u>al</u>.	141 to 992	192.5	-0.0986

values and their temperature coefficients. Poindexter and Kernaghan's results were excluded. The average melting-point surface tension value and temperature coefficient are 196.9 dyne/cm and -0.10 dyne/cm-°C, respectively. The recommended surface tension-temperature relationship is

$$\sigma = 206.7 - 0.10\ t, \tag{7.9}$$

where σ and t are in dyne/cm and degrees centigrade, respectively. The above can be rewritten as

$$\sigma = 0.01429 - 3.81 \times 10^{-6}\ t, \tag{7.9a}$$

where σ and t are in units of lb/ft and degrees Fahrenheit, respectively. Extrapolation of Eq. (7.9a) to 2500°F, as is shown in Fig. 7.1, may involve some error. Grosse[94] recommends using log-log plots of surface tension vs. temperature over wide temperature limits approaching the critical point; these plots appear to be linear for the alkali metals. We made a log-log plot of $(\sigma + 1)$ dyne/cm and $(T_C - T + 55)$ degrees Kelvin as proposed by Weatherford,[95] using values calculated from the recommended Eq. (7.9a) up to 900°C (the critical temperature T_C was assumed equal to 2780°K). We drew a best straight line through the calculated point and obtained a value of 75 dyne/cm for σ, corresponding to the coordinate $(T_C - T + 55)$ equal to 2500°F. A value of σ equal to 70 dyne/cm is obtained from the recommended linear relationship. Thus the advantage of using the log-log method of extrapolation over the linear extrapolation is not evident, at least up to 2500°F. Tabular values of surface tension are reported in Appendix C in engineering units.

VIII. THERMAL EXPANSION COEFFICIENT, COMPRESSIBILITY, AND SONIC VELOCITY FOR LIQUID SODIUM

by David Miller

In the absence of direct dilatometric measurements of the thermal expansion at high temperatures, the thermal expansion coefficient α_P is estimated from Eq. (2.1) as follows:

$$\alpha_P \equiv \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P \cong \alpha_s \equiv \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_s, \tag{8.1}$$

where the subscript s refers to saturation conditions. The thermal expansion computed from this approximate expression is plotted vs. temperature in Fig. 8.1.

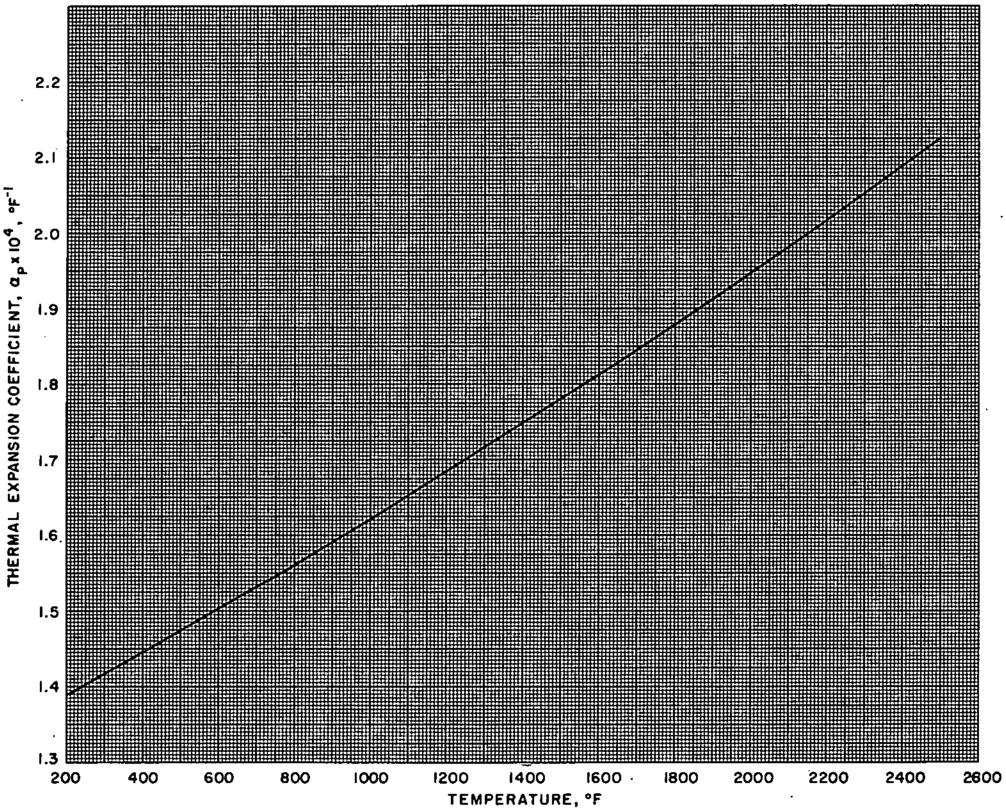

Fig. 8.1. Thermal Expansion Coefficient for Sodium

Since Eq. (2.1) is valid only for liquid sodium in coexistence with its saturated vapor, a small correction can be made if the pressure is significantly greater than the vapor pressure. For this the isothermal compressibility:

$$\beta_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T, \tag{8.2}$$

is used in the following equation:

$$\alpha_P = \alpha_s - \frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T\left(\frac{\partial P}{\partial T}\right)_s = \alpha_s + \beta_T\left(\frac{\partial P}{\partial T}\right)_s. \tag{8.3}$$

The derivative $(\partial P/\partial T)_s$ can be obtained from the slope of the vapor pressure equation by means of the equations of Ditchburn and Gilmour[25] and of Stone et al.[10] in the appropriate temperature range.

Although there have been many studies of the compressibility of solid sodium, no direct measurements of isothermal compressibility have been made over the temperature range of interest, although Bridgeman[112] measured the change in compressibility on melting. However, β_T is related to the easily and accurately measured adiabatic compressibility, β_S, by the relations

$$\beta_T = \frac{C_P}{C_V}\beta_S \tag{8.4}$$

or

$$\beta_T = \beta_S + \frac{T\alpha_P^2}{\rho C_P} \cong \beta_S + \frac{T\alpha_s^2}{\rho C_P}, \tag{8.5}$$

where now the subscript S refers to an adiabatic process. The adiabatic compressibility is in turn determined from the velocity of sound, C, by

$$\beta_S = 1/\rho C^2. \tag{8.6}$$

Sonic velocities have been measured in sodium by a number of investigators, some of whom also established the temperature variation. A summary of these studies is given in Table VIII.1. The work of Trelin, Vasil'ev, and Roshchupkin[113] covered the widest temperature range but gave a value for the velocity at the melting point which disagreed with that found by other studies. Trelin and associates found the velocity was linear with temperature over the entire range. This indicates the restructurization noted in some metals,[114] which is also reflected in other structure-sensitive properties, such as conductivity, is not present. The purity of the sodium and details of its handling were not described, but the maximum measurement error was stated to be less than 1.8%.

The measurements of Pochapsky,[116] Abowitz and Gordon,[117] Jarzynski and Litovitz,[118] Letcher and Beyer,[119] and Ying and Scott[120] all agree well on the sonic velocity at the melting point. Measurements by Ilgunas and Barsauskas[121] are in fair agreement, and the study of Kleppa,[115] whose sodium had a stated impurity content of over 1%, is clearly lower by an amount outside his own stated error.

TABLE VIII.1. Experimental Determinations of Sonic Velocity in Liquid Sodium

Reference	Sonic Velocity at Melting Point (m/sec)	Temperature Coefficient (m/sec/°C)	Temperature Range (°C)	Comment
Kleppa[115]	2395 ± 25 @ 98°C	-0.3	98-235	1% calcium and other impurities including gas
Pochapsky[116]	2526 ± 5 @ 97.6 ± 0.1°C	-0.524 ± 0.003	97.6-272	Acoustic interferometer; good purity.
Abowitz and Gordon[117]	2526 ± 5	-0.524 ± 0.003	100-140	
Trelin *et al.*[113]	2595 ± 47	-0.577	100-700	Pulsed interferometer
Jarzynski and Litovitz[118]	2526	-0.50	104-154	
Letcher and Beyer[119]	2525 ± 25	-0.50	97.8-150	
Ilgunas and Barsauskas[121]	2533	-0.66	100-180	
Ying and Scott[120]	2526 @ 97.8°C	-0.523	97.8-315	

Although Pochapsky's temperature range is smaller than that of Trelin and associates, he used triply distilled sodium and an acoustic interferometer, and measured the temperature coefficient with excellent accuracy and consistency. His temperature coefficient has been substantiated by the work of Abowitz and Gordon and of Ying and Scott. The coefficients of Jarzynski and Litovitz and of Letcher and Beyer are in better agreement with Pochapsky's work then that of Trelin, Vasil'ev, and Roshchupkin. The temperature dependence of Kleppa and of Ilgunas and Barsauskas appear to be erroneous. The slope of the data of Trelin *et al.* is possibly high because of the higher initial value of their sonic velocity due to impurities such as solids.

An equation based on Pochapsky's linear relation between sonic velocity and temperature was used with the density relation, Eq. (2.1), to calculate the adiabatic compressibility as a function of temperature, although this required extrapolation outside the experimental range.

Also extrapolated was the heat capacity relation of Ginnings, Douglas, and Ball[49] as justified by Stone *et al.*[10] With the approximation indicated in Eq. (8.5), values of the isothermal compressibility are plotted in Fig. 8.2. In addition, the heat capacity at constant volume and the thermal pressure coefficient γ_V, where

$$\gamma_V = \left(\frac{\partial P}{\partial T}\right)_V = \frac{\alpha_P}{\beta_T}, \qquad (8.7)$$

were calculated. The thermal pressure coefficient, which is plotted in Fig. 8.3, can be used to calculate the pressure change for sodium in a

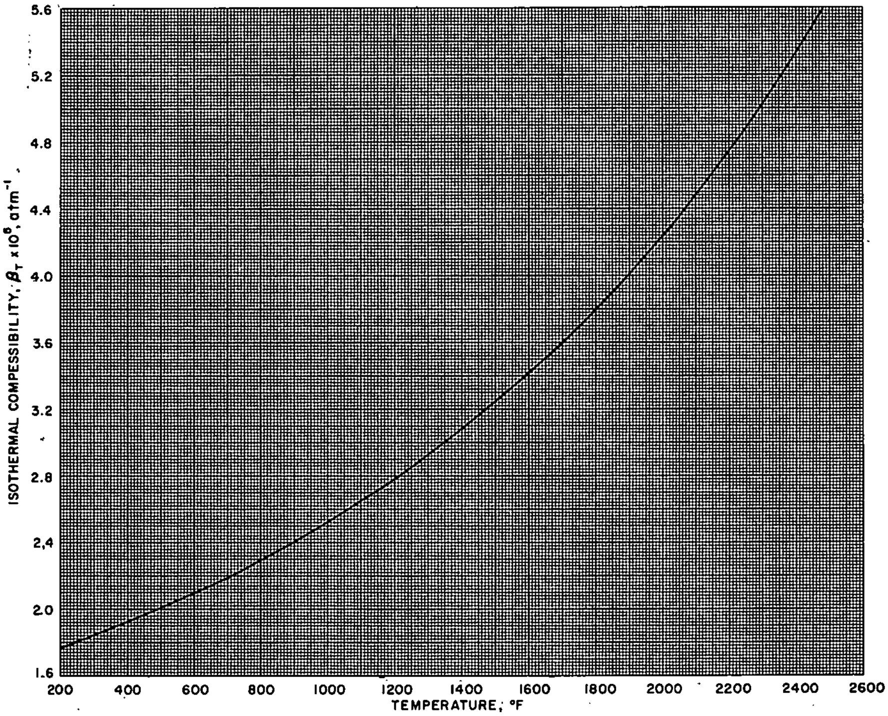

Fig. 8.2. Isothermal Compressibility of Sodium

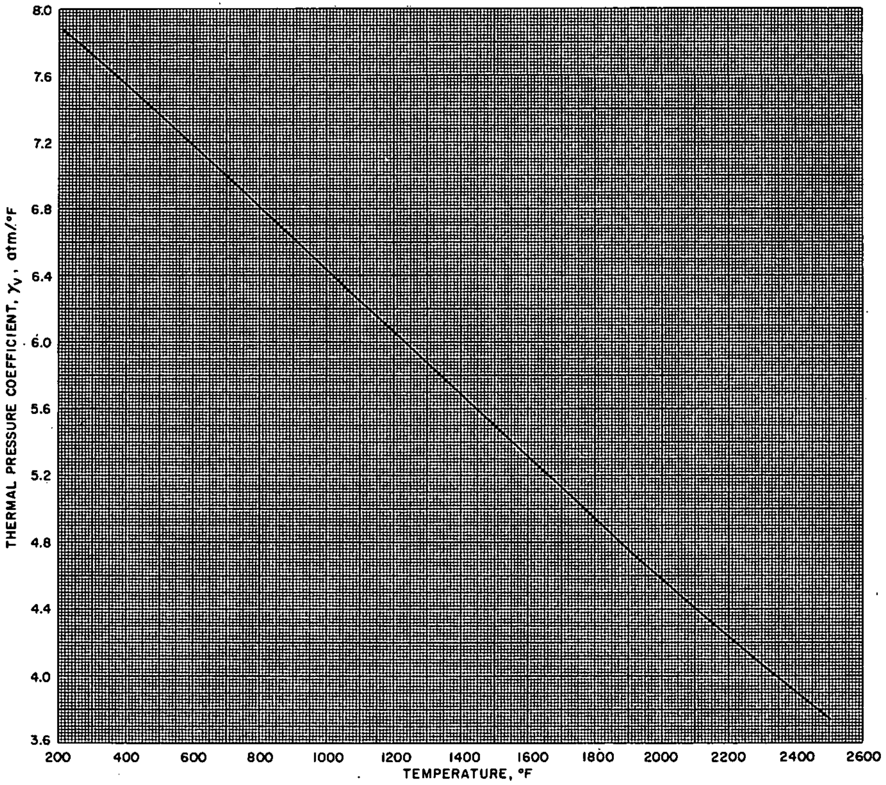

Fig. 8.3. Thermal Pressure Coefficient for Sodium

confined space with heat addition from the relation

$$dP = \left(\frac{\partial P}{\partial T}\right)_V dT + \left(\frac{\partial P}{\partial V}\right)_T dV. \tag{8.8}$$

This gives

$$\Delta P \cong \gamma_V \Delta T - \frac{1}{\beta_T}\frac{\Delta V}{V} \tag{8.9}$$

on substitution and integration.

Values of α_P as approximated by α_s, C, β_S, β_T, C_P, and C_V are tabulated as functions of temperature in Appendix E.

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APPENDIX A. Sodium P-V-T and Thermodynamic Properties Subroutine

```
      SUBROUTINF NAPROP(TEMPR,PATM)
      T=TEMPR
C     CALCULATION OF SATURATION PROPERTIES
  100 IF(T-2059.7)110,110,112
  110 PSAT=(3.03266E6/T**.5)*(EXPF(-2.30733E4/T))                      ATM
  111 GO TO 120
  112 PSAT=(6.8817602E6/(T**.61344))*EXPF(-22981.96/T)                 ATM
  113 GO TO 120
  120 HLS=.389352*T-.5529955E-4*(T)**2+.113726E-7*(T)**3-29.02         BTU/LB
  130 SLS=.389344*(LOGF(T))-1.10557E-4*T+.170408E-7*(T**2)-1.792026    BTU/LBR
  140 DL=59.566-7.9504E-3*(T-459.7)-.2872E-6*((T-459.7)**2)+.06035E-9* LB/FT3
     1((T-459.7)**3)
  150 TWO=EXPF(-9.95845+(16588.3/T))                                   ATM-1
  160 FOUR=EXPF(-24.59115+(37589.7/T))                                 ATM-3
  170 U=PSAT*TWO
  180 W=((PSAT)**3)*FOUR
  190 X1=0.8
  200 X1P=X1
  203 X1=X1-(W*(X1)**4+U*(X1)**2+X1-1.)/(4.*W*(X1)**3+2.*U*X1+1.)
  205 IF(ABSF(X1-X1P)/X1-1.E-6)210,210,200
  210 X2=U*(X1)**2
  212 X4=1.-X1-X2
  214 ABAR=22.991*(X1+2.*X2+4.*X4)
  216 VSAT=(.730229*T)/(ABAR*PSAT)                                     FT3/LB
  217 Z=22.991/ABAR
  218 DHF1=25980.7-2.21312*T+7.06278E-4*(T)**2-1.4526E-7*(T)**3        CAL/MNA1
  220 DHF2=2.*DHF1-18304.                                              CAL/MNA2
  222 DHF4=4.*DHF1-41478.                                              CAL/MNA4
  224 DHV=1.8*(X1*DHF1+X2*DHF2+X4*DHF4)/ABAR                           BTU/LB
  226 HGS=HLS+DHV
  228 SGS=SLS+(DHV/T)
C     TEST FOR STATE,I.E.,SUBCOOLED,SATURATED,SUPERHEATED
  250 IF(ABSF(PATM-PSAT)/PATM-1.E-4)463,463,260
  260 IF(PATM-PSAT)270,463,410
C     CALCULATION OF SUPERHEATED VAPOR PROPERTIES
  270 UH=PATM*TWO
  272 WH=((PATM)**3)*FOUR
  275 X1H=0.8                                                          MOLEFRX1
  278 X1PH=X1H
  280 X1H=X1H-(WH*(X1H)**4+UH*(X1H)**2+X1H-1.)/(4.*WH*(X1H)**3+2.*UH*
     1X1H+1.)
  282 IF(ABSF(X1H-X1PH)/X1H-1.E-6)284,284,278
  284 X2H=UH*(X1H)**2                                                  MOLEFRX2
  286 X4H=1.-X1H-X2H                                                   MOLEFRX4
  288 ABARH=22.991*(X1H+2.*X2H+4.*X4H)
  290 VH=(.730229*T)/(ABARH*PATM)                                      FT3/LB
  292 ZH=22.991/ABARH
  294 BD=X1+2.*X2+4.*X4
  296 B2=2.*X2/BD                                                      WTFRX2S
  297 B4=4.*X4/BD                                                      WTFRX4S
  298 BDH=X1H+2.*X2H+4.*X4H
  300 B2H=2.*X2H/BDH                                                   WTFRX2H
  301 B4H=4.*X4H/BDH                                                   WTFRX4H
  303 HGI=HGS+B2*716.54+B4*811.85
```

APPENDIX A (Contd.)

```
  305 HGH=HGI-B2H*716.54-B4H*811.85
  308 SGI=SGS+B2*716.54/T+B4*811.85/T+(1.987180/ABAR)*LOGF(PSAT)-(B2/
     145.982)*(-19.78923+(32963.9/T))-(B4/91.964)*(-48.86704+(74697.5/
     2T))+(1.987180/ABAR)*(X1*LOGF(X1)+X2*LOGF(X2)+X4*LOGF(X4))
  310 SGH=SGI-B2H*716.54/T-B4H*811.85/T-(1.987180/ABARH)*LOGF(PATM)+(
     1B2H/45.982)*(-19.78923+(32963.9/T))+(B4H/91.964)*(-48.86704+(746
     297.5/T))-(1.987180/ABARH)*(X1H*LOGF(X1H)+X2H*LOGF(X2H)+X4H*LOGF(
     3X4H))
      PRINT 350
  350 FORMAT(3X,4HTEMP,7X,4HPRES,10X,2HVH,9X,2HZH,7X,3HHGI,8X,3HHGH,7X,3
     1HSGI,9X,3HSGH,5X,5HABARH,8X,3HX2H,9X,3HX4H)
      PRINT 351
  351 FORMAT(2X,5HDEG-F,7X,3HATM,8X,6HFT3/LB,16X,6HBTU/LB,4X,6HBTU/LB,4X
     1,7HBTU/LBF,5X,7HBTU/LBF,15X,6HMOL FR,6X,6HMOL FR)
  360 PRINT 370,T,PATM,VH,ZH,HGI,HGH,SGI,SGH,ABARH,X2H,X4H
  370 FORMAT(/,1X,F7.1,2(2X,E11.4),2X,F8.5,2(2X,F8.2),2X,F8.5,4X,F8.5,2X
     1,F7.3,2(4X,F8.6))
      GO TO 80
C     CALCULATION OF SUBCOOLED LIQUID PROPERTIES
  410 DLP=-7.9504E-3-.5744E-6*(T-459.7)+.18105E-9*(T-459.7)**2
      HLC=HLS+(1./DL)*(1.+(T/DL)*DLP)*(PATM-PSAT)*2.721308
      SLC=SLS+2.721308*(1./(DL**2))*DLP*(PATM-PSAT)
      PRINT 415
  415 FORMAT(8X,4HTEMP,10X,4HPRES,11X,3HHLC,10X,3HSLC,/,8X,5HDEG-F,9X,3H
     1ATM,10X,6HBTU/LB,7X,7HBTU/LBF)
  420 PRINT 450,T,PATM,HLC,SLC
  450 FORMAT(/,6X,F7.1,5X,E11.4,5X,F8.2,5X,F8.5)
      GO TO 80
C      OUTPUT SATURATION PROPERTIES
  463 T=T-459.7
      PRINT 10
   10 FORMAT(1H1,2X,5HTEMPF,6X,4HPSAT,7X,4HVSAT,8X,1HZ,7X,2HDL,6X,3HHLS,
     16X,3HDHV,6X,3HHGS,6X,3HSLS,6X,3HSGS,5X,4HABAR,5X,2HX2,7X,2HX4)
      PRINT 11
   11 FORMAT(2X,5HDEG-F,6X,3HATM,7X,6HFT3/LB,13X,6HLB/FT3,3X,6HBTU/LB,3X
     1,6HBTU/LB,3X,6HBTU/LB,2X,7HBTU/LBF,2X,7HBTU/LBF,10X,6HMOL FR,3X,6H
     2MOL FR)
      PRINT 470,T,PSAT,VSAT,Z,DL,HLS,DHV,HGS,SLS,SGS,ABAR,X2,X4
  470 FORMAT(/,F7.1,1X,E11.5,1X,E11.5,2X,F7.5,1X,F7.3,2X,F7.2,1X,F8.2,1X
     1,F8.2,1X,F8.5,1X,F8.5,1X,F7.3,1X,F8.6,2X,F7.6)
   80 RETURN
   51 END
```

APPENDIX B. Saturation P-V-T and Thermodynamic Properties of Sodium

Property: Temp (°F)	Vapor Pressure: PSAT (atmos)	Vapor Sp. Vol.: VSAT (ft³/lb)	Compr. Factor: Z	Liquid Density: DL (lb/ft³)	Liquid Enthalpy: HLS (Btu/lb)	Heat of Vapn.: DHV (Btu/lb)	Vapor Enthalpy: HGS (Btu/lb)	Liquid Entropy: SLS (Btu/lb°F)	Vapor Entropy: SGS (Btu/lb°F)	Vapor Mol. Wt.: ABAR	Dimer Mole Fr.: X_2 (mole fr.)	Tetramer Mole Fr.: X_4 (mole fr.)
500.0	3.54292-6	8.55792+6	0.99470	55.527	303.76	1901.06	2204.83	0.79105	2.77194	23.113	0.005328	0.000000
510.0	4.51634-6	6.78099+6	0.99435	55.445	306.91	1899.58	2206.49	0.79430	2.75324	23.122	0.005679	0.000000
520.0	5.72845-6	5.39933+6	0.99399	55.363	310.04	1898.09	2208.13	0.79753	2.73494	23.130	0.006044	0.000000
530.0	7.23067-6	4.31961+6	0.99362	55.281	313.18	1896.57	2209.75	0.80071	2.71702	23.139	0.006425	0.000000
540.0	9.08395-6	3.47171+6	0.99323	55.199	316.31	1895.04	2211.36	0.80386	2.69947	23.148	0.006820	0.000000
550.0	1.13602-5	2.80271+6	0.99282	55.116	319.44	1893.50	2212.94	0.80697	2.68228	23.157	0.007231	0.000000
560.0	1.41440-5	2.27242+6	0.99240	55.034	322.56	1891.94	2214.50	0.81005	2.66543	23.167	0.007656	0.000000
570.0	1.75343-5	1.85021+6	0.99197	54.952	325.68	1890.36	2216.03	0.81309	2.64892	23.177	0.008097	0.000000
580.0	2.16466-5	1.51258+6	0.99152	54.870	328.79	1888.76	2217.55	0.81610	2.63274	23.188	0.008554	0.000000
590.0	2.66151-5	1.24147+6	0.99106	54.788	331.90	1887.14	2219.05	0.81908	2.61687	23.199	0.009025	0.000000
600.0	3.25952-5	1.02287+6	0.99058	54.705	335.01	1885.51	2220.52	0.82202	2.60131	23.210	0.009513	0.000000
610.0	3.97661-5	8.45906+5	0.99008	54.623	338.11	1883.86	2221.98	0.82494	2.58605	23.221	0.010015	0.000000
620.0	4.83342-5	7.02100+5	0.98958	54.541	341.21	1882.20	2223.41	0.82782	2.57108	23.233	0.010533	0.000000
630.0	5.85359-5	5.84798+5	0.98905	54.458	344.31	1880.52	2224.82	0.83067	2.55639	23.245	0.011067	0.000000
640.0	7.06413-5	4.88766+5	0.98852	54.376	347.40	1878.82	2226.21	0.83350	2.54198	23.258	0.011617	0.000000
650.0	8.49585-5	4.09866+5	0.98797	54.293	350.49	1877.10	2227.58	0.83629	2.52783	23.271	0.012181	0.000000
660.0	1.01837-4	3.44818+5	0.98740	54.211	353.57	1875.36	2228.93	0.83906	2.51394	23.284	0.012761	0.000000
670.0	1.21673-4	2.91010+5	0.98682	54.128	356.65	1873.61	2230.26	0.84180	2.50030	23.298	0.013357	0.000000
680.0	1.44913-4	2.46354+5	0.98622	54.046	359.73	1871.84	2231.57	0.84451	2.48691	23.312	0.013968	0.000000
690.0	1.72063-4	2.09174+5	0.98562	53.963	362.81	1870.06	2232.86	0.84720	2.47376	23.327	0.014594	0.000000
700.0	2.03686-4	1.78122+5	0.98499	53.881	365.88	1868.25	2234.13	0.84986	2.46084	23.341	0.015236	0.000000
710.0	2.40419-4	1.52111+5	0.98436	53.798	368.94	1866.43	2235.38	0.85249	2.44814	23.356	0.015892	0.000000
720.0	2.82969-4	1.30257+5	0.98371	53.715	372.01	1864.60	2236.61	0.85510	2.43567	23.372	0.016563	0.000000
730.0	3.32127-4	1.11843+5	0.98304	53.633	375.07	1862.74	2237.82	0.85769	2.42341	23.388	0.017249	0.000000
740.0	3.88771-4	9.62839+4	0.98237	53.550	378.13	1860.88	2239.01	0.86025	2.41137	23.404	0.017950	0.000000
750.0	4.53877-4	8.31016+4	0.98168	53.467	381.19	1858.99	2240.18	0.86278	2.39952	23.420	0.018665	0.000000
760.0	5.28524-4	7.19030+4	0.98097	53.384	384.24	1857.09	2241.33	0.86530	2.38788	23.437	0.019395	0.000000
770.0	6.13906-4	6.23647+4	0.98026	53.301	387.29	1855.18	2242.47	0.86779	2.37643	23.454	0.020139	0.000000

APPENDIX B (Contd.)

Temp (°F)	PSAT (atmos)	VSAT (ft^3/lb)	Z	DL (lb/ft^3)	HLS (Btu/lb)	DHV (Btu/lb)	HGS (Btu/lb)	SLS (Btu/lb°F)	SGS (Btu/lb°F)	ABAR	X_2 (mole fr.)	X_4 (mole fr.)
780.0	7.11337-4	5.42201+4	0.97953	53.219	390.34	1853.25	2243.59	0.87026	2.36517	23.471	0.020897	0.000000
790.0	8.22263-4	4.72483+4	0.97879	53.136	393.39	1851.30	2244.69	0.87270	2.35410	23.489	0.021669	0.000000
800.0	9.48273-4	4.12658+4	0.97804	53.053	396.43	1849.34	2245.77	0.87513	2.34321	23.507	0.022454	0.000000
810.0	1.09111-3	3.61203+4	0.97728	52.970	399.47	1847.37	2246.84	0.87753	2.33250	23.526	0.023253	0.000000
820.0	1.25267-3	3.16845+4	0.97650	52.887	402.51	1845.38	2247.89	0.87992	2.32196	23.544	0.024065	0.000000
830.0	1.43503-3	2.78517+4	0.97571	52.804	405.54	1843.38	2248.92	0.88228	2.31159	23.563	0.024890	0.000000
840.0	1.64045-3	2.45329+4	0.97492	52.721	408.58	1841.36	2249.94	0.88462	2.30138	23.583	0.025728	0.000000
850.0	1.87140-3	2.16528+4	0.97411	52.638	411.61	1839.34	2250.94	0.88695	2.29134	23.602	0.026578	0.000000
860.0	2.13055-3	1.91482+4	0.97329	52.555	414.64	1837.30	2251.93	0.88925	2.28146	23.622	0.027441	0.000000
870.0	2.42078-3	1.69657+4	0.97246	52.472	417.66	1835.24	2252.91	0.89153	2.27173	23.642	0.028316	0.000001
880.0	2.74524-3	1.50601+4	0.97162	52.388	420.69	1833.18	2253.87	0.89380	2.26215	23.662	0.029202	0.000001
890.0	3.10730-3	1.33929+4	0.97078	52.305	423.71	1831.10	2254.81	0.89605	2.25272	23.683	0.030100	0.000001
900.0	3.51062-3	1.19316+4	0.96992	52.222	426.73	1829.01	2255.74	0.89828	2.24344	23.704	0.031010	0.000001
910.0	3.95911-3	1.06482+4	0.96905	52.139	429.75	1826.91	2256.67	0.90049	2.23430	23.725	0.031931	0.000001
920.0	4.45701-3	9.51917+3	0.96818	52.056	432.77	1824.80	2257.57	0.90269	2.22529	23.747	0.032862	0.000001
930.0	5.00884-3	8.52403+3	0.96730	51.972	435.79	1822.68	2258.47	0.90486	2.21643	23.768	0.033804	0.000001
940.0	5.61948-3	7.64540+3	0.96641	51.889	438.80	1820.55	2259.35	0.90703	2.20770	23.790	0.034756	0.000001
950.0	6.29411-3	6.86830+3	0.96551	51.806	441.81	1818.41	2260.23	0.90917	2.19910	23.812	0.035719	0.000002
960.0	7.03832-3	6.17984+3	0.96460	51.722	444.83	1816.26	2261.09	0.91130	2.19063	23.835	0.036691	0.000002
970.0	7.85803-3	5.56890+3	0.96369	51.639	447.84	1814.10	2261.94	0.91341	2.18228	23.857	0.037672	0.000002
980.0	8.75957-3	5.02588+3	0.96277	51.556	450.85	1811.94	2262.78	0.91551	2.17406	23.880	0.038663	0.000003
990.0	9.74970-3	4.54247+3	0.96184	51.472	453.85	1809.76	2263.62	0.91759	2.16596	23.903	0.039663	0.000003
1000.0	1.08356-2	4.11145+3	0.96091	51.389	456.86	1807.58	2264.44	0.91966	2.15798	23.926	0.040671	0.000003
1010.0	1.20248-2	3.72657+3	0.95997	51.305	459.87	1805.39	2265.26	0.92171	2.15012	23.950	0.041688	0.000004
1020.0	1.33255-2	3.38237+3	0.95902	51.222	462.87	1803.19	2266.06	0.92375	2.14237	23.973	0.042713	0.000004
1030.0	1.47462-2	3.07410+3	0.95807	51.138	465.87	1800.99	2266.86	0.92577	2.13473	23.997	0.043746	0.000005
1040.0	1.62960-2	2.79763+3	0.95712	51.055	468.88	1798.78	2267.65	0.92778	2.12720	24.021	0.044786	0.000006
1050.0	1.79844-2	2.54932+3	0.95616	50.971	471.88	1796.56	2268.44	0.92977	2.11978	24.045	0.045834	0.000007
1060.0	1.98216-2	2.32600+3	0.95519	50.888	474.88	1794.34	2269.22	0.93175	2.11247	24.070	0.046888	0.000007

APPENDIX B (Contd.)

Temp (°F)	PSAT (atmos)	VSAT (ft^3/lb)	Z	DL (lb/ft^3)	HLS (Btu/lb)	DHV (Btu/lb)	HGS (Btu/lb)	SLS (Btu/lb°F)	SGS (Btu/lb°F)	ABAR	X_2 (mole fr.)	X_4 (mole fr.)
1070.0	2.18182-2	2.12489+3	0.95422	50.804	477.88	1792.11	2269.99	0.93372	2.10526	24.094	0.047950	0.000008
1080.0	2.39856-2	1.94354+3	0.95325	50.721	480.88	1789.87	2270.75	0.93568	2.09816	24.119	0.049018	0.000009
1090.0	2.63354-2	1.77978+3	0.95227	50.637	483.88	1787.63	2271.51	0.93762	2.09115	24.143	0.050092	0.000011
1100.0	2.88803-2	1.63174+3	0.95129	50.553	486.88	1785.39	2272.27	0.93955	2.08425	24.168	0.051172	0.000012
1110.0	3.16332-2	1.49774+3	0.95030	50.470	489.88	1783.14	2273.02	0.94146	2.07744	24.193	0.052258	0.000013
1120.0	3.46079-2	1.37629+3	0.94931	50.386	492.87	1780.89	2273.76	0.94337	2.07072	24.219	0.053350	0.000015
1130.0	3.78189-2	1.26608+3	0.94832	50.302	495.87	1778.63	2274.50	0.94526	2.06410	24.244	0.054446	0.000017
1140.0	4.12810-2	1.16597+3	0.94732	50.219	498.87	1776.37	2275.24	0.94714	2.05758	24.269	0.055548	0.000019
1150.0	4.50103-2	1.07492+3	0.94633	50.135	501.87	1774.11	2275.97	0.94900	2.05114	24.295	0.056654	0.000021
1160.0	4.90231-2	9.92012+2	0.94533	50.051	504.86	1771.84	2276.70	0.95086	2.04479	24.321	0.057765	0.000023
1170.0	5.33368-2	9.16439+2	0.94433	49.968	507.86	1769.57	2277.43	0.95271	2.03853	24.346	0.058880	0.000026
1180.0	5.79692-2	8.47476+2	0.94332	49.884	510.86	1767.30	2278.15	0.95454	2.03236	24.372	0.059999	0.000029
1190.0	6.29393-2	7.84477+2	0.94231	49.800	513.85	1765.02	2278.88	0.95636	2.02627	24.398	0.061121	0.000032
1200.0	6.82665-2	7.26866+2	0.94131	49.716	516.85	1762.74	2279.60	0.95817	2.02026	24.425	0.062247	0.000035
1210.0	7.39713-2	6.74127+2	0.94030	49.632	519.85	1760.46	2280.31	0.95997	2.01433	24.451	0.063377	0.000039
1220.0	8.00748-2	6.25800+2	0.93929	49.549	522.85	1758.18	2281.03	0.96176	2.00849	24.477	0.064509	0.000043
1230.0	8.65990-2	5.81470+2	0.93827	49.465	525.85	1755.90	2281.74	0.96354	2.00272	24.503	0.065644	0.000047
1240.0	9.35670-2	5.40769+2	0.93726	49.381	528.85	1753.61	2282.46	0.96531	1.99703	24.530	0.066782	0.000052
1250.0	1.01002-1	5.03362+2	0.93625	49.297	531.85	1751.32	2283.17	0.96707	1.99142	24.557	0.067922	0.000057
1260.0	1.08930-1	4.68950+2	0.93523	49.213	534.85	1749.04	2283.88	0.96882	1.98588	24.583	0.069064	0.000063
1270.0	1.17375-1	4.37264+2	0.93422	49.129	537.85	1746.75	2284.59	0.97056	1.98042	24.610	0.070208	0.000069
1280.0	1.26364-1	4.08062+2	0.93320	49.046	540.85	1744.46	2285.30	0.97229	1.97502	24.637	0.071354	0.000076
1290.0	1.35925-1	3.81125+2	0.93218	48.962	543.85	1742.16	2286.01	0.97401	1.96970	24.664	0.072501	0.000083
1300.0	1.46086-1	3.56254+2	0.93117	48.878	546.85	1739.87	2286.72	0.97572	1.96445	24.691	0.073650	0.000091
1310.0	1.56875-1	3.33272+2	0.93015	48.794	549.86	1737.58	2287.44	0.97742	1.95927	24.718	0.074799	0.000099
1320.0	1.68324-1	3.12017+2	0.92913	48.710	552.86	1735.28	2288.15	0.97912	1.95416	24.745	0.075950	0.000108
1330.0	1.80464-1	2.92342+2	0.92811	48.626	555.87	1732.99	2288.86	0.98080	1.94911	24.772	0.077101	0.000118
1340.0	1.93327-1	2.74116+2	0.92710	48.542	558.88	1730.69	2289.57	0.98248	1.94413	24.799	0.078253	0.000128
1350.0	2.06945-1	2.57217+2	0.92608	48.458	561.89	1728.40	2290.28	0.98414	1.93922	24.826	0.079405	0.000140

APPENDIX B (Contd.)

Temp (°F)	PSAT (atmos)	VSAT (ft^3/lb)	Z	DL (lb/ft^3)	HLS (Btu/lb)	DHV (Btu/lb)	HGS (Btu/lb)	SLS (Btu/lb°F)	SGS (Btu/lb°F)	ABAR	X_2 (mole fr.)	X_4 (mole fr.)
1360.0	2.21354-1	2.41536+2	0.92506	48.374	564.90	1726.10	2291.00	0.98580	1.93437	24.854	0.080557	0.000152
1370.0	2.36589-1	2.26975+2	0.92404	48.290	567.91	1723.80	2291.71	0.98745	1.92958	24.881	0.081709	0.000164
1380.0	2.52685-1	2.13443+2	0.92302	48.206	570.92	1721.50	2292.43	0.98909	1.92485	24.908	0.082861	0.000178
1390.0	2.69681-1	2.00857+2	0.92201	48.122	573.94	1719.21	2293.14	0.99073	1.92018	24.936	0.084013	0.000193
1400.0	2.87614-1	1.89142+2	0.92099	48.038	576.95	1716.91	2293.86	0.99235	1.91557	24.963	0.085163	0.000209
1410.0	3.06524-1	1.78231+2	0.91997	47.954	579.97	1714.61	2294.58	0.99397	1.91102	24.991	0.086314	0.000226
1420.0	3.26452-1	1.68060+2	0.91895	47.870	582.99	1712.31	2295.30	0.99558	1.90653	25.019	0.087463	0.000244
1430.0	3.47438-1	1.58573+2	0.91794	47.786	586.01	1710.01	2296.02	0.99719	1.90210	25.046	0.088611	0.000263
1440.0	3.69526-1	1.49717+2	0.91692	47.702	589.03	1707.71	2296.74	0.99878	1.89772	25.074	0.089758	0.000284
1450.0	3.92759-1	1.41446+2	0.91590	47.618	592.06	1705.41	2297.47	1.00037	1.89339	25.102	0.090904	0.000305
1460.0	4.17182-1	1.33714+2	0.91488	47.534	595.08	1703.11	2298.19	1.00195	1.88912	25.130	0.092048	0.000329
1470.0	4.42841-1	1.26481+2	0.91387	47.450	598.11	1700.81	2298.92	1.00352	1.88491	25.158	0.093190	0.000353
1480.0	4.69782-1	1.19712+2	0.91285	47.366	601.14	1698.50	2299.65	1.00509	1.88074	25.186	0.094331	0.000380
1490.0	4.98054-1	1.13373+2	0.91183	47.282	604.18	1696.20	2300.37	1.00665	1.87663	25.214	0.095470	0.000407
1500.0	5.27706-1	1.07431+2	0.91082	47.198	607.21	1693.89	2301.10	1.00820	1.87256	25.242	0.096606	0.000437
1510.0	5.58787-1	1.01859+2	0.90980	47.114	610.25	1691.59	2301.84	1.00975	1.86855	25.270	0.097740	0.000468
1520.0	5.91350-1	9.66307+1	0.90878	47.030	613.29	1689.28	2302.57	1.01128	1.86459	25.299	0.098872	0.000501
1530.0	6.25446-1	9.17214+1	0.90776	46.946	616.33	1686.97	2303.30	1.01282	1.86067	25.327	0.100001	0.000536
1540.0	6.61129-1	8.71092+1	0.90674	46.862	619.38	1684.66	2304.04	1.01434	1.85680	25.356	0.101128	0.000573
1550.0	6.98453-1	8.27734+1	0.90572	46.778	622.42	1682.35	2304.78	1.01586	1.85298	25.384	0.102252	0.000613
1560.0	7.37474-1	7.86950+1	0.90470	46.694	625.47	1680.04	2305.51	1.01738	1.84920	25.413	0.103373	0.000654
1570.0	7.78249-1	7.48566+1	0.90368	46.610	628.53	1677.73	2306.25	1.01888	1.84547	25.441	0.104491	0.000697
1580.0	8.20835-1	7.12420+1	0.90266	46.525	631.58	1675.41	2306.99	1.02039	1.84179	25.470	0.105605	0.000743
1590.0	8.65291-1	6.78362+1	0.90164	46.441	634.64	1673.09	2307.73	1.02188	1.83814	25.499	0.106717	0.000792
1600.0	9.11677-1	6.46254+1	0.90061	46.357	637.70	1670.77	2308.47	1.02337	1.83454	25.528	0.107825	0.000843
1610.0	9.57593-1	6.17683+1	0.89978	46.273	640.77	1668.72	2309.49	1.02485	1.83112	25.552	0.108706	0.000891
1618.6	1.00000+0	5.93350+1	0.89895	46.200	643.40	1666.79	2310.19	1.02612	1.82812	25.575	0.109594	0.000937
1620.0	1.00713+0	5.89506+1	0.89882	46.189	643.83	1666.48	2310.31	1.02633	1.82764	25.579	0.109738	0.000945
1630.0	1.05870+0	5.62880+1	0.89785	46.105	646.90	1664.24	2311.14	1.02781	1.82420	25.607	0.110767	0.001002

APPENDIX B (Contd.)

Temp (°F)	PSAT (atmos)	VSAT (ft^3/lb)	Z	DL (lb/ft^3)	HLS (Btu/lb)	DHV (Btu/lb)	HGS (Btu/lb)	SLS (Btu/lb°F)	SGS (Btu/lb°F)	ABAR	X_2 (mole fr.)	X_4 (mole fr.)
1640.0	1.11237+0	5.37706+1	0.89688	46.021	649.98	1661.99	2311.97	1.02927	1.82081	25.634	0.111791	0.001061
1650.0	1.16819+0	5.13893+1	0.89591	45.937	653.05	1659.74	2312.80	1.03073	1.81745	25.662	0.112810	0.001124
1660.0	1.22623+0	4.91356+1	0.89494	45.853	656.14	1657.49	2313.63	1.03219	1.81414	25.690	0.113825	0.001189
1670.0	1.28656+0	4.70016+1	0.89397	45.769	659.22	1655.24	2314.46	1.03364	1.81086	25.718	0.114835	0.001258
1680.0	1.34922+0	4.49799+1	0.89299	45.685	662.31	1652.98	2315.29	1.03509	1.80762	25.746	0.115841	0.001329
1690.0	1.41430+0	4.30638+1	0.89202	45.601	665.40	1650.72	2316.12	1.03653	1.80441	25.774	0.116842	0.001404
1700.0	1.48184+0	4.12467+1	0.89104	45.517	668.49	1648.46	2316.95	1.03796	1.80124	25.802	0.117838	0.001482
1710.0	1.55193+0	3.95229+1	0.89006	45.433	671.59	1646.19	2317.78	1.03939	1.79811	25.831	0.118828	0.001563
1720.0	1.62462+0	3.78867+1	0.88908	45.349	674.69	1643.92	2318.61	1.04082	1.79502	25.859	0.119814	0.001648
1730.0	1.69998+0	3.63330+1	0.88809	45.265	677.80	1641.65	2319.44	1.04224	1.79195	25.888	0.120795	0.001737
1740.0	1.77808+0	3.48570+1	0.88711	45.181	680.91	1639.37	2320.27	1.04366	1.78893	25.917	0.121771	0.001829
1750.0	1.85899+0	3.34541+1	0.88612	45.097	684.02	1637.08	2321.10	1.04507	1.78593	25.946	0.122741	0.001926
1760.0	1.94278+0	3.21201+1	0.88513	45.013	687.14	1634.80	2321.93	1.04648	1.78297	25.975	0.123706	0.002026
1770.0	2.02951+0	3.08512+1	0.88413	44.929	690.26	1632.50	2322.76	1.04788	1.78004	26.004	0.124665	0.002130
1780.0	2.11927+0	2.96435+1	0.88313	44.845	693.39	1630.20	2323.59	1.04928	1.77715	26.034	0.125619	0.002239
1790.0	2.21212+0	2.84937+1	0.88213	44.761	696.52	1627.90	2324.42	1.05067	1.77428	26.063	0.126567	0.002352
1800.0	2.30813+0	2.73986+1	0.88112	44.677	699.65	1625.59	2325.24	1.05206	1.77145	26.093	0.127510	0.002469
1810.0	2.40738+0	2.63550+1	0.88011	44.593	702.79	1623.28	2326.06	1.05345	1.76864	26.123	0.128447	0.002591
1820.0	2.50993+0	2.53603+1	0.87910	44.509	705.93	1620.96	2326.89	1.05483	1.76587	26.153	0.129378	0.002717
1830.0	2.61588+0	2.44116+1	0.87808	44.425	709.08	1618.63	2327.71	1.05621	1.76312	26.183	0.130304	0.002848
1840.0	2.72528+0	2.35066+1	0.87706	44.341	712.23	1616.29	2328.52	1.05758	1.76041	26.214	0.131223	0.002984
1850.0	2.83822+0	2.26428+1	0.87603	44.257	715.39	1613.95	2329.34	1.05895	1.75772	26.245	0.132137	0.003125
1860.0	2.95477+0	2.18181+1	0.87500	44.173	718.55	1611.60	2330.15	1.06031	1.75506	26.275	0.133045	0.003271
1870.0	3.07501+0	2.10304+1	0.87396	44.089	721.72	1609.25	2330.96	1.06168	1.75243	26.307	0.133946	0.003423
1880.0	3.19902+0	2.02777+1	0.87292	44.005	724.89	1606.89	2331.77	1.06303	1.74982	26.338	0.134841	0.003579
1890.0	3.32687+0	1.95583+1	0.87187	43.921	728.06	1604.51	2332.58	1.06439	1.74725	26.370	0.135730	0.003742
1900.0	3.45864+0	1.88704+1	0.87082	43.837	731.24	1602.14	2333.38	1.06574	1.74469	26.402	0.136613	0.003909
1910.0	3.59441+0	1.82124+1	0.86976	43.754	734.43	1599.75	2334.18	1.06708	1.74217	26.434	0.137490	0.004083
1920.0	3.73427+0	1.75828+1	0.86870	43.670	737.62	1597.35	2334.97	1.06843	1.73967	26.466	0.138360	0.004262

APPENDIX B (Contd.)

Temp (°F)	PSAT (atmos)	VSAT (ft^3/lb)	Z	DL (lb/ft^3)	HLS (Btu/lb)	DHV (Btu/lb)	HGS (Btu/lb)	SLS (Btu/lb°F)	SGS (Btu/lb°F)	ABAR	X_2 (mole fr.)	X_4 (mole fr.)
1930.0	3.87828+0	1.69801+1	0.86763	43.586	740.82	1594.95	2335.77	1.06977	1.73719	26.499	0.139223	0.004447
1940.0	4.02654+0	1.64030+1	0.86655	43.502	744.02	1592.54	2336.55	1.07110	1.73474	26.532	0.140081	0.004638
1950.0	4.17912+0	1.58501+1	0.86547	43.418	747.22	1590.11	2337.34	1.07244	1.73232	26.565	0.140931	0.004836
1960.0	4.33610+0	1.53204+1	0.86438	43.334	750.44	1587.68	2338.12	1.07377	1.72991	26.598	0.141775	0.005039
1970.0	4.49756+0	1.48127+1	0.86329	43.251	753.65	1585.24	2338.90	1.07509	1.72754	26.632	0.142612	0.005249
1980.0	4.66359+0	1.43258+1	0.86219	43.167	756.88	1582.79	2339.67	1.07642	1.72518	26.666	0.143443	0.005466
1990.0	4.83427+0	1.38588+1	0.86108	43.083	760.11	1580.33	2340.44	1.07774	1.72285	26.700	0.144267	0.005689
2000.0	5.00968+0	1.34108+1	0.85996	42.999	763.34	1577.86	2341.20	1.07905	1.72054	26.735	0.145084	0.005919
2010.0	5.18990+0	1.29807+1	0.85884	42.915	766.58	1575.38	2341.96	1.08037	1.71825	26.770	0.145894	0.006156
2020.0	5.37502+0	1.25678+1	0.85771	42.832	769.83	1572.88	2342.71	1.08168	1.71598	26.805	0.146697	0.006399
2030.0	5.56513+0	1.21713+1	0.85657	42.748	773.08	1570.38	2343.46	1.08299	1.71374	26.841	0.147494	0.006650
2040.0	5.76029+0	1.17904+1	0.85543	42.664	776.34	1567.87	2344.20	1.08429	1.71151	26.877	0.148283	0.006908
2050.0	5.96061+0	1.14243+1	0.85427	42.581	779.60	1565.34	2344.94	1.08560	1.70931	26.913	0.149065	0.007173
2060.0	6.16616+0	1.10724+1	0.85311	42.497	782.87	1562.80	2345.67	1.08690	1.70713	26.950	0.149840	0.007446
2070.0	6.37702+0	1.07340+1	0.85194	42.413	786.15	1560.25	2346.40	1.08819	1.70497	26.987	0.150608	0.007726
2080.0	6.59329+0	1.04086+1	0.85077	42.330	789.43	1557.69	2347.12	1.08949	1.70282	27.024	0.151369	0.008014
2090.0	6.81505+0	1.00955+1	0.84958	42.246	792.72	1555.12	2347.84	1.09078	1.70070	27.062	0.152122	0.008309
2100.0	7.04237+0	9.79414+0	0.84839	42.163	796.01	1552.54	2348.55	1.09207	1.69860	27.100	0.152869	0.008612
2110.0	7.27536+0	9.50405+0	0.84719	42.079	799.31	1549.94	2349.25	1.09335	1.69651	27.138	0.153608	0.008923
2120.0	7.51408+0	9.22471+0	0.84598	41.995	802.62	1547.33	2349.95	1.09464	1.69445	27.177	0.154339	0.009242
2130.0	7.75863+0	8.95566+0	0.84476	41.912	805.93	1544.71	2350.64	1.09592	1.69240	27.216	0.155063	0.009569
2140.0	8.00910+0	8.69644+0	0.84353	41.828	809.26	1542.08	2351.33	1.09720	1.69037	27.256	0.155780	0.009905
2150.0	8.26556+0	8.44662+0	0.84229	41.745	812.58	1539.43	2352.01	1.09848	1.68836	27.296	0.156490	0.010248
2160.0	8.52811+0	8.20581+0	0.84105	41.661	815.92	1536.77	2352.69	1.09975	1.68637	27.336	0.157191	0.010600
2170.0	8.79682+0	7.97360+0	0.83979	41.578	819.26	1534.10	2353.35	1.10102	1.68440	27.377	0.157886	0.010961
2180.0	9.07179+0	7.74965+0	0.83853	41.494	822.61	1531.41	2354.02	1.10229	1.68244	27.418	0.158573	0.011329
2190.0	9.35310+0	7.53360+0	0.83726	41.411	825.96	1528.71	2354.67	1.10356	1.68050	27.460	0.159252	0.011707
2200.0	9.64083+0	7.32512+0	0.83598	41.328	829.32	1526.00	2355.32	1.10483	1.67857	27.502	0.159923	0.012093
2210.0	9.93508+0	7.12389+0	0.83469	41.244	832.69	1523.27	2355.96	1.10609	1.67667	27.544	0.160587	0.012488

APPENDIX B (Contd.)

Temp (°F)	PSAT (atmos)	VSAT (ft^3/lb)	Z	DL (lb/ft^3)	HLS (Btu/lb)	DHV (Btu/lb)	HGS (Btu/lb)	SLS (Btu/lb°F)	SGS (Btu/lb°F)	ABAR	X_2 (mole fr.)	X_4 (mole fr.)
2220.0	1.02359+1	6.92961+0	0.83339	41.161	836.07	1520.53	2356.60	1.10735	1.67478	27.587	0.161244	0.012892
2230.0	1.05434+1	6.74200+0	0.83208	41.078	839.45	1517.78	2357.23	1.10861	1.67290	27.631	0.161892	0.013304
2240.0	1.08577+1	6.56078+0	0.83076	40.994	842.84	1515.01	2357.85	1.10987	1.67105	27.675	0.162533	0.013726
2250.0	1.11789+1	6.38570+0	0.82944	40.911	846.24	1512.23	2358.47	1.11113	1.66920	27.719	0.163166	0.014157
2260.0	1.15069+1	6.21651+0	0.82810	40.828	849.65	1509.43	2359.08	1.11238	1.66738	27.763	0.163791	0.014596
2270.0	1.18420+1	6.05297+0	0.82676	40.745	853.06	1506.62	2359.68	1.11363	1.66557	27.809	0.164409	0.015045
2280.0	1.21842+1	5.89485+0	0.82540	40.661	856.48	1503.80	2360.28	1.11488	1.66377	27.854	0.165019	0.015503
2290.0	1.25336+1	5.74194+0	0.82404	40.578	859.91	1500.96	2360.87	1.11613	1.66199	27.900	0.165621	0.015971
2300.0	1.28903+1	5.59405+0	0.82267	40.495	863.34	1498.11	2361.45	1.11738	1.66023	27.947	0.166215	0.016447
2310.0	1.32543+1	5.45096+0	0.82129	40.412	866.79	1495.24	2362.03	1.11862	1.65848	27.994	0.166801	0.016933
2320.0	1.36257+1	5.31249+0	0.81990	40.329	870.24	1492.36	2362.60	1.11986	1.65674	28.041	0.167379	0.017428
2330.0	1.40047+1	5.17848+0	0.81850	40.246	873.70	1489.47	2363.16	1.12111	1.65502	28.089	0.167950	0.017933
2340.0	1.43913+1	5.04873+0	0.81709	40.163	877.16	1486.56	2363.72	1.12235	1.65332	28.138	0.168512	0.018447
2350.0	1.47856+1	4.92310+0	0.81567	40.080	880.64	1483.63	2364.27	1.12358	1.65162	28.186	0.169067	0.018971
2360.0	1.51877+1	4.80143+0	0.81425	39.997	884.12	1480.70	2364.82	1.12482	1.64995	28.236	0.169614	0.019504
2370.0	1.55976+1	4.68356+0	0.81281	39.914	887.61	1477.74	2365.36	1.12606	1.64828	28.286	0.170153	0.020047
2380.0	1.60154+1	4.56936+0	0.81137	39.831	891.11	1474.78	2365.89	1.12729	1.64663	28.336	0.170684	0.020599
2390.0	1.64413+1	4.45869+0	0.80992	39.748	894.62	1471.80	2366.42	1.12852	1.64500	28.387	0.171207	0.021161
2400.0	1.68752+1	4.35142+0	0.80846	39.665	898.14	1468.80	2366.94	1.12976	1.64338	28.438	0.171722	0.021732
2410.0	1.73174+1	4.24742+0	0.80699	39.582	901.66	1465.79	2367.46	1.13099	1.64177	28.490	0.172229	0.022313
2420.0	1.77678+1	4.14658+0	0.80552	39.499	905.20	1462.77	2367.97	1.13221	1.64017	28.542	0.172728	0.022904
2430.0	1.82265+1	4.04877+0	0.80403	39.417	908.74	1459.73	2368.48	1.13344	1.63859	28.595	0.173220	0.023504
2440.0	1.86937+1	3.95390+0	0.80254	39.334	912.29	1456.68	2368.97	1.13467	1.63702	28.648	0.173703	0.024114
2450.0	1.91693+1	3.86185+0	0.80104	39.251	915.85	1453.62	2369.47	1.13589	1.63547	28.701	0.174179	0.024733
2460.0	1.96536+1	3.77253+0	0.79953	39.168	919.42	1450.54	2369.96	1.13712	1.63393	28.756	0.174646	0.025363
2470.0	2.01465+1	3.68584+0	0.79801	39.086	923.00	1447.45	2370.44	1.13834	1.63240	28.810	0.175106	0.026001
2480.0	2.06481+1	3.60168+0	0.79649	39.003	926.58	1444.34	2370.92	1.13956	1.63088	28.865	0.175558	0.026649
2490.0	2.11586+1	3.51997+0	0.79496	38.921	930.18	1441.22	2371.40	1.14078	1.62938	28.921	0.176002	0.027307
2500.0	2.16779+1	3.44062+0	0.79342	38.838	933.78	1438.08	2371.86	1.14200	1.62789	28.977	0.176438	0.027975
2510.0	2.22062+1	3.36355+0	0.79188	38.755	937.40	1434.93	2372.33	1.14322	1.62641	29.034	0.176867	0.028651

APPENDIX C. Transport and Related Properties of Sodium

Temp (°F)	VISC-LIQ (lb$_m$/ft-hr)	VISC-VAP (lb$_m$/ft-hr)	K-LIQ (Btu/hr-ft-°F)	K-VAP (Btu/hr-ft-°F)	CP-LIQ (Btu/lb$_m$-°F)	PR-LIQ	ALPHA-LIQ (ft^2/hr)	SURF-TEN (lb$_f$/ft)	RHO-E (μΩ-cm)
210.0	1.6657	.03598	50.45	.006285	.3305	.010914	2.636	.013489	9.67
220.0	1.6207	.03606	50.27	.006641	.3299	.010636	2.636	.013451	9.88
230.0	1.5780	.03615	50.09	.006995	.3293	.010372	2.635	.013413	10.08
240.0	1.5374	.03623	49.91	.007347	.3286	.010122	2.634	.013375	10.29
250.0	1.4989	.03631	49.74	.007697	.3280	.009885	2.634	.013337	10.49
260.0	1.4622	.03639	49.56	.008045	.3274	.009659	2.633	.013299	10.70
270.0	1.4272	.03647	49.38	.008391	.3268	.009444	2.632	.013261	10.91
280.0	1.3938	.03655	49.21	.008736	.3262	.009239	2.631	.013223	11.12
290.0	1.3620	.03664	49.03	.009078	.3256	.009044	2.631	.013185	11.32
300.0	1.3316	.03672	48.86	.009419	.3250	.008858	2.630	.013147	11.53
310.0	1.3025	.03680	48.68	.009757	.3244	.008680	2.629	.013108	11.75
320.0	1.2747	.03688	48.51	.010094	.3238	.008510	2.628	.013070	11.96
330.0	1.2480	.03696	48.33	.010429	.3232	.008347	2.627	.013032	12.17
340.0	1.2225	.03704	48.16	.010761	.3227	.008191	2.625	.012994	12.38
350.0	1.1980	.03713	47.98	.011092	.3221	.008042	2.624	.012956	12.60
360.0	1.1745	.03721	47.81	.011421	.3216	.007899	2.623	.012918	12.81
370.0	1.1519	.03729	47.64	.011748	.3210	.007762	2.622	.012880	13.03
380.0	1.1302	.03737	47.47	.012073	.3205	.007631	2.620	.012842	13.24
390.0	1.1093	.03745	47.29	.012396	.3200	.007505	2.619	.012804	13.46
400.0	1.0892	.03754	47.12	.012717	.3194	.007383	2.618	.012766	13.68
410.0	1.0698	.03762	46.95	.013036	.3189	.007267	2.616	.012727	13.90
420.0	1.0512	.03770	46.78	.013353	.3184	.007155	2.615	.012689	14.12
430.0	1.0332	.03778	46.61	.013669	.3179	.007047	2.613	.012651	14.34
440.0	1.0159	.03786	46.44	.013982	.3174	.006943	2.611	.012613	14.57
450.0	.9991	.03794	46.27	.014293	.3169	.006843	2.610	.012575	14.79
460.0	.9829	.03803	46.10	.014603	.3164	.006747	2.608	.012537	15.01
470.0	.9673	.03811	45.94	.014910	.3160	.006654	2.606	.012499	15.24
480.0	.9522	.03819	45.77	.015216	.3155	.006564	2.604	.012461	15.47
490.0	.9376	.03827	45.60	.015520	.3150	.006478	2.602	.012423	15.70
500.0	.9235	.03835	45.43	.015821	.3146	.006394	2.600	.012385	15.93
510.0	.9098	.03843	45.27	.016121	.3141	.006314	2.598	.012346	16.16
520.0	.8965	.03852	45.10	.016419	.3137	.006236	2.596	.012308	16.39
530.0	.8837	.03860	44.94	.016715	.3133	.006161	2.594	.012270	16.62
540.0	.8712	.03868	44.77	.017009	.3128	.006088	2.592	.012232	16.85
550.0	.8591	.03876	44.60	.017301	.3124	.006018	2.590	.012194	17.09
560.0	.8474	.03884	44.44	.017591	.3120	.005950	2.588	.012156	17.33
570.0	.8360	.03893	44.28	.017879	.3116	.005884	2.585	.012118	17.56
580.0	.8250	.03901	44.11	.018165	.3112	.005820	2.583	.012080	17.80
590.0	.8143	.03909	43.95	.018449	.3108	.005758	2.580	.012042	18.04
600.0	.8038	.03917	43.79	.018732	.3104	.005699	2.578	.012004	18.29
610.0	.7937	.03925	43.62	.019012	.3100	.005641	2.575	.011965	18.53
620.0	.7838	.03933	43.46	.019290	.3097	.005585	2.573	.011927	18.77
630.0	.7742	.03942	43.30	.019567	.3093	.005531	2.570	.011889	19.02

APPENDIX C (Contd.)

Temp (°F)	VISC-LIQ (lb_m/ft-hr)	VISC-VAP (lb_m/ft-hr)	K-LIQ (Btu/hr-ft-°F)	K-VAP (Btu/hr-ft-°F)	CP-LIQ (Btu/lb_m-°F)	PR-LIQ	ALPHA-LIQ (ft^2/hr)	SURF-TEN (lb_f/ft)	RHO-E (μΩ-cm)
640.0	.7649	.03950	43.14	.019841	.3089	.005478	2.567	.011851	19.27
650.0	.7558	.03958	42.98	.020114	.3086	.005427	2.565	.011813	19.51
660.0	.7470	.03966	42.82	.020385	.3082	.005377	2.562	.011775	19.76
670.0	.7383	.03974	42.66	.020653	.3079	.005329	2.559	.011737	20.02
680.0	.7299	.03982	42.50	.020920	.3076	.005283	2.556	.011699	20.27
690.0	.7218	.03991	42.34	.021185	.3072	.005238	2.553	.011661	20.52
700.0	.7138	.03999	42.18	.021448	.3069	.005194	2.550	.011623	20.78
710.0	.7060	.04007	42.02	.021709	.3066	.005151	2.547	.011584	21.04
720.0	.6984	.04015	41.86	.021968	.3063	.005110	2.544	.011546	21.29
730.0	.6910	.04023	41.71	.022225	.3060	.005070	2.541	.011508	21.55
740.0	.6837	.04032	41.55	.022480	.3057	.005031	2.537	.011470	21.82
750.0	.6767	.04040	41.39	.022733	.3054	.004993	2.534	.011432	22.08
760.0	.6698	.04048	41.24	.022985	.3052	.004956	2.531	.011394	22.34
770.0	.6630	.04056	41.08	.023234	.3049	.004921	2.527	.011356	22.61
780.0	.6564	.04064	40.93	.023481	.3046	.004886	2.524	.011318	22.88
790.0	.6500	.04072	40.77	.023727	.3044	.004853	2.520	.011280	23.15
800.0	.6437	.04081	40.62	.023970	.3041	.004820	2.517	.011242	23.42
810.0	.6375	.04089	40.46	.024212	.3039	.004788	2.513	.011203	23.69
820.0	.6315	.04097	40.31	.024452	.3036	.004757	2.509	.011165	23.97
830.0	.6256	.04105	40.15	.024689	.3034	.004727	2.506	.011127	24.24
840.0	.6198	.04113	40.00	.024925	.3032	.004698	2.502	.011089	24.52
850.0	.6142	.04121	39.85	.025159	.3030	.004670	2.498	.011051	24.80
860.0	.6087	.04130	39.70	.025391	.3028	.004642	2.494	.011013	25.08
870.0	.6033	.04138	39.55	.025621	.3026	.004616	2.490	.010975	25.37
880.0	.5980	.04146	39.39	.025849	.3024	.004590	2.486	.010937	25.65
890.0	.5928	.04154	39.24	.026075	.3022	.004564	2.482	.010899	25.94
900.0	.5877	.04162	39.09	.026299	.3020	.004540	2.478	.010861	26.23
910.0	.5827	.04171	38.94	.026521	.3018	.004516	2.474	.010822	26.52
920.0	.5778	.04179	38.79	.026741	.3017	.004493	2.470	.010784	26.81
930.0	.5730	.04187	38.64	.026960	.3015	.004471	2.466	.010746	27.11
940.0	.5683	.04195	38.50	.027176	.3013	.004449	2.461	.010708	27.40
950.0	.5637	.04203	38.35	.027390	.3012	.004428	2.457	.010670	27.70
960.0	.5592	.04211	38.20	.027603	.3011	.004407	2.453	.010632	28.00
970.0	.5548	.04220	38.05	.027813	.3009	.004387	2.448	.010594	28.30
980.0	.5504	.04228	37.91	.028022	.3008	.004368	2.444	.010556	28.61
990.0	.5461	.04236	37.76	.028229	.3007	.004349	2.439	.010518	28.91
1000.0	.5419	.04244	37.61	.028434	.3006	.004331	2.435	.010480	29.22
1010.0	.5378	.04252	37.47	.028636	.3004	.004313	2.430	.010441	29.53
1020.0	.5338	.04260	37.32	.028837	.3003	.004296	2.425	.010403	29.84
1030.0	.5298	.04269	37.18	.029036	.3003	.004279	2.421	.010365	30.16
1040.0	.5259	.04277	37.03	.029233	.3002	.004263	2.416	.010327	30.48
1050.0	.5221	.04285	36.89	.029428	.3001	.004247	2.411	.010289	30.79

APPENDIX C (Contd.)

Temp (°F)	VISC-LIQ ($\mathrm{lb_m}$/ft-hr)	VISC-VAP ($\mathrm{lb_m}$/ft-hr)	K-LIQ (Btu/hr-ft-°F)	K-VAP (Btu/hr-ft-°F)	CP-LIQ (Btu/$\mathrm{lb_m}$-°F)	PR-LIQ	ALPHA-LIQ ($\mathrm{ft^2}$/hr)	SURF-TEN ($\mathrm{lb_f}$/ft)	RHO-E (μΩ-cm)
1060.0	.5183	.04293	36.74	.029621	.3000	.004232	2.406	.010251	31.11
1070.0	.5146	.04301	36.60	.029812	.3000	.004217	2.401	.010213	31.44
1080.0	.5110	.04310	36.46	.030002	.2999	.004203	2.396	.010175	31.76
1090.0	.5074	.04318	36.32	.030189	.2998	.004189	2.391	.010137	32.09
1100.0	.5039	.04326	36.17	.030374	.2998	.004176	2.386	.010099	32.42
1110.0	.5004	.04334	36.03	.030558	.2998	.004163	2.381	.010060	32.75
1120.0	.4970	.04342	35.89	.030739	.2997	.004151	2.376	.010022	33.08
1130.0	.4937	.04350	35.75	.030919	.2997	.004139	2.371	.009984	33.42
1140.0	.4904	.04359	35.61	.031096	.2997	.004127	2.366	.009946	33.75
1150.0	.4872	.04367	35.47	.031272	.2997	.004116	2.360	.009908	34.09
1160.0	.4840	.04375	35.33	.031445	.2997	.004105	2.355	.009870	34.44
1170.0	.4808	.04383	35.19	.031617	.2997	.004095	2.350	.009832	34.78
1180.0	.4778	.04391	35.05	.031787	.2997	.004085	2.344	.009794	35.13
1190.0	.4747	.04399	34.91	.031955	.2997	.004075	2.339	.009756	35.48
1200.0	.4717	.04408	34.78	.032121	.2997	.004066	2.333	.009718	35.83
1210.0	.4688	.04416	34.64	.032285	.2998	.004057	2.328	.009679	36.18
1220.0	.4659	.04424	34.50	.032447	.2998	.004048	2.322	.009641	36.54
1230.0	.4630	.04432	34.37	.032607	.2998	.004040	2.317	.009603	36.90
1240.0	.4602	.04440	34.23	.032765	.2999	.004032	2.311	.009565	37.26
1250.0	.4574	.04449	34.09	.032921	.2999	.004024	2.305	.009527	37.62
1260.0	.4547	.04457	33.96	.033076	.3000	.004017	2.300	.009489	37.99
1270.0	.4520	.04465	33.82	.033228	.3001	.004010	2.294	.009451	38.36
1280.0	.4494	.04473	33.69	.033379	.3002	.004004	2.288	.009413	38.73
1290.0	.4468	.04481	33.56	.033527	.3002	.003998	2.282	.009375	39.10
1300.0	.4442	.04489	33.42	.033674	.3003	.003992	2.276	.009337	39.48
1310.0	.4417	.04498	33.29	.033818	.3004	.003986	2.270	.009298	39.86
1320.0	.4392	.04506	33.16	.033961	.3005	.003981	2.264	.009260	40.24
1330.0	.4367	.04514	33.02	.034102	.3006	.003976	2.258	.009222	40.62
1340.0	.4343	.04522	32.89	.034240	.3008	.003971	2.252	.009184	41.01
1350.0	.4319	.04530	32.76	.034377	.3009	.003967	2.246	.009146	41.40
1360.0	.4295	.04538	32.63	.034512	.3010	.003962	2.240	.009108	41.79
1370.0	.4272	.04547	32.50	.034645	.3012	.003959	2.234	.009070	42.18
1380.0	.4249	.04555	32.37	.034776	.3013	.003955	2.228	.009032	42.58
1390.0	.4226	.04563	32.24	.034905	.3015	.003952	2.222	.008994	42.98
1400.0	.4204	.04571	32.11	.035032	.3016	.003949	2.215	.008956	43.38
1410.0	.4181	.04579	31.98	.035158	.3018	.003946	2.209	.008917	43.78
1420.0	.4160	.04587	31.85	.035281	.3020	.003944	2.203	.008879	44.19
1430.0	.4138	.04596	31.72	.035402	.3021	.003941	2.197	.008841	44.60
1440.0	.4117	.04604	31.59	.035522	.3023	.003939	2.190	.008803	45.01
1450.0	.4096	.04612	31.47	.035639	.3025	.003938	2.184	.008765	45.43
1460.0	.4075	.04620	31.34	.035755	.3027	.003936	2.177	.008727	45.85
1470.0	.4055	.04628	31.21	.035868	.3029	.003935	2.171	.008689	46.27
1480.0	.4035	.04637	31.09	.035980	.3031	.003934	2.165	.008651	46.69

APPENDIX C (Contd.)

Temp (°F)	VISC-LIQ (lb_m/ft-hr)	VISC-VAP (lb_m/ft-hr)	K-LIQ (Btu/hr-ft-°F)	K-VAP (Btu/hr-ft-°F)	CP-LIQ (Btu/lb_m-°F)	PR-LIQ	ALPHA-LIQ (ft^2/hr)	SURF-TEN (lb_f/ft)	RHO-E (μΩ-cm)
1490.0	.4015	.04645	30.96	.036089	.3034	.003933	2.158	.008613	47.12
1500.0	.3995	.04653	30.84	.036197	.3036	.003933	2.152	.008575	47.55
1510.0	.3976	.04661	30.71	.036303	.3038	.003933	2.145	.008536	47.98
1520.0	.3956	.04669	30.59	.036407	.3041	.003933	2.138	.008498	48.42
1530.0	.3937	.04677	30.46	.036509	.3043	.003933	2.132	.008460	48.86
1540.0	.3919	.04686	30.34	.036609	.3046	.003934	2.125	.008422	49.30
1550.0	.3900	.04694	30.22	.036707	.3048	.003935	2.119	.008384	49.74
1560.0	.3882	.04702	30.09	.036803	.3051	.003935	2.112	.008346	50.19
1570.0	.3864	.04710	29.97	.036897	.3054	.003937	2.105	.008308	50.64
1580.0	.3846	.04718	29.85	.036990	.3057	.003938	2.099	.008270	51.09
1590.0	.3828	.04726	29.73	.037080	.3059	.003940	2.092	.008232	51.55
1600.0	.3811	.04735	29.61	.037168	.3062	.003942	2.085	.008194	52.01
1610.0	.3794	.04743	29.49	.037255	.3065	.003944	2.078	.008155	52.47
1618.6	.3779	.04750	29.38	.037327	.3068	.003946	2.072	.008123	52.87
1620.0	.3777	.04751	29.37	.037339	.3069	.003946	2.071	.008117	52.94
1630.0	.3760	.04759	29.25	.037422	.3072	.003949	2.065	.008079	53.40
1640.0	.3743	.04767	29.13	.037502	.3075	.003952	2.058	.008041	53.88
1650.0	.3727	.04776	29.01	.037581	.3078	.003955	2.051	.008003	54.35
1660.0	.3710	.04784	28.89	.037658	.3082	.003958	2.044	.007965	54.83
1670.0	.3694	.04792	28.77	.037732	.3085	.003961	2.037	.007927	55.31
1680.0	.3678	.04800	28.65	.037805	.3089	.003965	2.030	.007889	55.79
1690.0	.3663	.04808	28.54	.037876	.3092	.003969	2.023	.007851	56.28
1700.0	.3647	.04816	28.42	.037945	.3096	.003973	2.016	.007813	56.77
1710.0	.3632	.04825	28.30	.038012	.3099	.003977	2.009	.007774	57.26
1720.0	.3617	.04833	28.19	.038077	.3103	.003982	2.002	.007736	57.76
1730.0	.3601	.04841	28.07	.038140	.3107	.003986	1.995	.007698	58.26
1740.0	.3587	.04849	27.96	.038202	.3111	.003991	1.988	.007660	58.76
1750.0	.3572	.04857	27.84	.038261	.3115	.003996	1.981	.007622	59.27
1760.0	.3557	.04865	27.73	.038318	.3119	.004002	1.974	.007584	59.78
1770.0	.3543	.04874	27.61	.038374	.3123	.004007	1.967	.007546	60.29
1780.0	.3529	.04882	27.50	.038427	.3127	.004013	1.960	.007508	60.81
1790.0	.3514	.04890	27.39	.038479	.3132	.004019	1.953	.007470	61.33
1800.0	.3501	.04898	27.27	.038528	.3136	.004025	1.946	.007432	61.85
1810.0	.3487	.04906	27.16	.038576	.3140	.004031	1.939	.007393	62.38
1820.0	.3473	.04915	27.05	.038622	.3145	.004038	1.932	.007355	62.91
1830.0	.3459	.04923	26.94	.038665	.3149	.004044	1.925	.007317	63.44
1840.0	.3446	.04931	26.83	.038707	.3154	.004051	1.918	.007279	63.98
1850.0	.3433	.04939	26.72	.038747	.3159	.004059	1.911	.007241	64.52
1860.0	.3420	.04947	26.61	.038785	.3163	.004066	1.904	.007203	65.06
1870.0	.3407	.04955	26.50	.038821	.3168	.004073	1.896	.007165	65.61
1880.0	.3394	.04964	26.39	.038855	.3173	.004081	1.889	.007127	66.16
1890.0	.3381	.04972	26.28	.038887	.3178	.004089	1.882	.007089	66.72

APPENDIX C (Contd.)

Temp (°F)	VISC-LIQ ($\mathrm{lb_m}$/ft-hr)	VISC-VAP ($\mathrm{lb_m}$/ft-hr)	K-LIQ (Btu/hr-ft-°F)	K-VAP (Btu/hr-ft-°F)	CP-LIQ (Btu/$\mathrm{lb_m}$-°F)	PR-LIQ	ALPHA-LIQ (ft^2/hr)	SURF-TEN ($\mathrm{lb_f}$/ft)	RHO-E (μΩ-cm)
1900.0	.3368	.04980	26.17	.038917	.3183	.004097	1.875	.007051	67.28
1910.0	.3356	.04988	26.06	.038946	.3188	.004105	1.868	.007012	67.84
1920.0	.3343	.04996	25.95	.038972	.3193	.004114	1.861	.006974	68.40
1930.0	.3331	.05004	25.85	.038996	.3198	.004122	1.854	.006936	68.97
1940.0	.3319	.05013	25.74	.039019	.3204	.004131	1.846	.006898	69.54
1950.0	.3307	.05021	25.63	.039039	.3209	.004140	1.839	.006860	70.12
1960.0	.3295	.05029	25.53	.039058	.3214	.004149	1.832	.006822	70.70
1970.0	.3283	.05037	25.42	.039074	.3220	.004159	1.825	.006784	71.28
1980.0	.3272	.05045	25.32	.039089	.3225	.004168	1.818	.006746	71.87
1990.0	.3260	.05054	25.21	.039102	.3231	.004178	1.811	.006708	72.46
2000.0	.3249	.05062	25.11	.039113	.3237	.004188	1.803	.006670	73.05
2010.0	.3237	.05070	25.00	.039121	.3243	.004198	1.796	.006631	73.65
2020.0	.3226	.05078	24.90	.039128	.3248	.004209	1.789	.006593	74.25
2030.0	.3215	.05086	24.80	.039133	.3254	.004219	1.782	.006555	74.86
2040.0	.3204	.05094	24.69	.039136	.3260	.004230	1.775	.006517	75.47
2050.0	.3193	.05103	24.59	.039137	.3266	.004241	1.768	.006479	76.08
2060.0	.3182	.05111	24.49	.039137	.3272	.004252	1.761	.006441	76.70
2070.0	.3171	.05119	24.39	.039134	.3279	.004263	1.753	.006403	77.32
2080.0	.3161	.05127	24.29	.039129	.3285	.004275	1.746	.006365	77.94
2090.0	.3150	.05135	24.19	.039122	.3291	.004286	1.739	.006327	78.57
2100.0	.3139	.05143	24.09	.039114	.3297	.004298	1.732	.006289	79.20
2110.0	.3129	.05152	23.99	.039103	.3304	.004310	1.725	.006250	79.84
2120.0	.3119	.05160	23.89	.039091	.3310	.004322	1.718	.006212	80.48
2130.0	.3109	.05168	23.79	.039076	.3317	.004335	1.711	.006174	81.12
2140.0	.3099	.05176	23.69	.039060	.3324	.004347	1.704	.006136	81.77
2150.0	.3089	.05184	23.59	.039042	.3330	.004360	1.697	.006098	82.42
2160.0	.3079	.05193	23.49	.039021	.3337	.004373	1.689	.006060	83.08
2170.0	.3069	.05201	23.40	.038999	.3344	.004386	1.682	.006022	83.74
2180.0	.3059	.05209	23.30	.038975	.3351	.004399	1.675	.005984	84.40
2190.0	.3049	.05217	23.20	.038949	.3358	.004413	1.668	.005946	85.07
2200.0	.3040	.05225	23.11	.038921	.3365	.004426	1.661	.005908	85.74
2210.0	.3030	.05233	23.01	.038891	.3372	.004440	1.654	.005869	86.42
2220.0	.3021	.05242	22.92	.038859	.3379	.004454	1.647	.005831	87.10
2230.0	.3011	.05250	22.82	.038825	.3386	.004468	1.640	.005793	87.78
2240.0	.3002	.05258	22.73	.038790	.3394	.004483	1.633	.005755	88.47
2250.0	.2993	.05266	22.63	.038752	.3401	.004497	1.626	.005717	89.17
2260.0	.2984	.05274	22.54	.038712	.3409	.004512	1.619	.005679	89.86
2270.0	.2975	.05282	22.45	.038671	.3416	.004527	1.612	.005641	90.56
2280.0	.2966	.05291	22.35	.038627	.3424	.004542	1.605	.005603	91.27
2290.0	.2957	.05299	22.26	.038582	.3431	.004557	1.598	.005565	91.98
2300.0	.2948	.05307	22.17	.038534	.3439	.004573	1.592	.005527	92.69
2310.0	.2939	.05315	22.08	.038485	.3447	.004589	1.585	.005488	93.41

APPENDIX C (Contd.)

Temp (°F)	VISC-LIQ (lb_m/ft-hr)	VISC-VAP (lb_m/ft-hr)	K-LIQ (Btu/hr-ft-°F)	K-VAP (Btu/hr-ft-°F)	CP-LIQ (Btu/lb_m-°F)	PR-LIQ	ALPHA-LIQ (ft^2/hr)	SURF-TEN (lb_f/ft)	RHO-E (μΩ-cm)
2320.0	.2930	.05323	21.99	.038434	.3455	.004604	1.578	.005450	94.13
2330.0	.2922	.05332	21.90	.038381	.3463	.004620	1.571	.005412	94.86
2340.0	.2913	.05340	21.81	.038325	.3471	.004637	1.564	.005374	95.59
2350.0	.2905	.05348	21.72	.038268	.3479	.004653	1.557	.005336	96.32
2360.0	.2896	.05356	21.63	.038209	.3487	.004670	1.550	.005298	97.06
2370.0	.2888	.05364	21.54	.038148	.3495	.004686	1.544	.005260	97.81
2380.0	.2880	.05372	21.45	.038085	.3504	.004703	1.537	.005222	98.55
2390.0	.2871	.05381	21.36	.038021	.3512	.004720	1.530	.005184	99.31
2400.0	.2863	.05389	21.28	.037954	.3520	.004738	1.523	.005146	100.06
2410.0	.2855	.05397	21.19	.037885	.3529	.004755	1.517	.005107	100.82
2420.0	.2847	.05405	21.10	.037814	.3537	.004773	1.510	.005069	101.59
2430.0	.2839	.05413	21.02	.037742	.3546	.004791	1.503	.005031	102.36
2440.0	.2831	.05421	20.93	.037667	.3555	.004809	1.497	.004993	103.13
2450.0	.2823	.05430	20.84	.037591	.3563	.004827	1.490	.004955	103.91
2460.0	.2816	.05438	20.76	.037512	.3572	.004845	1.483	.004917	104.70
2470.0	.2808	.05446	20.67	.037432	.3581	.004864	1.477	.004879	105.49
2480.0	.2800	.05454	20.59	.037350	.3590	.004882	1.470	.004841	106.28
2490.0	.2793	.05462	20.51	.037265	.3599	.004901	1.463	.004803	107.08
2500.0	.2785	.05471	20.42	.037179	.3608	.004920	1.457	.004765	107.88

APPENDIX D. Provisional Specific Heat, Prandtl Number, and Thermal Diffusivity of the Vapor

Temp (°F)	CP-VAP (Btu/lb$_m$-°F)	PR-VAP	ALPHA-VAP (ft^2/hr)	Temp (°F)	CP-VAP (Btu/lb$_m$-°F)	PR-VAP	ALPHA-VAP (ft^2/hr)
500.0	.349	.846	.387E 06	930.0	.578	.898	.397E 03
510.0	.354	.846	.307E 06	940.0	.581	.898	.357E 03
520.0	.360	.846	.245E 06	950.0	.585	.898	.321E 03
530.0	.366	.846	.196E 06	960.0	.588	.898	.289E 03
540.0	.372	.847	.158E 06	970.0	.591	.898	.261E 03
550.0	.378	.847	.128E 06	980.0	.595	.897	.236E 03
560.0	.384	.848	.104E 06	990.0	.598	.897	.214E 03
570.0	.390	.849	.847E 05	1000.0	.600	.897	.194E 03
580.0	.396	.851	.693E 05	1010.0	.603	.896	.176E 03
590.0	.402	.852	.569E 05	1020.0	.606	.895	.160E 03
600.0	.408	.853	.469E 05	1030.0	.608	.895	.146E 03
610.0	.414	.855	.388E 05	1040.0	.611	.894	.133E 03
620.0	.420	.857	.322E 05	1050.0	.613	.893	.122E 03
630.0	.426	.859	.268E 05	1060.0	.615	.892	.111E 03
640.0	.432	.860	.224E 05	1070.0	.618	.891	.102E 03
650.0	.438	.862	.188E 05	1080.0	.619	.890	.940E 02
660.0	.444	.864	.158E 05	1090.0	.621	.889	.864E 02
670.0	.450	.866	.133E 05	1100.0	.623	.888	.794E 02
680.0	.456	.868	.112E 05	1110.0	.625	.886	.731E 02
690.0	.461	.870	.959E 04	1120.0	.626	.885	.674E 02
700.0	.467	.872	.816E 04	1130.0	.628	.884	.622E 02
710.0	.473	.874	.697E 04	1140.0	.629	.882	.575E 02
720.0	.479	.876	.597E 04	1150.0	.631	.881	.532E 02
730.0	.484	.877	.512E 04	1160.0	.632	.879	.493E 02
740.0	.490	.879	.441E 04	1170.0	.633	.878	.457E 02
750.0	.495	.881	.381E 04	1180.0	.634	.876	.424E 02
760.0	.501	.882	.329E 04	1190.0	.635	.874	.394E 02
770.0	.506	.884	.286E 04	1200.0	.636	.873	.366E 02
780.0	.511	.885	.248E 04	1210.0	.637	.871	.341E 02
790.0	.516	.887	.216E 04	1220.0	.637	.869	.318E 02
800.0	.522	.888	.189E 04	1230.0	.638	.867	.297E 02
810.0	.526	.889	.165E 04	1240.0	.638	.865	.277E 02
820.0	.531	.891	.145E 04	1250.0	.639	.863	.259E 02
830.0	.536	.892	.128E 04	1260.0	.639	.862	.242E 02
840.0	.541	.893	.112E 04	1270.0	.640	.860	.227E 02
850.0	.545	.894	.998E 03	1280.0	.640	.858	.212E 02
860.0	.550	.895	.883E 03	1290.0	.640	.856	.199E 02
870.0	.554	.895	.783E 03	1300.0	.640	.854	.187E 02
880.0	.558	.896	.696E 03	1310.0	.640	.852	.175E 02
890.0	.563	.897	.620E 03	1320.0	.640	.849	.165E 02
900.0	.566	.897	.553E 03	1330.0	.640	.847	.155E 02
910.0	.570	.897	.494E 03	1340.0	.640	.845	.146E 02
920.0	.574	.898	.442E 03	1350.0	.640	.843	.138E 02

APPENDIX D (Contd.)

Temp (°F)	CP-VAP (Btu/lb$_m$-°F)	PR-VAP	ALPHA-VAP (ft^2/hr)	Temp (°F)	CP-VAP (Btu/lb$_m$-°F)	PR-VAP	ALPHA-VAP (ft^2/hr)
1360.0	.640	.841	.130E 02	1780.0	.605	.769	.188E 01
1370.0	.639	.839	.122E 02	1790.0	.604	.768	.181E 01
1380.0	.639	.837	.116E 02	1800.0	.603	.767	.174E 01
1390.0	.639	.835	.109E 02	1810.0	.602	.766	.168E 01
1400.0	.638	.833	.103E 02	1820.0	.601	.766	.162E 01
1410.0	.638	.831	.981E 01	1830.0	.600	.765	.157E 01
1420.0	.637	.829	.929E 01	1840.0	.600	.764	.151E 01
1430.0	.637	.827	.880E 01	1850.0	.599	.763	.146E 01
1440.0	.636	.825	.835E 01	1860.0	.598	.763	.141E 01
1450.0	.636	.823	.792E 01	1870.0	.597	.762	.136E 01
1460.0	.635	.821	.752E 01	1880.0	.596	.762	.132E 01
1470.0	.634	.819	.714E 01	1890.0	.595	.761	.127E 01
1480.0	.634	.817	.679E 01	1900.0	.595	.761	.123E 01
1490.0	.633	.815	.645E 01	1910.0	.594	.761	.119E 01
1500.0	.632	.813	.614E 01	1920.0	.593	.760	.115E 01
1510.0	.631	.811	.585E 01	1930.0	.592	.760	.111E 01
1520.0	.631	.809	.557E 01	1940.0	.591	.760	.108E 01
1530.0	.630	.807	.531E 01	1950.0	.591	.760	.104E 01
1540.0	.629	.805	.506E 01	1960.0	.590	.760	.101E 01
1550.0	.628	.804	.483E 01	1970.0	.589	.760	.981E 00
1560.0	.627	.802	.461E 01	1980.0	.588	.760	.950E 00
1570.0	.627	.800	.440E 01	1990.0	.588	.760	.921E 00
1580.0	.626	.798	.420E 01	2000.0	.587	.760	.892E 00
1590.0	.625	.797	.402E 01	2010.0	.586	.760	.865E 00
1600.0	.624	.795	.384E 01	2020.0	.586	.760	.838E 00
1610.0	.623	.793	.369E 01	2030.0	.585	.761	.813E 00
1618.6	.622	.791	.355E 01	2040.0	.584	.761	.788E 00
1620.0	.622	.791	.353E 01	2050.0	.584	.761	.765E 00
1630.0	.621	.789	.339E 01	2060.0	.583	.762	.742E 00
1640.0	.619	.788	.325E 01	2070.0	.583	.762	.720E 00
1650.0	.618	.786	.312E 01	2080.0	.582	.763	.699E 00
1660.0	.617	.784	.299E 01	2090.0	.581	.763	.678E 00
1670.0	.616	.783	.287E 01	2100.0	.581	.764	.658E 00
1680.0	.615	.781	.276E 01	2110.0	.580	.765	.639E 00
1690.0	.614	.780	.265E 01	2120.0	.580	.765	.621E 00
1700.0	.613	.779	.255E 01	2130.0	.579	.766	.603E 00
1710.0	.612	.777	.245E 01	2140.0	.579	.767	.586E 00
1720.0	.611	.776	.235E 01	2150.0	.578	.768	.569E 00
1730.0	.610	.775	.226E 01	2160.0	.578	.769	.553E 00
1740.0	.609	.773	.218E 01	2170.0	.577	.770	.538E 00
1750.0	.608	.772	.210E 01	2180.0	.577	.771	.523E 00
1760.0	.607	.771	.202E 01	2190.0	.576	.772	.508E 00
1770.0	.606	.770	.195E 01	2200.0	.575	.773	.495E 00

APPENDIX D (Contd.)

Temp (°F)	CP-VAP (Btu/lb$_m$-°F)	PR-VAP	ALPHA-VAP (ft^2/hr)	Temp (°F)	CP-VAP (Btu/lb$_m$-°F)	PR-VAP	ALPHA-VAP (ft^2/hr)
2210.0	.575	.774	.481E 00	2360.0	.568	.796	.322E 00
2220.0	.575	.775	.468E 00	2370.0	.567	.798	.314E 00
2230.0	.574	.776	.455E 00	2380.0	.566	.799	.306E 00
2240.0	.574	.778	.443E 00	2390.0	.566	.801	.299E 00
2250.0	.573	.779	.431E 00	2400.0	.565	.803	.291E 00
2260.0	.572	.780	.420E 00	2410.0	.565	.805	.284E 00
2270.0	.572	.782	.408E 00	2420.0	.564	.807	.277E 00
2280.0	.572	.783	.398E 00	2430.0	.564	.809	.270E 00
2290.0	.571	.785	.387E 00	2440.0	.563	.811	.264E 00
2300.0	.571	.786	.377E 00	2450.0	.563	.813	.257E 00
2310.0	.570	.787	.367E 00	2460.0	.562	.815	.251E 00
2320.0	.570	.789	.358E 00	2470.0	.561	.817	.245E 00
2330.0	.569	.791	.348E 00	2480.0	.561	.819	.239E 00
2340.0	.569	.792	.340E 00	2490.0	.560	.821	.233E 00
2350.0	.568	.794	.331E 00	2500.0	.559	.823	.228E 00

APPENDIX E. Thermal Expansion, Compressibility, and Thermal Pressure Coefficient of Liquid Sodium

Temp (°F)	ALPHA-P ($°F^{-1}$)	BETA-T ($atmos^{-1}$)	GAMMA-V (atmos/°F)	SONIC-VEL (ft/sec)	BETA-S ($atmos^{-1}$)	CV-LIQ (Btu/lb_m-°F)
210	1.3930-004	1.7663-005	7.89	8285	1.7150-005	0.3573
220	1.3958-004	1.7737-005	7.87	8276	1.7214-005	0.3568
230	1.3986-004	1.7812-005	7.85	8266	1.7277-005	0.3563
240	1.4014-004	1.7888-005	7.83	8257	1.7342-005	0.3559
250	1.4042-004	1.7964-005	7.82	8247	1.7406-005	0.3554
260	1.4070-004	1.8040-005	7.80	8237	1.7471-005	0.3549
270	1.4098-004	1.8117-005	7.78	8228	1.7537-005	0.3545
280	1.4126-004	1.8194-005	7.76	8218	1.7602-005	0.3540
290	1.4155-004	1.8272-005	7.75	8209	1.7668-005	0.3535
300	1.4183-004	1.8350-005	7.73	8199	1.7734-005	0.3530
310	1.4211-004	1.8428-005	7.71	8190	1.7801-005	0.3526
320	1.4239-004	1.8507-005	7.69	8180	1.7868-005	0.3521
330	1.4268-004	1.8587-005	7.68	8171	1.7935-005	0.3516
340	1.4296-004	1.8667-005	7.66	8161	1.8003-005	0.3512
350	1.4324-004	1.8747-005	7.64	8151	1.8071-005	0.3507
360	1.4353-004	1.8829-005	7.62	8142	1.8140-005	0.3503
370	1.4381-004	1.8910-005	7.61	8132	1.8208-005	0.3498
380	1.4410-004	1.8992-005	7.59	8123	1.8277-005	0.3493
390	1.4438-004	1.9075-005	7.57	8113	1.8347-005	0.3489
400	1.4467-004	1.9158-005	7.55	8104	1.8417-005	0.3484
410	1.4495-004	1.9241-005	7.53	8094	1.8487-005	0.3479
420	1.4524-004	1.9325-005	7.52	8085	1.8558-005	0.3475
430	1.4553-004	1.9410-005	7.50	8075	1.8629-005	0.3470
440	1.4581-004	1.9495-005	7.48	8066	1.8700-005	0.3465
450	1.4610-004	1.9580-005	7.46	8056	1.8772-005	0.3461
460	1.4639-004	1.9666-005	7.44	8046	1.8844-005	0.3456
470	1.4667-004	1.9753-005	7.43	8037	1.8916-005	0.3452
480	1.4696-004	1.9840-005	7.41	8027	1.8989-005	0.3447
490	1.4725-004	1.9928-005	7.39	8018	1.9063-005	0.3442
500	1.4754-004	2.0016-005	7.37	8008	1.9136-005	0.3438
510	1.4783-004	2.0105-005	7.35	7999	1.9210-005	0.3433
520	1.4812-004	2.0194-005	7.33	7989	1.9285-005	0.3429
530	1.4841-004	2.0284-005	7.32	7980	1.9360-005	0.3424
540	1.4870-004	2.0374-005	7.30	7970	1.9435-005	0.3420
550	1.4899-004	2.0465-005	7.28	7960	1.9511-005	0.3415
560	1.4928-004	2.0557-005	7.26	7951	1.9587-005	0.3410
570	1.4957-004	2.0649-005	7.24	7941	1.9663-005	0.3406
580	1.4986-004	2.0741-005	7.23	7932	1.9740-005	0.3401
590	1.5015-004	2.0834-005	7.21	7922	1.9817-005	0.3397
600	1.5044-004	2.0928-005	7.19	7913	1.9895-005	0.3392
610	1.5073-004	2.1023-005	7.17	7903	1.9973-005	0.3388
620	1.5102-004	2.1118-005	7.15	7894	2.0052-005	0.3383
630	1.5132-004	2.1213-005	7.13	7884	2.0131-005	0.3379

APPENDIX E (Contd.)

Temp (°F)	ALPHA-P ($°F^{-1}$)	BETA-T ($atmos^{-1}$)	GAMMA-V (atmos/°F)	SONIC-VEL (ft/sec)	BETA-S ($atmos^{-1}$)	CV-LIQ (Btu/lb_m-°F)
640	1.5161-004	2.1309-005	7.11	7874	2.0210-005	0.3374
650	1.5190-004	2.1406-005	7.10	7865	2.0290-005	0.3370
660	1.5219-004	2.1503-005	7.08	7855	2.0371-005	0.3365
670	1.5249-004	2.1601-005	7.06	7846	2.0451-005	0.3361
680	1.5278-004	2.1700-005	7.04	7836	2.0533-005	0.3356
690	1.5308-004	2.1799-005	7.02	7827	2.0614-005	0.3351
700	1.5337-004	2.1898-005	7.00	7817	2.0696-005	0.3347
710	1.5367-004	2.1999-005	6.99	7808	2.0779-005	0.3343
720	1.5396-004	2.2100-005	6.97	7798	2.0862-005	0.3338
730	1.5426-004	2.2201-005	6.95	7789	2.0945-005	0.3334
740	1.5455-004	2.2304-005	6.93	7779	2.1029-005	0.3329
750	1.5485-004	2.2406-005	6.91	7769	2.1114-005	0.3325
760	1.5515-004	2.2510-005	6.89	7760	2.1198-005	0.3320
770	1.5544-004	2.2614-005	6.87	7750	2.1284-005	0.3316
780	1.5574-004	2.2719-005	6.86	7741	2.1370-005	0.3311
790	1.5604-004	2.2825-005	6.84	7731	2.1456-005	0.3307
800	1.5634-004	2.2931-005	6.82	7722	2.1543-005	0.3302
810	1.5663-004	2.3037-005	6.80	7712	2.1630-005	0.3298
820	1.5693-004	2.3145-005	6.78	7703	2.1717-005	0.3293
830	1.5723-004	2.3253-005	6.76	7693	2.1806-005	0.3289
840	1.5753-004	2.3362-005	6.74	7683	2.1894-005	0.3285
850	1.5783-004	2.3471-005	6.72	7674	2.1983-005	0.3280
860	1.5813-004	2.3582-005	6.71	7664	2.2073-005	0.3276
870	1.5843-004	2.3693-005	6.69	7655	2.2163-005	0.3271
880	1.5873-004	2.3804-005	6.67	7645	2.2254-005	0.3267
890	1.5903-004	2.3917-005	6.65	7636	2.2345-005	0.3263
900	1.5933-004	2.4030-005	6.63	7626	2.2437-005	0.3258
910	1.5964-004	2.4143-005	6.61	7617	2.2529-005	0.3254
920	1.5994-004	2.4258-005	6.59	7607	2.2622-005	0.3249
930	1.6024-004	2.4373-005	6.57	7598	2.2715-005	0.3245
940	1.6054-004	2.4489-005	6.56	7588	2.2809-005	0.3241
950	1.6085-004	2.4605-005	6.54	7578	2.2903-005	0.3236
960	1.6115-004	2.4723-005	6.52	7569	2.2998-005	0.3232
970	1.6145-004	2.4841-005	6.50	7559	2.3093-005	0.3228
980	1.6176-004	2.4960-005	6.48	7550	2.3189-005	0.3223
990	1.6206-004	2.5080-005	6.46	7540	2.3286-005	0.3219
1000	1.6237-004	2.5200-005	6.44	7531	2.3383-005	0.3215
1010	1.6267-004	2.5321-005	6.42	7521	2.3480-005	0.3210
1020	1.6298-004	2.5443-005	6.41	7512	2.3578-005	0.3206
1030	1.6328-004	2.5566-005	6.39	7502	2.3677-005	0.3202
1040	1.6359-004	2.5689-005	6.37	7492	2.3776-005	0.3197
1050	1.6389-004	2.5814-005	6.35	7483	2.3876-005	0.3193
1060	1.6420-004	2.5939-005	6.33	7473	2.3976-005	0.3189

APPENDIX E (Contd.)

Temp (°F)	ALPHA-P (°F^{-1})	BETA-T (atmos^{-1})	GAMMA-V (atmos/°F)	SONIC-VEL (ft/sec)	BETA-S (atmos^{-1})	CV-LIQ (Btu/lb$_m$-°F)
1070	1.6451-004	2.6065-005	6.31	7464	2.4077-005	0.3185
1080	1.6482-004	2.6191-005	6.29	7454	2.4179-005	0.3180
1090	1.6512-004	2.6319-005	6.27	7445	2.4281-005	0.3176
1100	1.6543-004	2.6447-005	6.26	7435	2.4384-005	0.3172
1110	1.6574-004	2.6576-005	6.24	7426	2.4487-005	0.3168
1120	1.6605-004	2.6707-005	6.22	7416	2.4591-005	0.3163
1130	1.6636-004	2.6837-005	6.20	7406	2.4695-005	0.3159
1140	1.6667-004	2.6969-005	6.18	7397	2.4800-005	0.3155
1150	1.6698-004	2.7102-005	6.16	7387	2.4906-005	0.3151
1160	1.6729-004	2.7235-005	6.14	7378	2.5012-005	0.3146
1170	1.6760-004	2.7369-005	6.12	7368	2.5119-005	0.3142
1180	1.6791-004	2.7504-005	6.10	7359	2.5227-005	0.3138
1190	1.6822-004	2.7640-005	6.09	7349	2.5335-005	0.3134
1200	1.6854-004	2.7777-005	6.07	7340	2.5444-005	0.3130
1210	1.6885-004	2.7915-005	6.05	7330	2.5553-005	0.3125
1220	1.6916-004	2.8054-005	6.03	7321	2.5663-005	0.3121
1230	1.6947-004	2.8193-005	6.01	7311	2.5774-005	0.3117
1240	1.6979-004	2.8334-005	5.99	7301	2.5885-005	0.3113
1250	1.7010-004	2.8475-005	5.97	7292	2.5997-005	0.3109
1260	1.7042-004	2.8618-005	5.95	7282	2.6110-005	0.3104
1270	1.7073-004	2.8761-005	5.94	7273	2.6223-005	0.3100
1280	1.7105-004	2.8905-005	5.92	7263	2.6337-005	0.3096
1290	1.7136-004	2.9050-005	5.90	7254	2.6452-005	0.3092
1300	1.7168-004	2.9196-005	5.88	7244	2.6567-005	0.3088
1310	1.7199-004	2.9343-005	5.86	7235	2.6683-005	0.3084
1320	1.7231-004	2.9491-005	5.84	7225	2.6800-005	0.3080
1330	1.7263-004	2.9640-005	5.82	7215	2.6917-005	0.3076
1340	1.7294-004	2.9790-005	5.81	7206	2.7035-005	0.3072
1350	1.7326-004	2.9941-005	5.79	7196	2.7154-005	0.3067
1360	1.7358-004	3.0093-005	5.77	7187	2.7274-005	0.3063
1370	1.7390-004	3.0246-005	5.75	7177	2.7394-005	0.3059
1380	1.7422-004	3.0400-005	5.73	7168	2.7515-005	0.3055
1390	1.7454-004	3.0555-005	5.71	7158	2.7636-005	0.3051
1400	1.7485-004	3.0711-005	5.69	7149	2.7759-005	0.3047
1410	1.7517-004	3.0868-005	5.68	7139	2.7882-005	0.3043
1420	1.7550-004	3.1026-005	5.66	7130	2.8005-005	0.3039
1430	1.7582-004	3.1185-005	5.64	7120	2.8130-005	0.3035
1440	1.7614-004	3.1345-005	5.62	7110	2.8255-005	0.3031
1450	1.7646-004	3.1506-005	5.60	7101	2.8381-005	0.3027
1460	1.7678-004	3.1668-005	5.58	7091	2.8508-005	0.3023
1470	1.7710-004	3.1832-005	5.56	7082	2.8636-005	0.3019
1480	1.7743-004	3.1996-005	5.55	7072	2.8764-005	0.3015
1490	1.7775-004	3.2162-005	5.53	7063	2.8893-005	0.3011

APPENDIX E (Contd.)

Temp (°F)	ALPHA-P (°F^{-1})	BETA-T (atmos^{-1})	GAMMA-V (atmos/°F)	SONIC-VEL (ft/sec)	BETA-S (atmos^{-1})	CV-LIQ (Btu/lb$_m$-°F)
1500	1.7807-004	3.2328-005	5.51	7053	2.9023-005	0.3007
1510	1.7840-004	3.2496-005	5.49	7044	2.9154-005	0.3003
1520	1.7872-004	3.2665-005	5.47	7034	2.9285-005	0.2999
1530	1.7905-004	3.2835-005	5.45	7024	2.9417-005	0.2995
1540	1.7937-004	3.3006-005	5.43	7015	2.9551-005	0.2991
1550	1.7970-004	3.3178-005	5.42	7005	2.9684-005	0.2987
1560	1.8002-004	3.3351-005	5.40	6996	2.9819-005	0.2983
1570	1.8035-004	3.3526-005	5.38	6986	2.9955-005	0.2979
1580	1.8067-004	3.3702-005	5.36	6977	3.0091-005	0.2975
1590	1.8100-004	3.3879-005	5.34	6967	3.0228-005	0.2972
1600	1.8133-004	3.4057-005	5.32	6958	3.0366-005	0.2968
1610	1.8166-004	3.4236-005	5.31	6948	3.0505-005	0.2964
1620	1.8199-004	3.4416-005	5.29	6939	3.0645-005	0.2960
1630	1.8231-004	3.4598-005	5.27	6929	3.0785-005	0.2956
1640	1.8264-004	3.4781-005	5.25	6919	3.0927-005	0.2952
1650	1.8297-004	3.4965-005	5.23	6910	3.1069-005	0.2948
1660	1.8330-004	3.5151-005	5.21	6900	3.1212-005	0.2944
1670	1.8363-004	3.5337-005	5.20	6891	3.1356-005	0.2941
1680	1.8396-004	3.5525-005	5.18	6881	3.1501-005	0.2937
1690	1.8430-004	3.5714-005	5.16	6872	3.1647-005	0.2933
1700	1.8463-004	3.5905-005	5.14	6862	3.1794-005	0.2929
1710	1.8496-004	3.6097-005	5.12	6853	3.1941-005	0.2925
1720	1.8529-004	3.6290-005	5.11	6843	3.2090-005	0.2922
1730	1.8562-004	3.6484-005	5.09	6833	3.2240-005	0.2918
1740	1.8596-004	3.6680-005	5.07	6824	3.2390-005	0.2914
1750	1.8629-004	3.6877-005	5.05	6814	3.2541-005	0.2910
1760	1.8663-004	3.7075-005	5.03	6805	3.2694-005	0.2906
1770	1.8696-004	3.7275-005	5.02	6795	3.2847-005	0.2903
1780	1.8730-004	3.7476-005	5.00	6786	3.3001-005	0.2899
1790	1.8763-004	3.7678-005	4.98	6776	3.3156-005	0.2895
1800	1.8797-004	3.7882-005	4.96	6767	3.3312-005	0.2892
1810	1.8830-004	3.8087-005	4.94	6757	3.3470-005	0.2888
1820	1.8864-004	3.8294-005	4.93	6747	3.3628-005	0.2884
1830	1.8898-004	3.8502-005	4.91	6738	3.3787-005	0.2880
1840	1.8931-004	3.8711-005	4.89	6728	3.3947-005	0.2877
1850	1.8965-004	3.8922-005	4.87	6719	3.4108-005	0.2873
1860	1.8999-004	3.9135-005	4.85	6709	3.4270-005	0.2869
1870	1.9033-004	3.9348-005	4.84	6700	3.4434-005	0.2866
1880	1.9067-004	3.9564-005	4.82	6690	3.4598-005	0.2862
1890	1.9101-004	3.9780-005	4.80	6681	3.4763-005	0.2858
1900	1.9135-004	3.9999-005	4.78	6671	3.4929-005	0.2855
1910	1.9169-004	4.0218-005	4.77	6662	3.5097-005	0.2851
1920	1.9203-004	4.0440-005	4.75	6652	3.5265-005	0.2848

APPENDIX E (Contd.)

Temp (°F)	ALPHA-P (°F^{-1})	BETA-T (atmos^{-1})	GAMMA-V (atmos/°F)	SONIC-VEL (ft/sec)	BETA-S (atmos^{-1})	CV-LIQ (Btu/lb$_m$-°F)
1930	1.9237-004	4.0662-005	4.73	6642	3.5435-005	0.2844
1940	1.9271-004	4.0887-005	4.71	6633	3.5605-005	0.2840
1950	1.9305-004	4.1112-005	4.70	6623	3.5777-005	0.2837
1960	1.9340-004	4.1340-005	4.68	6614	3.5950-005	0.2833
1970	1.9374-004	4.1569-005	4.66	6604	3.6124-005	0.2830
1980	1.9408-004	4.1799-005	4.64	6595	3.6299-005	0.2826
1990	1.9443-004	4.2032-005	4.63	6585	3.6475-005	0.2822
2000	1.9477-004	4.2265-005	4.61	6576	3.6652-005	0.2819
2010	1.9512-004	4.2501-005	4.59	6566	3.6831-005	0.2815
2020	1.9546-004	4.2738-005	4.57	6556	3.7010-005	0.2812
2030	1.9581-004	4.2977-005	4.56	6547	3.7191-005	0.2808
2040	1.9615-004	4.3217-005	4.54	6537	3.7373-005	0.2805
2050	1.9650-004	4.3459-005	4.52	6528	3.7556-005	0.2801
2060	1.9685-004	4.3703-005	4.50	6518	3.7740-005	0.2798
2070	1.9719-004	4.3948-005	4.49	6509	3.7926-005	0.2794
2080	1.9754-004	4.4195-005	4.47	6499	3.8113-005	0.2791
2090	1.9789-004	4.4444-005	4.45	6490	3.8300-005	0.2787
2100	1.9824-004	4.4695-005	4.44	6480	3.8490-005	0.2784
2110	1.9859-004	4.4947-005	4.42	6471	3.8680-005	0.2780
2120	1.9894-004	4.5201-005	4.40	6461	3.8872-005	0.2777
2130	1.9929-004	4.5457-005	4.38	6451	3.9064-005	0.2774
2140	1.9964-004	4.5715-005	4.37	6442	3.9259-005	0.2770
2150	1.9999-004	4.5975-005	4.35	6432	3.9454-005	0.2767
2160	2.0034-004	4.6236-005	4.33	6423	3.9651-005	0.2763
2170	2.0069-004	4.6499-005	4.32	6413	3.9849-005	0.2760
2180	2.0104-004	4.6764-005	4.30	6404	4.0048-005	0.2757
2190	2.0140-004	4.7031-005	4.28	6394	4.0249-005	0.2753
2200	2.0175-005	4.7300-005	4.27	6385	4.0451-005	0.2750
2210	2.0210-004	4.7571-005	4.25	6375	4.0654-005	0.2747
2220	2.0246-004	4.7843-005	4.23	6365	4.0859-005	0.2743
2230	2.0281-004	4.8118-005	4.21	6356	4.1065-005	0.2740
2240	2.0317-004	4.8395-005	4.20	6346	4.1272-005	0.2737
2250	2.0352-004	4.8673-005	4.18	6337	4.1481-005	0.2733
2260	2.0388-004	4.8954-005	4.16	6327	4.1691-005	0.2730
2270	2.0423-004	4.9236-005	4.15	6318	4.1903-005	0.2727
2280	2.0459-004	4.9520-005	4.13	6308	4.2116-005	0.2723
2290	2.0495-004	4.9807-005	4.11	6299	4.2330-005	0.2720
2300	2.0530-004	5.0095-005	4.10	6289	4.2546-005	0.2717
2310	2.0566-004	5.0386-005	4.08	6279	4.2763-005	0.2714
2320	2.0602-004	5.0679-005	4.07	6270	4.2982-005	0.2710
2330	2.0638-004	5.0973-005	4.05	6260	4.3202-005	0.2707
2340	2.0674-004	5.1270-005	4.03	6251	4.3424-005	0.2704
2350	2.0710-004	5.1569-005	4.02	6241	4.3647-005	0.2701

APPENDIX E (Contd.)

Temp (°F)	ALPHA-P ($°F^{-1}$)	BETA-T ($atmos^{-1}$)	GAMMA-V (atmos/°F)	SONIC-VEL (ft/sec)	BETA-S ($atmos^{-1}$)	CV-LIQ (Btu/lb_m-°F)
2360	2.0746-004	5.1870-005	4.00	6232	4.3872-005	0.2698
2370	2.0782-004	5.2174-005	3.98	6222	4.4098-005	0.2694
2380	2.0818-004	5.2479-005	3.97	6213	4.4326-005	0.2691
2390	2.0854-004	5.2787-005	3.95	6203	4.4555-005	0.2688
2400	2.0890-004	5.3097-005	3.93	6194	4.4786-005	0.2685
2410	2.0926-004	5.3409-005	3.92	6184	4.5019-005	0.2682
2420	2.0963-004	5.3723-005	3.90	6174	4.5253-005	0.2679
2430	2.0999-004	5.4040-005	3.89	6165	4.5488-005	0.2676
2440	2.1035-004	5.4359-005	3.87	6155	4.5726-005	0.2672
2450	2.1072-004	5.4680-005	3.85	6146	4.5964-005	0.2669
2460	2.1108-004	5.5003-005	3.84	6136	4.6205-005	0.2666
2470	2.1145-004	5.5329-005	3.82	6127	4.6447-005	0.2663
2480	2.1181-004	5.5657-005	3.81	6117	4.6691-005	0.2660
2490	2.1218-004	5.5988-005	3.79	6108	4.6937-005	0.2657
2500	2.1255-004	5.6321-005	3.77	6098	4.7184-005	0.2654

APPENDIX F. H-S and T-S Charts for Sodium

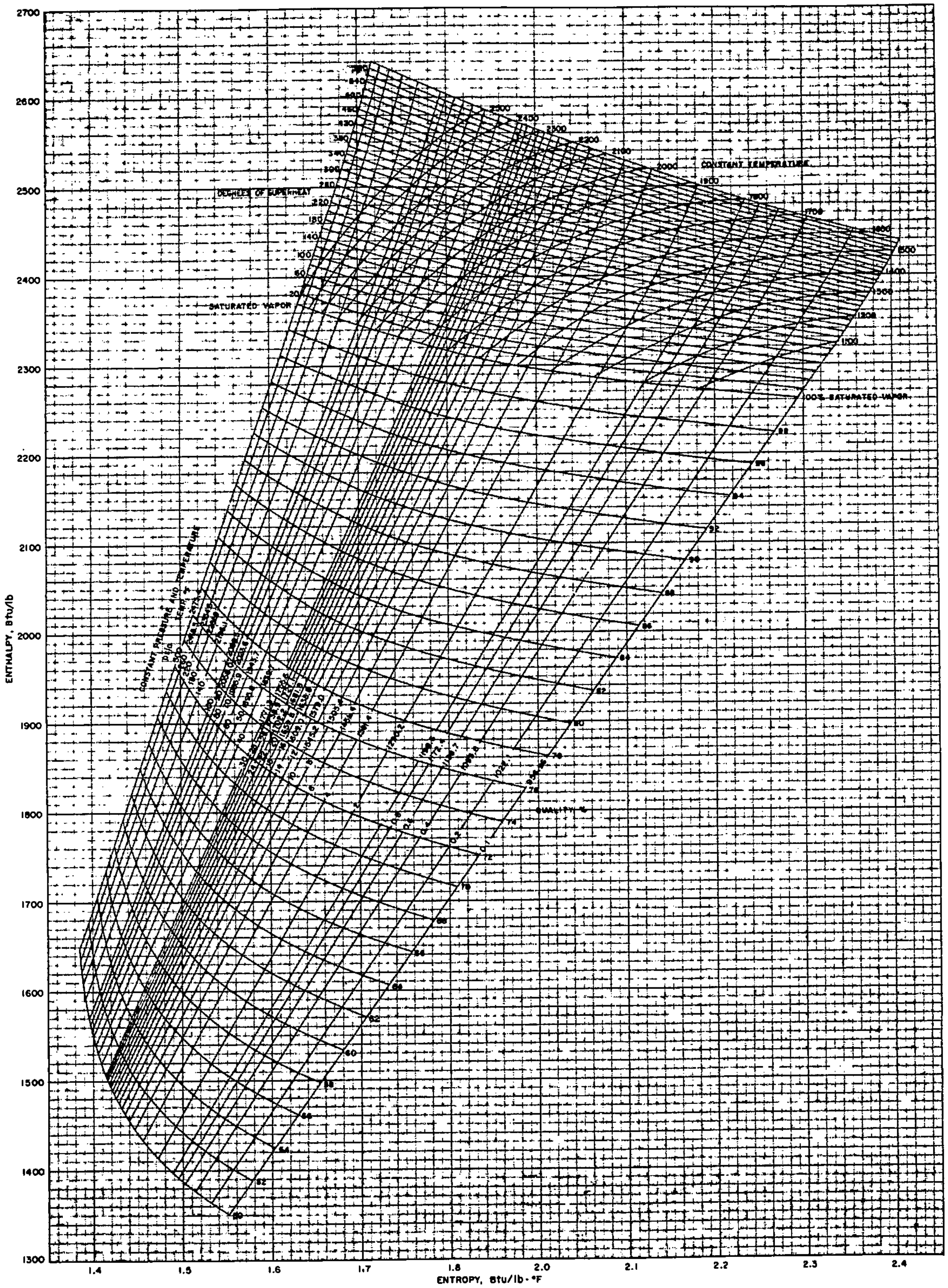

Fig. F.1. Mollier Diagram for Sodium

APPENDIX F (Contd.)

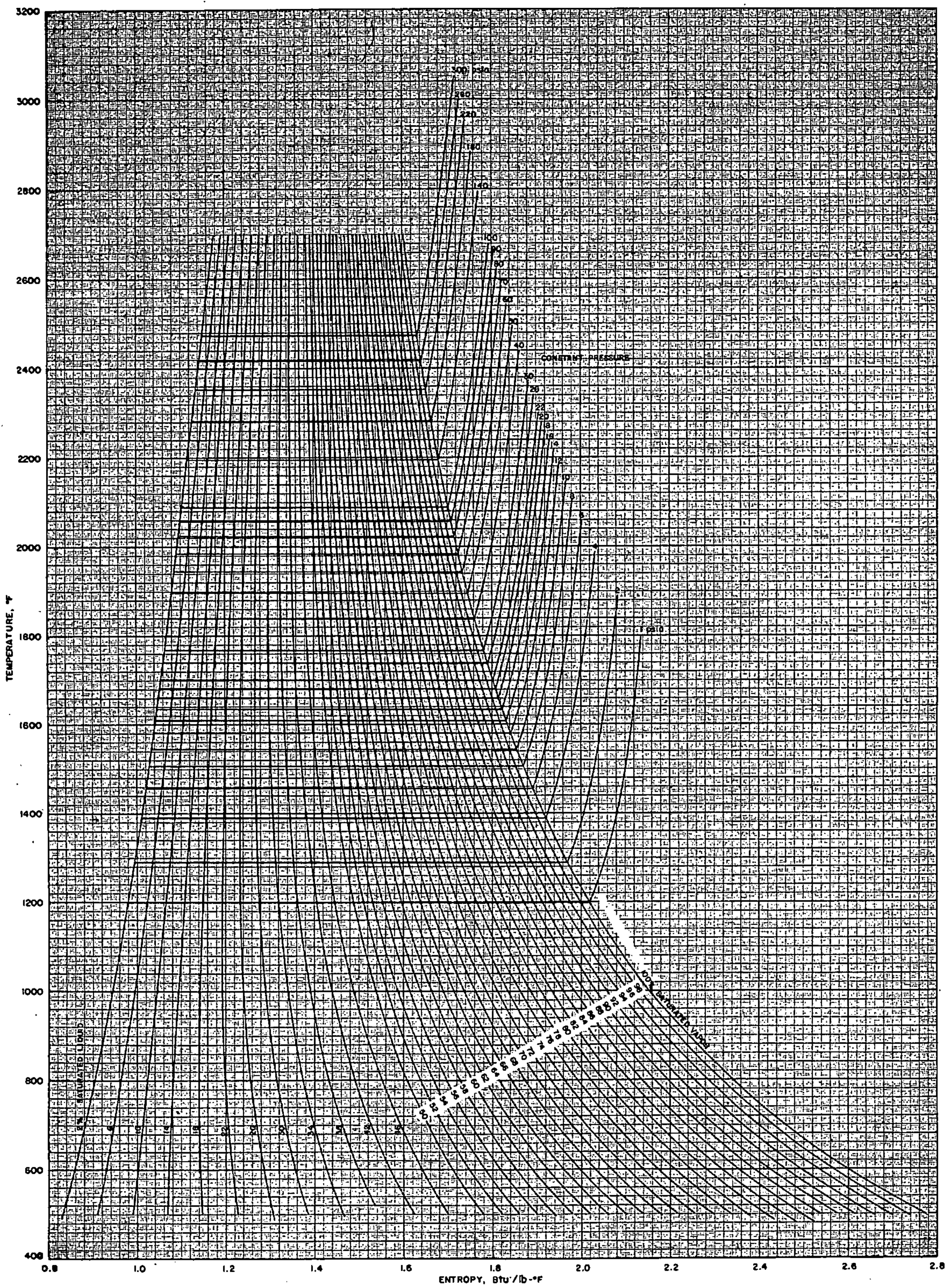

Fig. F.2. Temperature-Entropy Diagram for Sodium

NOMENCLATURE

Symbol	Definition
C	Sonic velocity; ft/sec
C_p	Specific heat at constant pressure; Btu/lb-°F
C_v	Specific heat at constant volume; Btu/lb-°F
E	Internal energy; Btu/lb, Btu/lb mole
F	Free energy; Btu/lb, Btu/lb mole
H	Enthalpy; Btu/lb, Btu/lb mole
K	R'/R = 2.72131 Btu/atmos-ft^3
k	Thermal conductivity; Btu/hr-ft-°F, cal/sec-cm-°C
M	Molecular weight ($M_1 \equiv 22.991$)
N	Mole fraction
P	Pressure; atmos abs
Pr	Prandtl number $\eta C_p/k$
R	Gas constant; 0.730229 atmos-ft^3/lb-mole-°R
R'	Gas constant; 1.98718 Btu/lb-mole-°R
S	Entropy; Btu/lb-°R, Btu/lb-mole-°R
T	Absolute temperature; °R(≡ °F + 459.7), °K(≡ °C + 273.15)
t	Temperature; °F, °C
V	Specific volume; ft^3/lb
v	Specific volume; ft^3/lb-mole monomer, cm^3/gm
X	Weight fraction
α	Thermal diffusivity; $k/\rho_\ell C_p$; ft^2/hr
α_P	Thermal expansion coefficients; 1/°F
β_T	Isothermal compressibility; atmos^{-1}

Symbol	Definition
β_S	Adiabatic compressibility; atmos^{-1}
γ_ν	Thermal pressure coefficient; atmos/°F
η	Dynamic viscosity; lb$_m$/hr-ft
ρ	Vapor density; lb/ft^3, lb-mole monomer/ft^3
ρ_ℓ	Liquid density; lb/ft^3, lb-mole monomer/ft^3
ρ_e	Electrical resistivity; $\mu\Omega$-cm
σ	Surface tension; lb$_f$/ft

Subscripts

f	Formation
s	Saturation
v	Vaporization
D	Dimerization
T	Tetramerization
0	Absolute zero
1	Monomer
2	Dimer
4	Tetramer

Superscripts

0	Standard state
ℓ	Liquid phase
g	Gaseous phase
s	Solid phase

NOMENCLATURE ➡

APPENDIX F. H-S and T-S Charts for Sodium

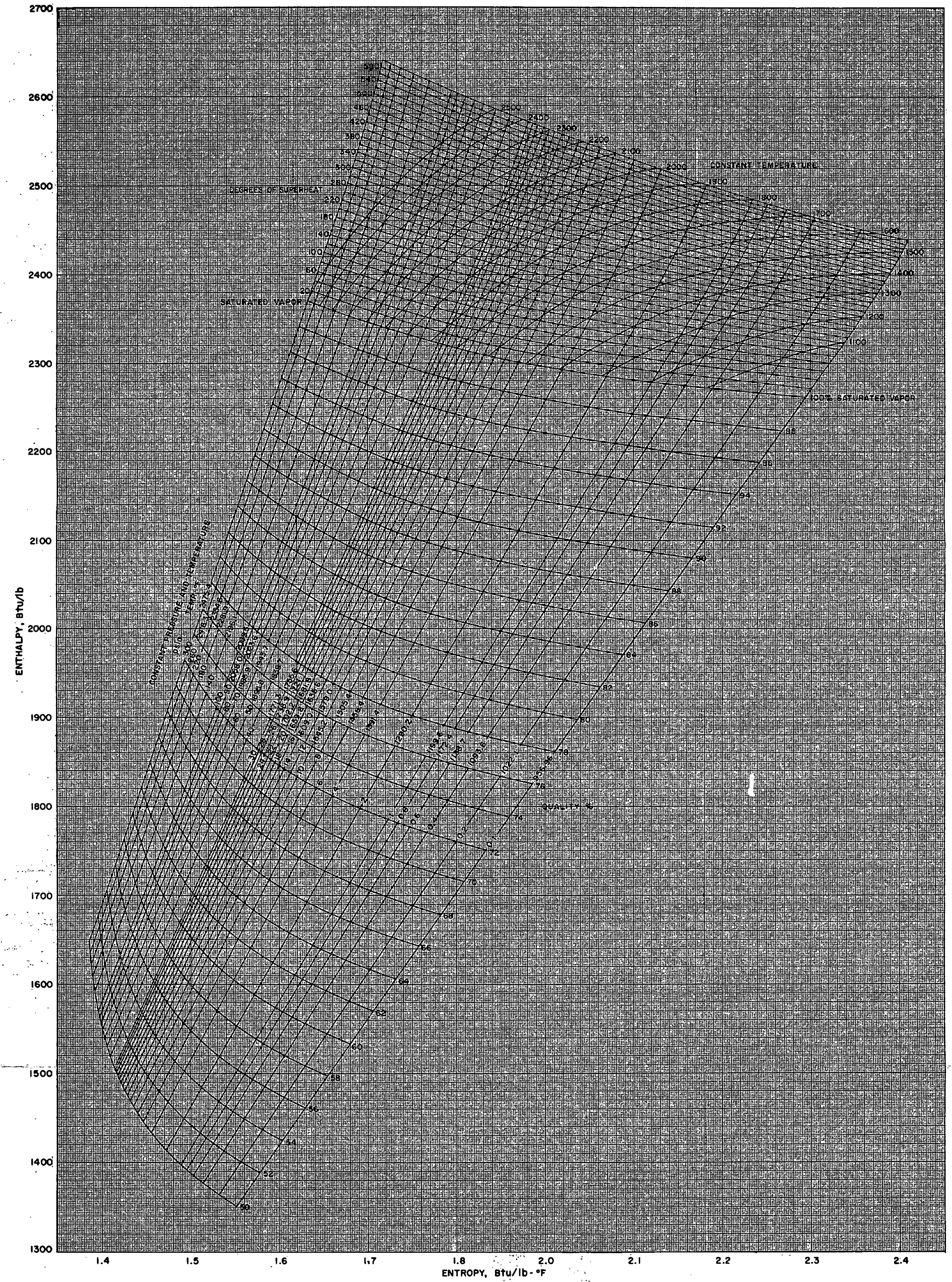

Fig. F.1. Mollier Diagram for Sodium

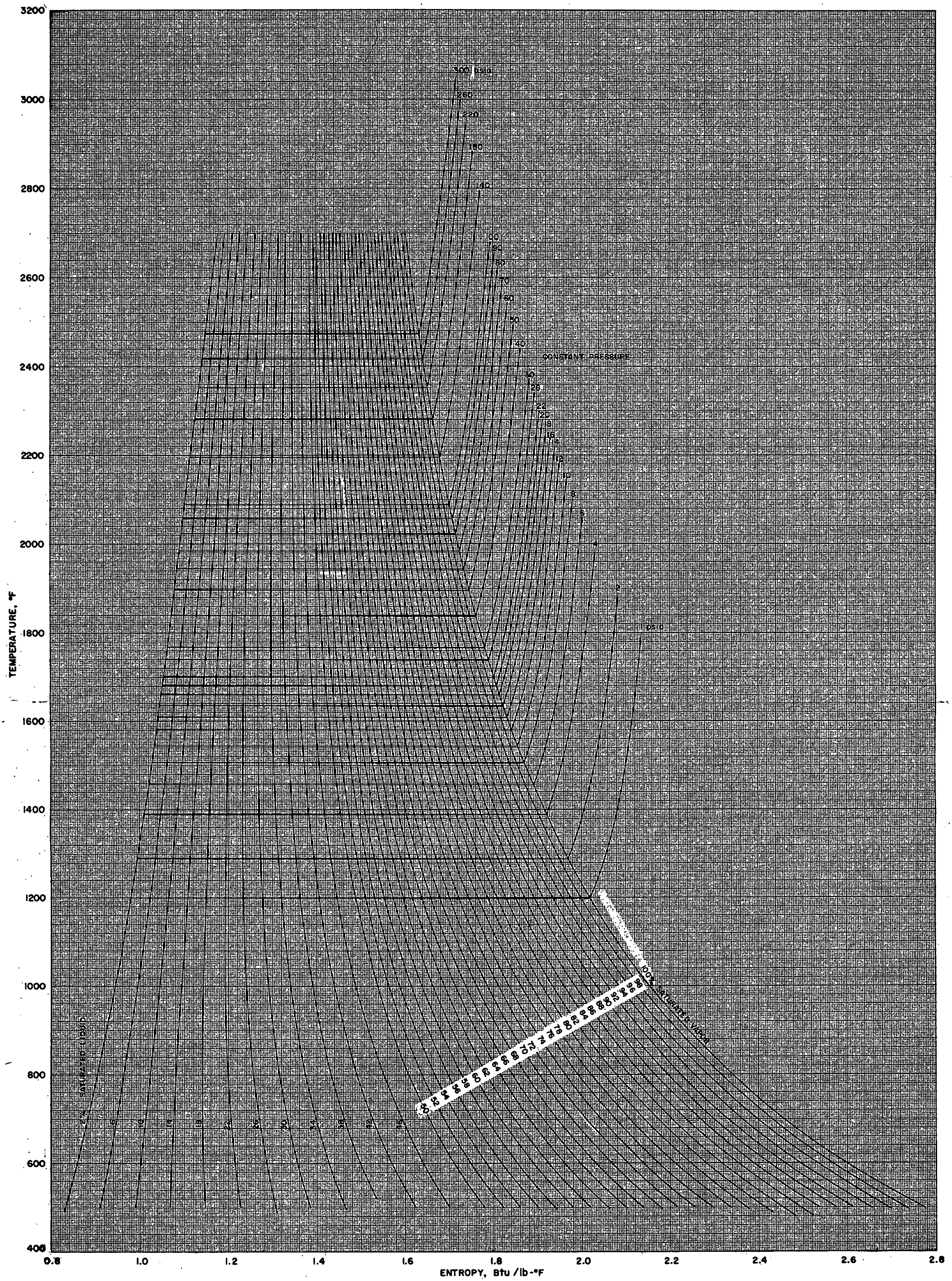

Fig. F.2. Temperature-Entropy Diagram for Sodium