

# High-Temperature Properties of Sodium

J. P. STONE, C. T. EWING, J. R. SPANN,  
E. W. STEINKULLER, D. D. WILLIAMS, AND R. R. MILLER

*Inorganic and Nuclear Chemistry Branch  
Chemistry Division*

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## ABSTRACT

An experimental program is in progress at this Laboratory to measure various thermophysical properties of sodium, potassium, and cesium. A final reporting of the experimental results for sodium (saturation and superheat properties of the vapor, density and specific heat of the liquid) is presented together with a thermodynamic treatment of the data. Two equations of state are advanced, one virial and one quasi-chemical; and additional saturation and superheat properties of the vapor are derived from these equations. Either of two paths can be used to compute thermodynamic properties, the monomeric gas path or the liquid path; but results obtained by the former procedure are believed to be more accurate. Enthalpy, entropy, specific volume, specific heat, and compositional information (weight fraction of dimer, weight fraction of tetramer, and average molecular weight) are tabulated for some 700 selected vapor states in the temperature range from 1625° to 2575° F and in the pressure range from 0.2 to 25 atm.

## PROBLEM STATUS

This is a final report on the experimental work with sodium.

## AUTHORIZATION

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# HIGH-TEMPERATURE PROPERTIES OF SODIUM

## INTRODUCTION

In the development of compact turboelectric systems for space vehicles, the National Aeronautics and Space Administration is sponsoring a property measurement program for the evaluation of several liquid metals as possible working fluids. As an integral part of this program, the U.S. Naval Research Laboratory has measured several thermo-physical properties of potassium to 2300° F, sodium to 2500° F, and cesium to 2300° F.

The saturated liquid properties which have been determined experimentally include density, vapor pressure, and specific heat (except for cesium). Saturated and superheated vapor properties including specific volume, specific heat, enthalpy, and entropy have been derived from experimental pressure-volume-temperature (PVT) studies. All phases of this measurement program have been completed. The final properties of potassium and cesium are published in companion reports (1), and those of sodium are presented in this report.

## EXPERIMENTAL MATERIALS AND METHODS COMMON TO ALL MEASUREMENTS

A number of materials, methods, and techniques were common to many of the experimental measurements. These include the container alloy, the high-pressure furnace systems, the temperature measurements, and techniques for purifying and transferring the alkali metals. All are discussed at some length in the companion report on potassium (1a), and only a short section related to the purity of the sodium will be included in this report.

Sodium samples for the density and specific heat determinations were distilled directly from a small nickel still (2) into each apparatus. However, for the PVT determinations this procedure was impractical, and the alkali metal was distilled and introduced into small capsules (1a) for subsequent transfer into the PVT apparatuses. Sodium introduced to the distillation retort was a pure grade of E. I. du Pont de Nemours and Company; a typical spectrographic analysis after one distillation at this Laboratory is presented in Table 1. It will be noted that metal impurities are present in very low concentrations.

Sodium oxides, which may be present in low concentrations in the distilled metal, should be effectively gettered by the columbium and zirconium of the container alloy. Therefore, oxygen analyses of the metal samples used in these studies were not made, but the oxygen content of sodium (as purified in previous studies (3) at this Laboratory by the same distillation technique) was determined to be below 10 ppm by the amalgamation method.

Table 1  
Spectrographic Analysis of Distilled Sodium

Metal	Analyses (Parts per Million by Weight)
K	1 to 100
Rb	Not Detected
Cs	Not Detected
Li	Not Detected

## EXPERIMENTAL MEASUREMENTS

### Pressure-Volume-Temperature Measurements of Sodium

Experimental Superheat Results - The PVT measurements in both the superheat and saturation regions were made with small closed chambers using flexible diaphragms as null-detectors. This high-temperature columbium-1% zirconium apparatus and the methods employed are described in detail for potassium (1a); thus, only the new experimental results for sodium are included in this report.

The nine PVT experiments for sodium (Table 2) covered a wide range in the superheat region with measured temperatures extending from 1760° to 2590° F and pressures from 1.9 to 25.1 atm. For each experimental point in this table, pressure and temperature were directly observed and the specific volume was computed from the weight of sodium added to the chamber. The inconsistent numbering of the sodium experiments may be misleading; it results from these experiments being performed concurrently with those for potassium and cesium.

At each equilibrium point represented by the data in Table 2, multiple readings of temperature and pressure were made at 5 to 10 min intervals until successive readings showed a temperature drift of 0.07° F/min or less and a temperature difference across the chamber less than 2° F (and generally less than 1° F). In the measurement of pressures with the diaphragm device, the excellent reproducibility obtained during the potassium measurements (1a) continued for sodium. Measurements for each experiment (except experiment 18) were made over a minimum of one full cycle from the normal boiling point to about 2525° F, and equilibrium pressures were reproduced in the superheat region to better than  $\pm 0.1$  psi before, during, and after cycling.

Specific Volumes of Saturated Vapor - Specific volumes\* of several saturated vapor states (Table 3) were observed over the temperature range from 1750° to 2555° F. The measurements were made in the course of the PVT studies, and each point represents an intersection of the saturated and superheated vapor curves for one of the nine PVT experiments. However, for the low-weight and low-pressure experiments (particularly 3, 4, 18, and 19), the observed pressures near the intersection of the saturation and superheat curves were found to be abnormally low. To study this phenomenon, a large number of observed points were taken in this region for experiment 3, and a portion of this experimental curve is presented as Fig. 1. It will be noted that for a temperature range of about 150° F observed pressures are significantly below the true saturation and superheat curves. The several factors which may contribute to this lowering phenomenon include the existence of dual states, elevation of the boiling point by nonvolatile impurities, and the retention of condensed alkali metal on the walls by adsorption and capillarity effects. These factors are discussed in some detail in Ref. 1a.

The saturated specific volume for each PVT experiment was obtained, as illustrated for experiment 3 in Fig. 1, by a short extrapolation of the superheated vapor curve to the true saturation curve as defined by the vapor-pressure equation (Eq. (1)). Although the extrapolation procedure tended to minimize any error in the saturated specific volume resulting from the depression phenomenon, it is believed that specific volumes obtained from the virial equation (Eq. (14)) and the vapor-pressure equation (Eq. (1)) will be of higher reliability than those observed at the intersection points (Table 3). Even so, corresponding values computed from the virial equation show an average deviation of only  $\pm 0.57\%$  from the observed values.

\*Preliminary values for the specific volume of saturated sodium vapor (29) were based on incorrect thermal expansion values for columbium-1% zirconium.

Table 2  
Pressure-Volume-Temperature Measurements Superheat Region

Temperature (°F)	Pressure (abs atm)	Specific Volume (cu ft/lb)	Temperature (°F)	Pressure (abs atm)	Specific Volume (cu ft/lb)
Experiment 3			Experiment 20		
2126.7	6.623	10.750	2317.9	9.709	7.8521
2231.4	7.033	10.767	2382.2	10.027	7.8600
2324.3	7.375	10.783	2449.4	10.368	7.8684
2414.3	7.701	10.798	2514.0	10.677	7.8766
2508.6	8.025	10.814	2486.4	10.549	7.8731
2472.8	7.909	10.808	2419.5	10.216	7.8646
2376.9	7.568	10.792	2353.8	9.886	7.8565
2287.8	7.236	10.777	2284.2	9.536	7.8479
2185.9	6.860	10.760	2238.1	9.304	7.8424
2113.3	6.579	10.748	2204.6	9.123	7.8383
2095.5	6.478	10.745	Experiment 23		
2099.3	6.497	10.746	2399.9	13.250	5.8001
2102.9	6.514	10.746	2517.3	14.053	5.8110
Experiment 4			2536.1	14.175	5.8128
1807.3	1.9237	33.399	2491.4	13.884	5.8086
1959.8	2.1162	33.472	2456.3	13.628	5.8053
2110.5	2.2999	33.547	2417.4	13.367	5.8017
2333.5	2.5442	33.662	2373.2	13.078	5.7977
2445.5	2.6613	33.722	2341.9	12.860	5.7948
2537.2	2.7552	33.772	2306.2	12.547	5.7916
2397.9	2.6089	33.697	Experiment 7		
2258.1	2.4605	33.623	2571.6	24.837	3.0693
2157.4	2.3510	33.571	2572.3	24.850	3.0693
2059.3	2.2394	33.522	2576.5	24.935	3.0695
2019.4	2.1931	33.502	2579.0	24.983	3.0696
1891.2	2.0427	33.439	2581.9	25.044	3.0698
1825.2	1.9604	33.407	2582.6	25.054	3.0698
1767.4	1.8849	33.380	2586.4	25.123	3.0700
1758.2	1.8631	33.375	2588.0	25.146	3.0701
Experiment 18			2579.9	25.014	3.0697
2051.1	4.992	13.920	Experiment 25		
2172.0	5.326	13.945	2439.5	17.259	4.3766
2273.6	5.612	13.967	2479.2	17.632	4.3794
2387.1	5.921	13.992	2524.5	18.020	4.3826
2521.8	6.268	14.022	2511.9	17.917	4.3817
2479.6	6.162	14.012	2491.8	17.745	4.3803
Experiment 19			2468.2	17.540	4.3786
1971.9	3.4737	19.759	2452.1	17.403	4.3775
2099.4	3.7241	19.796	2433.5	17.209	4.3762
2193.0	3.9194	19.824	Experiment 17		
2306.9	4.1270	19.859	2534.4	21.023	3.6747
2417.5	4.3161	19.894	2516.1	20.832	3.6736
2520.7	4.4985	19.927	2506.6	20.723	3.6730
2472.4	4.4121	19.911	2502.7	20.676	3.6728
2373.2	4.2474	19.880	2496.6	20.604	3.6724
2248.6	4.0269	19.841	2495.7	20.589	3.6724
2141.7	3.8174	19.809	2490.5	20.506	3.6721
2038.8	3.6023	19.778			
1942.4	3.4145	19.750			
1910.2	3.3472	19.741			

Table 3  
Specific Volumes of Saturated Sodium Vapor

Experiment Number	Temperature (°F)	Specific Volume (cu ft/lb)
4	1750.1	33.37
19	1888.3	19.73
18	1988.8	13.90
3	2071.8	10.74
20	2177.6	7.835
23	2289.0	5.790
25	2402.3	4.374
17	2474.4	3.671
7	2555.1	3.069

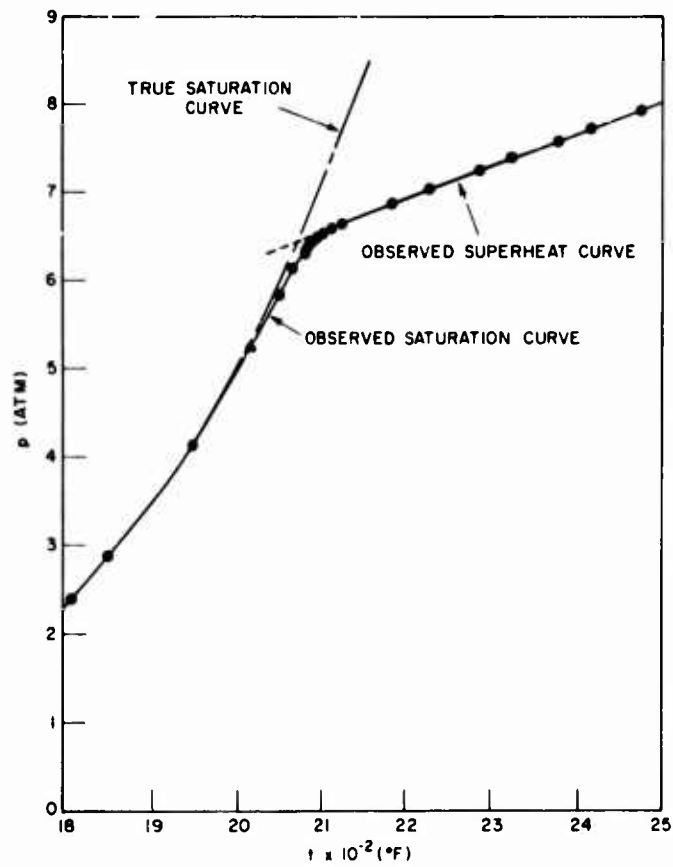


Fig. 1 - Phenomenon at intersection of saturation and superheat curves (illustrated with experiment 3)

Discussion of Superheat Results - The sources and magnitudes of errors in the PVT measurements were discussed in detail for potassium (1a). Many of these are common to the PVT studies of all the alkali metals, and only those which are specific to the sodium work are included here.

Although the procedures developed with potassium for the degassing and closing of null-point apparatuses were very effective in excluding all inert gas from the chambers, the possibility of inadvertently trapping gas in a chamber still existed. Therefore, each sodium apparatus was checked for gas at the conclusion of an experiment by opening the chamber to an evacuated manometer. Gas pressures as low as 0.01 psi were detectable in this manner, and no gas was detected in any of the nine experiments for sodium.

Two apparatuses of significantly different surface-to-volume ratios were used in the potassium study (1a). A comparison of compressibility factors measured with the two apparatuses provided evidence that any adsorption of potassium on the metal surfaces was insignificant. For sodium, two experiments (18 and 19) were again made with a large apparatus of nominal 113 cc volume and a surface-to-volume ratio of  $1.64 \text{ cm}^{-1}$ . The remaining experiments were made with the standard 57-cc apparatus having a surface-to-volume ratio of  $2.15 \text{ cm}^{-1}$ . If adsorption of sodium had been significant, one would expect the low-weight experiments performed with the lower surface-to-volume chambers to have observed pressures which would appear high relative to the other experiments. The fact that the observed pressures for these two experiments are not high provides additional evidence that any surface adsorption was insignificant.

The factor of thermal ionization was discussed for potassium vapor in Ref. 1a. An estimate of the degree of ionization was obtained for sodium from its ionization potential (4). For the metal vapor at  $2500^\circ\text{F}$  and 1 atm, the degree of ionization was estimated to be less than  $10^{-7}$ . This calculation leads to the conclusion that the degree of thermal ionization is several orders of magnitude too low to produce a measurable increase in pressure.

The results of PVT measurements are generally reported in the form of compressibility factors ( $p\bar{V}/RT$ ), since these factors, in one form or another, are employed directly in the thermodynamic reduction of data. It is then desirable to express experimental error in terms of these factors. If we take into account all known sources of uncertainty, the percent probable error in the compressibility factor ranges from a minimum of 0.26% to a maximum of 0.44%. The relatively large error occurred in experiment 4 and was generated by uncertainty in the weight of the very small sample of sodium employed.

Experimental Saturation Pressures - Saturation pressures of sodium for the full temperature range (0.34 atm at  $1437^\circ\text{F}$  to 23.8 atm at  $2539^\circ\text{F}$ ) were measured with a separate PVT apparatus using a large excess of the alkali metal, and the results are presented in the "Vapor-Pressure Experiments" section of Table 4. Pressures to 12.9 atm which were measured in the course of eight PVT experiments are presented in the second section of the same table. It has been shown that saturation pressures observed for each experiment near the intersection of the saturation and superheat curves were below corresponding values on the true saturation curve. This lowering of the vapor pressure can be satisfactorily explained (1a), and observed pressures in these regions are not included in the table.

The vapor-pressure data in Table 4 are presented graphically in Fig. 2. It is evident from a large-scale plot that  $\log p$  versus  $1/T$  for sodium is not linear, but the data can be effectively fitted for the full temperature range (normal boiling point to  $2040^\circ\text{F}$ ) with one three-term equation of the Kirchhoff type ( $\log p = a/T + b/T + c \log T$ ). A few measurements of vapor pressure below 1 atm are included in Table 4 and Fig. 2, but these are believed to be of lower precision and were given no weight in determining the coefficients of the vapor-pressure equation.

Table 4  
Saturated Vapor Pressures of Sodium

Temperature (°F)	Pressure (abs atm)	Temperature (°F)	Pressure (abs atm)
Vapor-Pressure Experiments			
1693.3	1.4283	2304.8	13.077
1800.7	2.3197	2223.9	10.363
1910.1	3.587	2152.5	8.329
2009.2	5.172	2053.0	6.023
2116.7	7.442	1947.0	4.131
2183.3	9.155	1837.3	2.7035
2262.4	11.582	1722.1	1.6399
2331.4	14.063	1628.1	1.0472
2413.1	17.466	1593.6	0.8737
2470.1	20.164	1557.7	0.7172
2539.2	23.821	1513.1	0.5512
2511.6	22.297	1478.7	0.4464
2443.4	18.851	1437.0	0.3362
2381.1	16.065		
Vapor Pressures from PVT Experiments			
1690.0	1.4242	1640.5	1.1187
1769.2	2.0325	1772.4	2.0645
1851.4	2.8729	1872.0	3.1138
1947.4	4.113	1976.7	4.607
1810.4	2.4081	2075.5	6.505
1661.5	1.2391	2189.7	9.347
1692.9	1.4249	2299.8	12.916
1635.8	1.0807	2149.2	8.237
1709.2	1.5365	2017.0	5.318
1651.5	1.1697	1906.7	3.562
1634.4	1.0744	1738.4	1.7835
1645.5	1.1500	1636.9	1.1085
1758.2	1.9291	1688.4	1.4017
1854.1	2.8933	1633.4	1.0772
1958.9	4.301	1695.8	1.4630
2062.0	6.212	1825.3	2.5681
2168.6	8.764	1760.5	1.9522
2135.3	7.831	1696.9	1.4671
2020.6	5.348	1629.1	1.0629
1905.0	3.506	1636.9	1.0860
1716.4	1.601	1863.9	2.9831
1765.5	1.9700	1810.4	2.4102
1873.6	3.1056	1678.0	1.3371
1988.7	4.799	1648.4	1.1622
1937.6	3.994	1779.6	2.1366
1813.7	2.4442	1880.6	3.2288
1700.7	1.4820	1998.7	4.986
1623.7	1.0221	1937.0	3.996
1639.2	1.0853	1728.4	1.7052
1760.3	1.9223		

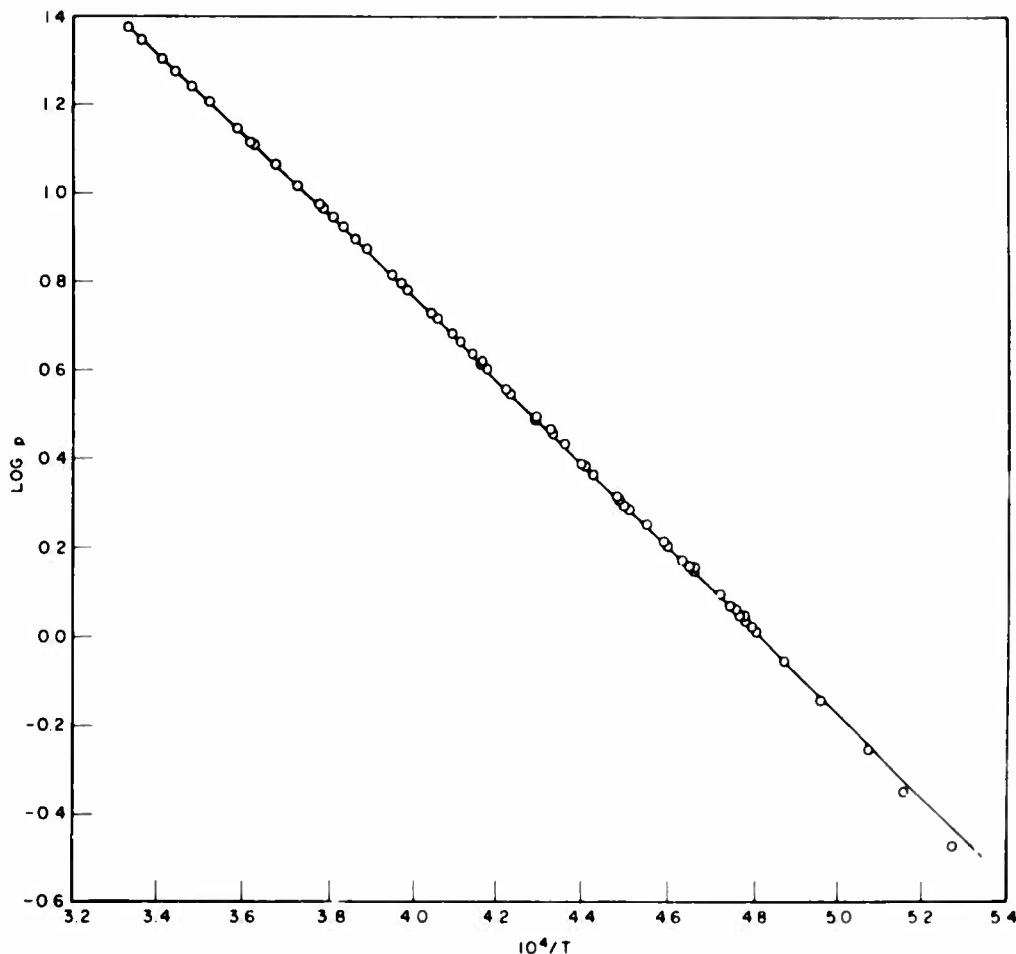


Fig. 2 - Vapor pressure of sodium as a function of the reciprocal absolute temperature

### Three vapor-pressure equations

$$\log p = 6.83770 - \frac{9,980.94}{T} - 0.61344 \log T \quad (1)$$

$$\log p = 7.11285 - \frac{10,063.7}{T} - 0.68464 \log T \quad (2)$$

$$\log p = 7.00980 - \frac{10,035.2}{T} - 0.65769 \log T \quad (3)$$

for sodium were obtained by least-squares (computer) treatments of the data. Eq. (1) was derived from a treatment using all the observed vapor pressures above the normal boiling point. Eq. (2) was derived from twenty points selected at equal intervals of  $1/T$  from a smoothed plot of  $\log p$  versus  $1/T$  for all the data. Eq. (3) was derived from the data of the vapor-pressure experiments in the first section of Table 4. The average deviation of all the observed vapor-pressure data in Table 4 from corresponding values computed from any one of the three equations is  $\pm 0.37\%$ . The three equations are, therefore, effectively equivalent, but other thermodynamic quantities in this report are based on Eq. (1). The normal boiling point as obtained from Eq. (1) is  $1618.6^\circ\text{F}$  ( $881.4^\circ\text{C}$ ) and from Eqs. (2) and (3) is  $1619.0^\circ\text{F}$  ( $881.7^\circ\text{C}$ ).

The NRL vapor pressures are compared to those of previous investigators in Fig. 3. Vapor pressures of sodium above the normal boiling point have been observed by Bowles and Rosenblum (5) over the temperature range from  $1778^\circ$  to  $3418^\circ\text{F}$ , by Sowa (6) over

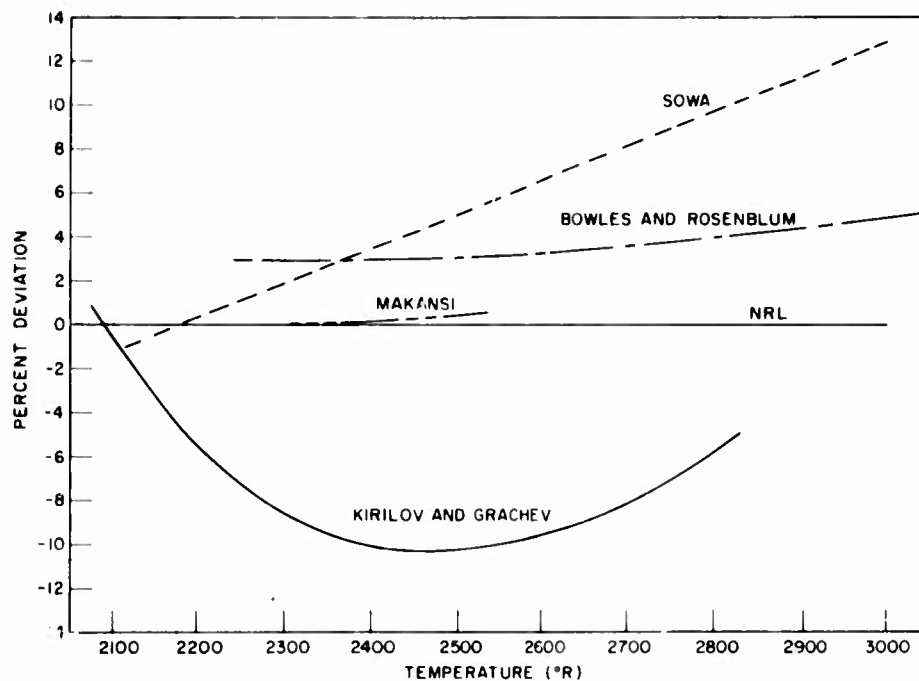


Fig. 3 - Comparison of vapor pressure data of sodium by several investigators using the NRL data as standard

the range from 1652° to 2534° F, by Kirilov and Grachev (7) over the range from 1616° to 2372° F, and by Makansi et al. (8) over the range from 1146° to 2075° F. In Fig. 3 the NRL results have been arbitrarily taken as standard, and the percent deviation of the vapor pressure of each investigator from that of NRL is plotted as a function of temperature. It will be noted that the vapor pressures observed by Makansi are in excellent agreement and those by Bowles and Rosenblum in good agreement with the NRL data. The data by Sowa exhibit a positive deviation at higher temperatures which apparently is outside the range of combined experimental errors. Kirilov and Grachev have reported results for both potassium (9) and sodium (7), and the data for each metal deviate widely from all published work.

As an independent check on the internal consistency of the vapor-pressure measurements, the heat of vaporization to the monomer at absolute zero was computed for each observed saturation point with the relationship

$$\begin{aligned}
 (\Delta h_0^0) = & -\frac{RT}{M_1} \left[ \frac{2B}{\tilde{V}} + \frac{3C}{2\tilde{V}^2} + \frac{4D}{3\tilde{V}^3} + \ln p - \ln \frac{p\tilde{V}}{RT} \right] \\
 & + 2.20399T - 0.399185T \log T + 0.552615 \times 10^{-4} T^2 \\
 & - 0.056682 \times 10^{-7} T^3 - 12.172 e^{-43,830/T} - 29.023.
 \end{aligned} \tag{4}$$

This working equation was derived from the third law as described for potassium (1a). The computed vaporization heats (converted to cgs units) are plotted as a function of temperature in Fig. 4. Theoretically, the same value of  $(\Delta h_0^0)_v$  should be obtained for all the saturation points, and there is reasonable constancy. The small temperature trend of  $(\Delta h_0^0)_v$  can result from errors in the vapor pressure, the virial coefficients, or in any of the free-energy functions employed in the computations. The free-energy functions of the liquid appear to be the least reliable quantities. These functions are known precisely

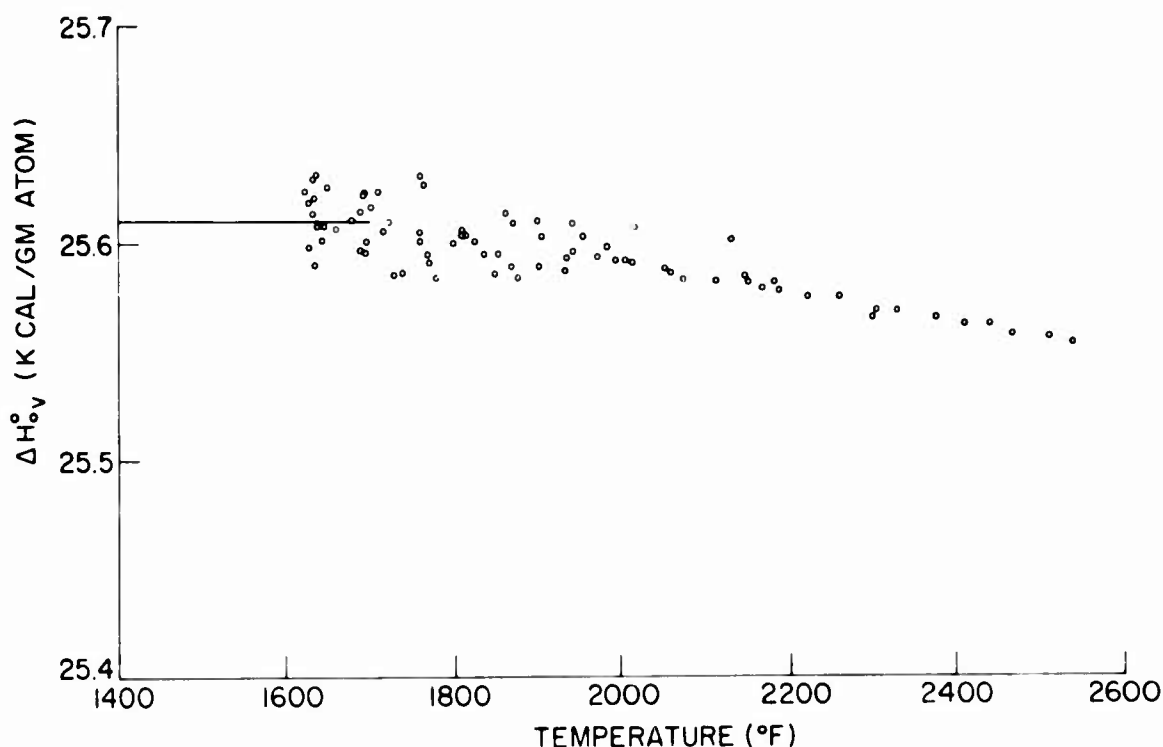


Fig. 4 - Heat of vaporization of monomeric sodium at absolute zero as computed from observed vapor-pressure data

only to 1650°F and above this temperature must be obtained by an extrapolation of the liquid specific-heat results of Ginnings (see "Specific Heat" section). This extrapolation was roughly justified to 2100°F by a few specific-heat measurements made at this Laboratory, but it is believed that the true vaporization heat (25.61 kcal/mole) may be obtained from saturation data below 1700°F and that the temperature trend above this point results from error in extrapolating the specific heat of the liquid.

**Discussion of Saturation Pressures** - The measurement of saturation pressures directly with a diaphragm detector is new to the high-temperature field. The relative merits of the apparatus and the uncertainties to be expected in the various measurement parameters are discussed in the potassium report (1a). If we take into account all known sources of error in the saturation measurements, the percent probable error in the pressure ranges from  $\pm 0.64\%$  at 1 atm to a maximum of  $\pm 0.80\%$  at 23 atm.

Makansi (8) has measured vapor pressures of a number of the alkali metals including sodium and potassium by the boiling-point method. The NRL results for both potassium and sodium by a static method are in close agreement with the corresponding results of Makansi. This fact tends to increase the degree of confidence which can be placed in the observed saturation pressures for both metals.

#### Density Measurements of Liquid Sodium

The density\* of liquid sodium was determined with columbium-1% zirconium pycnometers of 30 cc nominal volume by the method described for potassium (1a). Measured densities over the temperature range from 1577° to 2491°F are reported in Table 5 and presented graphically along with those of other investigators in Fig. 5. The recommended

\*Preliminary values and equations for the density of sodium (29) were based on incorrect values for the thermal expansion of columbium-1% zirconium.

Table 5  
Density of Liquid Sodium  
at High Temperatures

Temperature (° F)	Density (lb/cu ft)
1576.8	46.738
1886.2	43.926
2093.5	42.224
2268.9	40.641
2491.2	38.933

density equation for liquid sodium from the melting point to 2500° F is

$$d^l = 59.566 - 7.9504 \times 10^{-3} t - 0.2872 \times 10^{-6} t^2 + 0.06035 \times 10^{-9} t^3. \quad (5)$$

This equation was derived by fitting the best curve to the density determinations of Hagen (10) and NRL (11) at lower temperatures, Novikov et al. (12), Jackson et al. (13), Rinck (14), and Nishibayashi (15) at moderate temperatures, and NRL (Table 5) at higher temperatures. All these measurements are summarized in Table 6. For each investigation, the temperature range, the general method, and the average deviation from Eq. (5) are presented. In general, the dilatometric measurements show good internal consistency over the full temperature range, and it is believed that Eq. (5) will give density values which are accurate to  $\pm 0.3\%$  between the melting point and 1100° F and to  $\pm 0.4\%$  between 1100° and 2500° F.

Table 6  
Summary of Density Measurements for Liquid Sodium

Investigator	Method	Temp. Range (° F)	% Average Deviation [Obs. - Calc. (Eq. (5))] Calc.
NRL (11)	Dilatometric	mp to 503	$\pm 0.08$
Jackson (13)	Buoyancy	937 to 1314	-0.74
Rinck (14)	Buoyancy	804 to 1183	+0.15
Hagen (10)	Dilatometric	mp to 336	$\pm 0.05$
NRL (Table 5)	Dilatometric (Pycnometers)	1577 to 2491	$\pm 0.17$
Novikov (A)*	Buoyancy	248 to 505	-0.14
(12) (B)†	Buoyancy	275 to 1324	+0.71
Nishibayashi (15)	Buoyancy	486 to 1580	$\pm 1.09$

\*(A) with steel sinker.

†(B) with tungsten sinker.

The uncertainties to be expected in the various parameters of the NRL density measurements were discussed in the potassium report (1a). If all known uncertainties are taken into account, the percent probable error of the reported densities range from  $\pm 0.25$  to  $\pm 0.30\%$ .

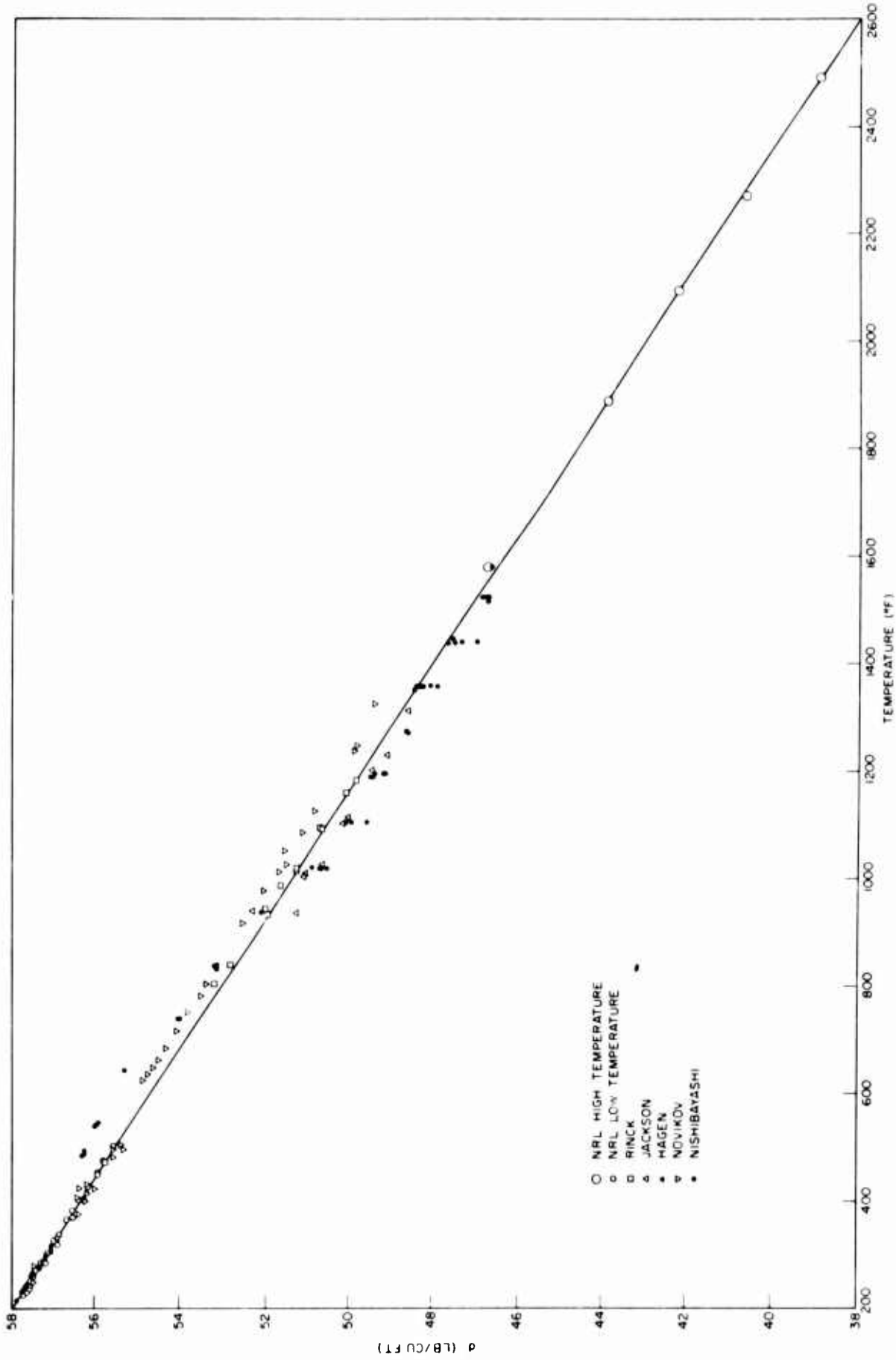


Fig. 5 - Density of liquid sodium

## Specific-Heat Measurements of Liquid Sodium

Specific heats of saturated liquid sodium were determined from 212° to 2140° F. A bucket containing the alkali metal was equilibrated at a known temperature in a specially designed furnace and dropped into a copper-block calorimeter, permitting a measurement of the heat evolved in cooling the sample to 30°C. This procedure was repeated at a number of furnace temperatures for both filled and empty buckets, and the heat capacities of the sample were derived by standard calorimetric procedures. The specific-heat system and the methods employed have been described in detail by Walker et al. (17).

The heat capacities of sodium and of sapphire, a calorimetric standard, are presented in Tables 7 and 8. The observed values for each material are compared to corresponding values obtained at the National Bureau of Standards (18). Comparison results for sodium above 1650° F, the limit of the NBS measurements, represent an extrapolation using the NBS specific-heat equation. Although the deviations for each material are generally below ±3%, they are higher than those obtained in previous measurements with the same calorimetric system. The major portion of this error stems from a large random uncertainty observed in duplicate measurements. During the potassium study (1a), the method and the calorimetric system were completely re-examined for possible sources of error, but no significant source was discovered. It is now believed that the reduced measurement precision resulted from the relatively low sample-to-container heat-content ratio (1:3) which tended to magnify nominal system errors. It was necessary to use the thick-walled Inconel container, with its accompanying unfavorable heat-content ratio, in order to withstand the pressure of potassium vapor at operating temperature.

Table 7  
Specific Heat of Saturated Liquid Sodium (High-Temperature System)

Temp (°F)	NRL $c_p$ (Btu/lb-°F)	NBS $c_p$ (Btu/lb-°F)	Percent Deviation $\left( \frac{\text{NRL } c_p - \text{NBS } c_p}{\text{NBS } c_p} \right)$
1111.1	0.301	0.300	+0.3
1335.0	0.291	0.301	-3.3
1519.5	0.297	0.304	-2.3
1688.9	0.313	0.309*	+1.3
1848.0	0.324	0.316*	+2.5
2029.3	0.325	0.326*	0.0
			Mean ±1.6

\*Extrapolated with NBS equation.

Specific heats of sodium at intermediate temperatures were measured at NRL several years ago but were not published. These results are now reported in Table 9 and compared with corresponding NBS values. The mean deviation of the data is only ±0.5%, because the measurements were made under more favorable conditions using an iron bucket with a sample-to-container heat-content ratio of 2:1.

The specific-heat results at both high and intermediate temperatures are presented graphically in Fig. 6 and are compared to the existing data and curve of Ginnings, Douglas, and Ball (18). The intermediate temperature results of NRL are in good agreement with those of NBS. The dashed curve above 1650° F represents a temperature extension of Ginnings' data using his specific-heat equation. Although the higher temperature NRL

Table 8  
Specific Heat of Sapphire (High-Temperature System)

Temp (°F)	NRL $c_p$ (Btu/lb-°F)	NBS $c_p$ (Btu/lb-°F)	Percent Deviation $\left(\frac{\text{NRL } c_p - \text{NBS } c_p}{\text{NBS } c_p}\right)$
533.8	0.246	0.250	-1.6
1197.5	0.279	0.286	-2.4
1334.1	0.285	0.292	-2.4
1516.3	0.292	0.296	-1.4
1682.8	0.292	0.298*	-2.2
1848.9	0.304	0.301*	+1.2
2034.3	0.303	0.303*	0.0
			Mean ±1.6

\*Extrapolated with NBS equation.

Table 9  
Specific Heat of Saturated Liquid Sodium (Low-Temperature System)

Temp (°F)	NRL $c_p$ (Btu/lb-°F)	NBS $c_p$ (Btu/lb-°F)	Percent Deviation $\left(\frac{\text{NRL } c_p - \text{NBS } c_p}{\text{NBS } c_p}\right)$
311.4	0.325	0.325	0.0
491.5	0.315	0.315	0.0
665.6	0.312	0.308	+1.3
841.5	0.304	0.303	+0.3
1031.5	0.297	0.300	-1.2
1206.7	0.300	0.300	0.0
			Mean ±0.5

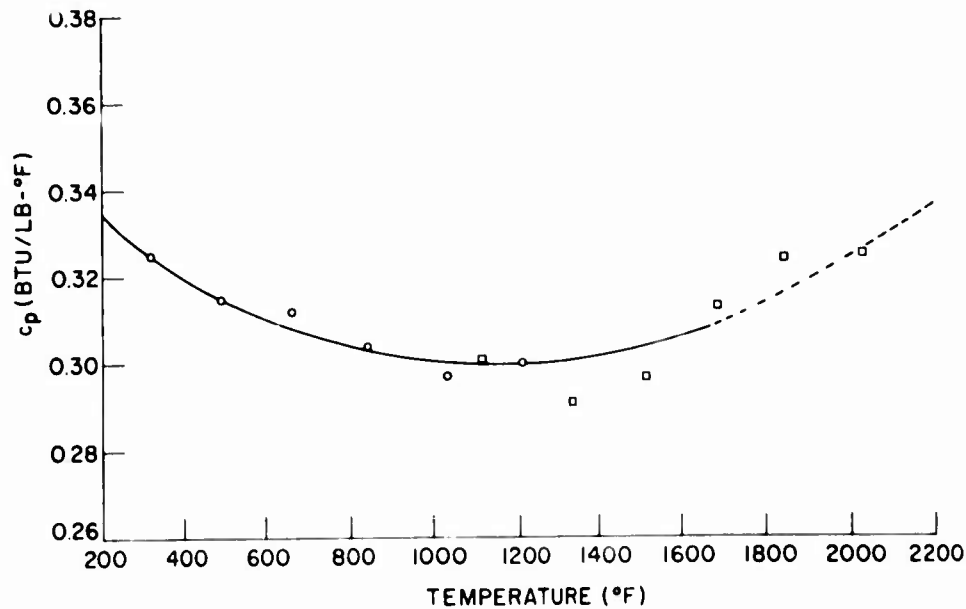


Fig. 6 - Specific heat of liquid sodium  
 ● NRL (low-temperature system)    ■ NRL (high-temperature system)

results tend to verify an extension of the NBS equation to 2200° F, the true specific-heat curve for the liquid above 1650° F is in question.

### SUMMARY OF FUNDAMENTAL PROPERTIES USED IN THE THERMODYNAMIC TREATMENTS

#### Density of Liquid Sodium

Densities of the condensed phase were obtained from Eq. (5), which was derived from the observed data of this Laboratory and of other investigators.

#### Enthalpy and Entropy of Monomeric Sodium Vapor

Equations for absolute enthalpy and entropy of monomeric vapor as functions of temperature were derived from the work of Evans et al. (19) and are based on their standard enthalpies and entropies for the monomeric gas over the temperature range from 0° to 2800° F and on the enthalpy of vaporization at 0° R (26.10 mean kcal/mole) as obtained from the vapor-pressure data of this Laboratory. The equations for the monomeric gas at 1 atm (relative to the solid at 0° R) are

$$(h^g)^o = 2005.15 + 0.21598 T + 12,172 e^{-43,830/T} \quad (6)$$

$$(s^g)^o = 0.23859 + 0.21598 \ln T. \quad (7)$$

#### Specific Heat at Constant Pressure of Monomeric Sodium Vapor

The temperature equation for the specific heat of monomeric vapor at constant pressure was also derived from the work of Evans et al. (19) and is based on their computed specific heats over the temperature range from 0° to 3300° F. The relation for the monomeric gas at 1 atm is

$$(c_p^g)^o = 0.21598 + 6.053 e^{-37,280/T}. \quad (8)$$

#### Enthalpy and Entropy of Liquid Sodium

The thermodynamic properties presented in this report are based on the properties of the monomeric gas at 1 atm, but comparison calculations were made using the properties of the saturated liquid as a starting point. The absolute properties of the liquid (relative to the solid at 0° R) were computed with

$$h_s^l = 0.389352 T - 0.552955 \times 10^{-4} T^2 + 0.113726 \times 10^{-7} T^3 - 29.023 \quad (9)$$

$$s_s^l = 0.896497 \log T - 1.10557 \times 10^{-4} T + 0.170408 \times 10^{-7} T^2 - 1.792026. \quad (10)$$

These equations were derived directly from the work of Ginnings et al. (18) and are based on their specific-heat equations for the solid and liquid over the temperature range 32° to 1650° F. The absolute enthalpy and entropy of solid sodium at 32° F were taken from the work of Evans et al. (19). The specific heat of liquid sodium was also measured

at this Laboratory (see "Specific Heat" section) for the temperature range from 600° to 2150° F. The NRL results overlap and extend the NBS range with an average deviation from their equation of only  $\pm 1.5\%$ . Therefore, the upper measured limit of Eqs. (9) and (10) is extended to 2150° F, but thermodynamic calculations to 2575° F with the liquid base still require a 400° F extrapolation of the specific-heat data.

### Saturation Pressure of Liquid Sodium

Three vapor-pressure equations were derived from least-squares correlations, but Eq. (1) was selected to compute other thermodynamic quantities in this report.

### Enthalpy and Entropy of Vaporization of Sodium

Heats of vaporization were calculated with

$$\Delta h_v = Jp_s \left[ \frac{22,982}{T} - 0.61344 \right] (v_s^g - v_s^l) \quad (11)$$

which was derived by a differentiation of Eq. (1) and a substitution into the Clapeyron equation. A value of  $v_s^l$  at each temperature was obtained from Eq. (5) and a value of  $v_s^g$  from the virial equation of state (Eq. (14)).

The entropy of vaporization at each saturation point was obtained by dividing the appropriate enthalpy change by the absolute temperature as shown in

$$\Delta s_v = \frac{\Delta h_v}{T} \quad (12)$$

### THERMODYNAMIC TREATMENT OF PVT AND ASSOCIATED PROPERTIES

The imperfections which occur in the alkali metal vapors and the various treatments of these imperfections in the reduction of PVT data are discussed at some length in the potassium report (1a). A quasi-chemical analysis of the PVT data presented later in this report tends to identify the dimeric and tetrameric species, and it is believed that the major imperfection in sodium vapor stems from the existence of these higher-molecular-weight species. The species are present in sufficient abundance to require consideration of their presence in the determination of the thermodynamic properties of the vapor.

The important properties (enthalpy, entropy, and specific heat) may be reduced from the PVT data by the use of either of two methods, the virial or the quasi-chemical. In the first, the gas is treated as a monatomic assembly with all apparent imperfections given by a virial equation of state, and the thermodynamic quantities are obtained as corrections to those of the monatomic gas in terms of the virial coefficients. In the second method, equilibrium constants are derived for the mobile equilibria by treating the gas as a mixture of molecular species, and other thermodynamic quantities are derived from the enthalpy changes associated with changes in the molecular composition of the vapor. For the latter method, it is assumed that all species behave as perfect gases.

The virial equation of state with coefficients through the fourth virial was reduced from the raw PVT data and used to compute enthalpies, entropies, specific volumes, and specific heats for the vapor states of sodium. The alternative equation of state consisting of the perfect gas equation and the equilibrium constants of the association reactions was

used as a check to compute the same engineering properties and, in addition, to compute the molecular composition for saturated and superheated vapor states. Since both of these methods were used in preliminary analyses of the compressibility data, the application of each method to the sodium data will be described in some detail later in this report.

The thermodynamic properties of sodium by both the virial method and the quasi-chemical method were computed along constant temperature lines. The starting point for a particular property could have been the absolute value of that property for either the saturated liquid or for the monomeric gas at 1 atm. Therefore, two computational paths exist for obtaining each absolute property in the superheat region. The engineering properties were computed along both paths by the virial method, and the results are compared in this report.

### Virial Coefficients of Sodium

The virial equation of state in the volume expansion form

$$\frac{p\tilde{V}}{RT} = 1 + \frac{B}{\tilde{V}} + \frac{C}{\tilde{V}^2} + \frac{D}{\tilde{V}^3} + \dots \quad (13)$$

was used for the analyses of all three alkali metal systems. The virial coefficients for sodium in this equation were reduced from the PVT data by the method described for potassium (1a). The coefficients are temperature dependent and were derived graphically by plotting functions along constant temperature lines. The small experimental errors in the PVT data were again largely systematic, which permitted the use of the adjustment procedure (1a) to derive a more precise temperature coefficient for each virial.

The adjustment procedure required the selection of a reference isotherm with the maximum pressure range of compressibility factors in order to obtain the maximum definition of the virial coefficient. Accordingly, a reference temperature of 2525° F was selected. The compressibility factor  $z$  at this temperature was plotted as a function  $1/\tilde{V}$  (Fig. 7), and the second virial coefficient  $B$  was obtained as the  $\lim dz/d(1/\tilde{V})$  as  $1/\tilde{V} \rightarrow 0$ . Also,  $(z-1)\tilde{V}$  was plotted as a function of  $1/\tilde{V}$  and  $B$  was obtained as the  $\lim (z-1)\tilde{V}$  as  $1/\tilde{V} \rightarrow 0$ . The value of  $B$  by either procedure appeared to lie between 22 and 26, but 24.3 was selected, since this gave the best internal consistency between the low- and high-pressure results as determined from a plot of  $[(z-1)\tilde{V} - B]\tilde{V}$  versus  $1/\tilde{V}$ . From this final plot of the quantity  $[(z-1)\tilde{V} - B]\tilde{V}$  versus  $1/\tilde{V}$ , the adjustment factors were computed from the best linear curve drawn through the data (Fig. 8).

Assuming all errors to be systematic, the compressibility factors for each of the nine experiments were adjusted at all temperatures by the factors obtained at 2525° F. Using these adjusted compressibility factors, which are identified by  $z^*$  in all quantities,  $(z^*-1)\tilde{V}$  was plotted as a function of  $1/\tilde{V}$  for isotherms at 50-degree intervals between 2175° and 2575° F, and second virial coefficients were obtained from these plots. Third and fourth virial coefficients were obtained by plotting the quantity  $[(z^*-1)\tilde{V} - B]\tilde{V}$  versus  $1/\tilde{V}$  for isotherms at 50-degree intervals between 2175° and 2575° F. Additional second virial coefficients in the lower temperature range from 1775° to 2125° F were obtained by computing the average value of  $[(z-1)\tilde{V} - C/\tilde{V} - D/\tilde{V}^2]$  for the lower pressure experiments on each isotherm. The values of  $C$  and  $D$  required for these calculations were obtained by extrapolating their temperature equations. Virial coefficients are functions of equilibrium constants (1a), and each coefficient can be represented for the full measured temperature range by a simple exponential relationship in  $1/T$  (Eq. (14)).

Experimental PVT data were also obtained from 2175° to 1775° F, but the number of experimental points in this region did not permit one to obtain reliable virial coefficients

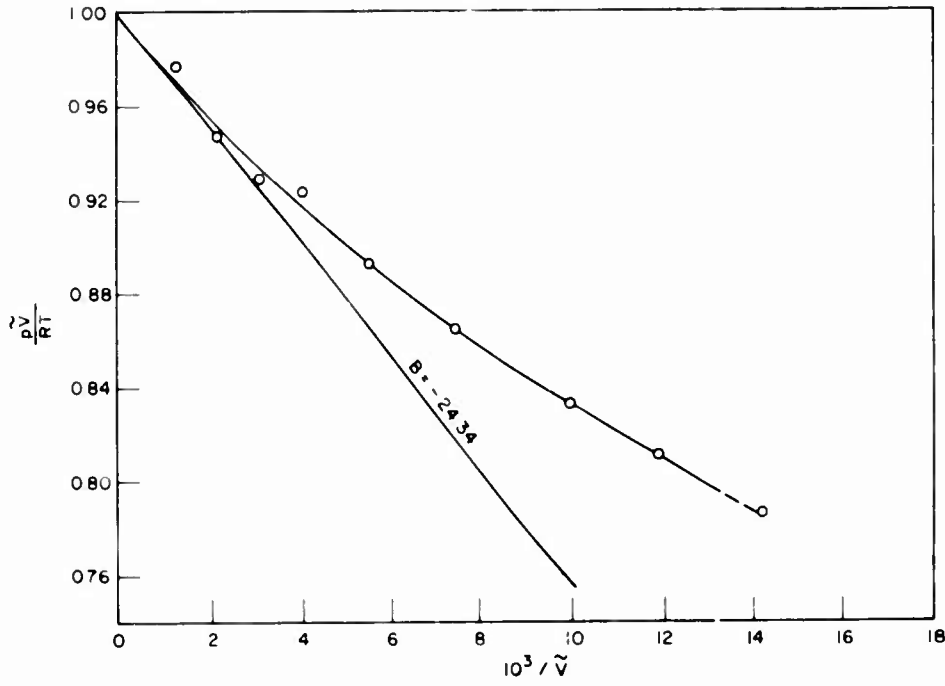


Fig. 7 - Plot of  $p\tilde{V}/RT$  versus  $1/\tilde{V}$  for sodium at  $2525^\circ\text{F}$

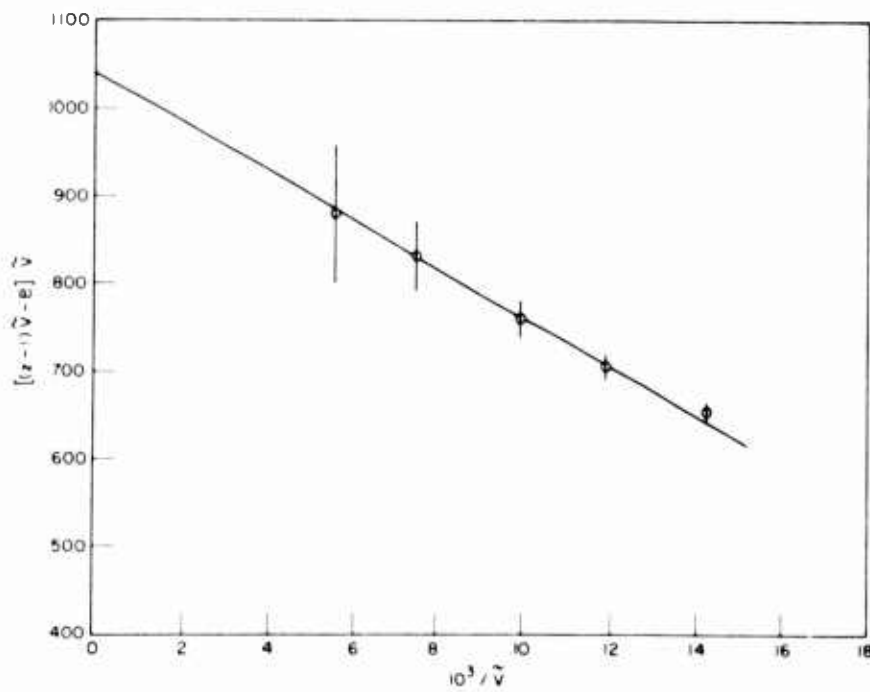


Fig. 8 - Plot of  $[(z-1)\tilde{V} - B]\tilde{V}$  versus  $1/\tilde{V}$  for sodium at  $2525^\circ\text{F}$  (vertical line for each point represents probable error)

by the graphical method. Consequently, before the virial equation of state for sodium was acceptable for calculations below 2175° F, it was necessary to determine its fit to the observed lower temperature data. At temperatures and pressures corresponding to the observed low-temperature points, compressibility factors were calculated and compared to the observed values. The fit of the virial equation of state to the lower temperature data was found to be practically equivalent to that obtained at higher temperatures.

It should be emphasized that the procedure of adjusting the data (in no case did an adjustment factor exceed 0.7% of  $z$ ) was used only as an expedient in obtaining more precise temperature coefficients for the virials. Equally valid virial and temperature coefficients could have been obtained more laboriously from unadjusted data.

### The Virial Equation of State of Sodium

The virial equation of state of sodium\* with coefficients through the fourth virial is

$$\frac{p\bar{V}}{RT} = 1 + \frac{B}{\bar{V}} + \frac{C}{\bar{V}^2} + \frac{D}{\bar{V}^3} \quad (14)$$

where

$$\log |B| = -4.3519 + \frac{6755.3}{T} + \log T$$

$$B < 0$$

$$\log C = -0.6137 + \frac{10,839}{T}$$

$$C > 0$$

$$\log |D| = -0.0000 + \frac{13,539}{T}$$

$$D < 0$$

The fit of the virial equation to measured data is shown graphically in Fig. 9, where compressibility isotherms generated with Eq. (14) are compared to experimental compressibilities at 100-degree intervals from 1775° to 2575° F. The observed specific-volume data in Table 2, or compressibility factors derived from that data, may be calculated from the virial equation with an average deviation of  $\pm 0.26\%$ . As in the case of the potassium data (1a), this deviation is of a magnitude predicted by random and systematic errors in the null-point measurements.

### Thermodynamic Properties of Sodium by the Virial Method (Monomeric Gas Path)

Expressions for the thermodynamic properties (monomeric gas path) in terms of the second and third virial coefficients were derived by Hirschfelder et al. (20). By the same method, another set of equations was derived and extended to include the fourth virial

\*The preliminary virial equation for sodium (29) was based on incorrect values for the thermal expansion of columbium-1% zirconium.

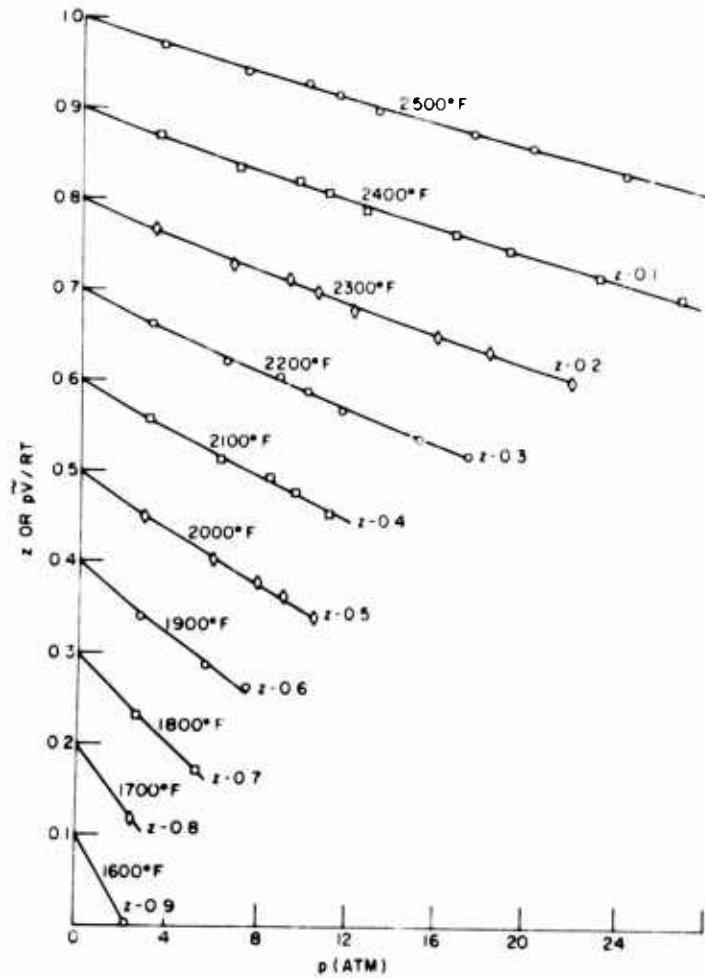


Fig. 9 - Compressibility of sodium vapor at several temperatures

coefficient. These equations were used to compute the thermodynamic properties of sodium vapor (Appendixes A and B) and are presented in this section.

Enthalpy, Entropy, and Specific Heat of Saturated and Superheated Vapor – These properties at all vapor states were computed along isotherms using the following equations:

$$h_i^g = (h^g)^o + \frac{RT}{M_1} \left\{ \frac{1}{\tilde{V}} \left[ B - T \left( \frac{dB}{dT} \right) \right] + \frac{1}{\tilde{V}^2} \left[ C - \frac{T}{2} \left( \frac{dC}{dT} \right) \right] + \frac{1}{\tilde{V}^3} \left[ D - \frac{T}{3} \left( \frac{dD}{dT} \right) \right] \right\} \quad (15)$$

$$s_i^g = (s^g)^o - \frac{R}{M_1} \left[ \ln p - \ln \frac{p\tilde{V}}{RT} + \frac{B}{\tilde{V}} + \frac{T}{\tilde{V}} \left( \frac{dB}{dT} \right) + \frac{C}{2\tilde{V}^2} + \frac{T}{2\tilde{V}^2} \left( \frac{dC}{dT} \right) + \frac{D}{3\tilde{V}^3} + \frac{T}{3\tilde{V}^3} \left( \frac{dD}{dT} \right) \right] \quad (16)$$

$$\left( c_p^g \right)_i = \left( c_p^g \right)^o - \frac{R}{M_1} + \frac{R}{M_1} \left\{ \frac{\left[ 1 + \frac{1}{\tilde{V}} \left( B + T \frac{dB}{dT} \right) + \frac{1}{\tilde{V}^2} \left( C + T \frac{dC}{dT} \right) + \frac{1}{\tilde{V}^3} \left( D + T \frac{dD}{dT} \right) \right]^2}{1 + 2 \frac{B}{\tilde{V}} + 3 \frac{C}{\tilde{V}^2} + 4 \frac{D}{\tilde{V}^3}} \right\}$$

$$- \frac{RT}{\tilde{V}M_1} \left[ \left( T \frac{d^2B}{dT^2} + 2 \frac{dB}{dT} \right) + \frac{1}{2\tilde{V}} \left( T \frac{d^2C}{dT^2} + 2 \frac{dC}{dT} \right) + \frac{1}{3\tilde{V}^2} \left( T \frac{d^2D}{dT^2} + 2 \frac{dD}{dT} \right) \right] \quad (17)$$

Specific Volume of Saturated and Superheated Vapor – This property at all vapor states (Appendixes A and B) was computed from the virial equation of state (Eq. (14)) by a trial and error solution.

Enthalpy and Entropy of the Condensed Phase – These properties of the saturated liquid (Appendix A) at each temperature were obtained by subtracting the enthalpy or entropy of vaporization from the corresponding properties of the saturated vapor.

#### Thermodynamic Properties of Sodium by the Virial Method (Liquid Path)

Expressions for the thermodynamic quantities with the properties of the condensed liquid as a base were derived directly from those in the preceding section. These new equations together with a procedural outline of the methods of calculation are presented below.

Enthalpy, Entropy, and Specific Heat of the Saturated Vapor – The enthalpy and entropy of the saturated vapor at a given temperature were obtained by adding the enthalpy or entropy of vaporization to the corresponding properties of the saturated liquid. The specific heat at saturation was obtained by numerically evaluating at 50-degree intervals the differential

$$(c_p^g)_s = \left[ \left( \frac{\partial h^g}{\partial T} \right)_p \right]_s = \left[ \left( \frac{\partial h^g}{\partial T} \right)_p \right]_s \quad (18)$$

Enthalpy, Entropy, and Specific Heat of Superheated Vapor – These properties in the superheat region were computed along constant temperature lines with each saturated state as a starting point. The general equations in virial form are

$$h_i^g = h_s^g + \frac{RT}{M_1} \left\{ \frac{1}{\tilde{V}} \left[ B + T \left( \frac{dB}{dT} \right) \right] + \frac{1}{\tilde{V}^2} \left[ C + T \left( \frac{dC}{dT} \right) \right] + \frac{1}{\tilde{V}^3} \left[ D + T \left( \frac{dD}{dT} \right) \right] \right\}_{\tilde{V}_i}^{\tilde{V}_s} \quad (19)$$

$$s_i^g = s_s^g + \frac{R}{M_1} \left[ \ln p - \ln \frac{p \tilde{V}}{RT} + \frac{B}{\tilde{V}} + \frac{T}{\tilde{V}} \left( \frac{dB}{dT} \right) + \frac{C}{2\tilde{V}^2} + \frac{T}{2\tilde{V}^2} \left( \frac{dC}{dT} \right) + \frac{D}{3\tilde{V}^3} + \frac{T}{3\tilde{V}^3} \left( \frac{dD}{dT} \right) \right]_{\tilde{V}_i}^{\tilde{V}_s} \quad (20)$$

$$(c_p^g)_i = (c_p^g)_s + \frac{R}{M_1} \left\{ \frac{\left[ 1 + \frac{1}{\tilde{V}} \left( B + T \frac{dB}{dT} \right) + \frac{1}{\tilde{V}^2} \left( C + T \frac{dC}{dT} \right) + \frac{1}{\tilde{V}^3} \left( D + T \frac{dD}{dT} \right) \right]^2}{\left( 1 + 2 \frac{B}{\tilde{V}} + 3 \frac{C}{\tilde{V}^2} + 4 \frac{D}{\tilde{V}^3} \right)} \right\}_{\tilde{V}_i}^{\tilde{V}_s} \\ + \frac{RT}{\tilde{V} M_1} \left[ T \frac{d^2 B}{dT^2} + 2 \frac{dB}{dT} \right] + \frac{1}{2\tilde{V}^2} \left[ T \frac{d^2 C}{dT^2} + 2 \frac{dC}{dT} \right] + \frac{1}{3\tilde{V}^3} \left[ T \frac{d^2 D}{dT^2} + 2 \frac{dD}{dT} \right]_{\tilde{V}_i}^{\tilde{V}_s} \quad (21)$$

Table 10  
Comparison of Monomeric Gas and Liquid Path Calculations  
(Virial Method)

Temp. (°F)	Pressure (atm)	Monomeric Gas Path			Liquid Path		
		$h^g$	$s^g$	$c_p^g$	$h^l$	$s^l$	$c_p^l$
1625	1.0	2322.2	1.8342	0.658	2334.8	1.8400	0.640
	0.2	2427.2	2.0165	0.316	2439.8	2.0223	0.298
1800	2.0	2347.9	1.7922	0.609	2357.9	1.7968	0.599
	1.0	2416.3	1.8776	0.442	2426.3	1.8822	0.432
	0.2	2477.3	2.0397	0.264	2487.4	2.0443	0.254
2000	5.0	2345.0	1.7216	0.591	2353.6	1.7257	0.586
	1.0	2491.8	1.9097	0.328	2500.4	1.9138	0.323
	0.2	2527.3	2.0609	0.239	2535.9	2.0649	0.234
2200	9.0	2372.8	1.6892	0.539	2380.2	1.6929	0.530
	5.0	2450.8	1.7631	0.467	2458.2	1.7668	0.458
	1.0	2551.7	1.9331	0.277	2559.1	1.9368	0.267
	0.2	2573.9	2.0791	0.228	2581.4	2.0828	0.219
2500	20.0	2399.9	1.6416	0.512	2400.4	1.6431	0.466
	15.0	2448.3	1.6786	0.482	2448.8	1.6802	0.436
	10.0	2504.2	1.7282	0.431	2504.7	1.7297	0.385
	5.0	2569.8	1.8056	0.341	2570.3	1.8071	0.295
	1.0	2628.9	1.9606	0.243	2629.3	1.9622	0.197
	0.2	2641.3	2.1031	0.222	2641.7	2.1046	0.176

#### A Comparison of the Monomeric Gas Path and the Liquid Path for Thermodynamic Calculations

The thermodynamic properties of sodium were computed along constant temperature lines. The starting point for a particular property could have been the absolute value of that property for either the saturated liquid or for the monomeric gas at 1 atm. As an example of using the liquid property as a base, the enthalpy of the saturated vapor at a given temperature is obtained by adding the enthalpy of vaporization to the corresponding absolute enthalpy of the saturated liquid, and the enthalpy at any state in the superheat region is obtained by adding the enthalpy change in the superheat region to the enthalpy of the saturated vapor. For the monomeric gas base, the enthalpy of the vapor at saturation or at any other pressure is obtained by adding the enthalpy change to the corresponding absolute value of the ideal gas at 1 atm. The enthalpy of the saturated liquid is then obtained by subtracting the enthalpy of vaporization from that of the saturated vapor.

Three properties (enthalpy, entropy, and specific heat)\* of sodium vapor were computed by both paths at selected states in the superheat region (Table 10) covering the temperature range of the measured data. The properties of the liquid for the full temperature range were obtained from Eqs. (9) and (10), which are based on the specific-heat measurements of Ginnings et al. (18) and NRL and on the absolute properties of solid

\*Preliminary properties as computed by the monomeric gas path (29) were based on incorrect values for the thermal expansion of columbium-1% zirconium. They differ significantly in some cases from the final values in this report.

sodium at 32° F from the work of Evans et al. (19). The base properties of the monomeric gas were computed from Eqs. (6), (7), and (8), which were derived directly from the monomeric gas properties of Evans (19).

In order for the comparison of the two computational paths to be more meaningful, several points should be considered. The virial equation of state, common to both paths, was reduced from PVT data covering a pressure range of 1.86 to 25.1 atm and a temperature range of 1758° to 2588° F. The PVT data, therefore, effectively cover the full temperature and pressure ranges of the properties reported in Appendix B, and only a short extrapolation of the equation is required at pressure states below 1.86 atm. Even so, small errors in the specific volume of the vapor, resulting from an extension of the virial equation or from slight inconsistencies in the virial or in the saturated vapor-pressure equations, will be reflected strongly in the properties computed along the liquid path, since these properties are dependent upon vaporization quantities. Properties computed along the liquid path at higher temperatures are also influenced by any error due to the required extrapolation of the liquid specific heat above its measured limit, 2150° F. Properties computed along the monomeric gas path are independent of both the liquid specific-heat measurements and the vaporization quantities.

The best comparison of the properties by the two computational paths can be made at temperatures below 2200° F, since this approximately represents the measured limit of the liquid specific heat. In the temperature range from 1625° to 2200° F, absolute enthalpies in the superheat region, based on the properties of the saturated liquid, were 8 to 12 Btu/lb (approximately 0.3 to 0.5%) higher than corresponding values based on the monomeric gas properties. Likewise, entropies by the liquid path were .004 to .006 Btu/lb-° F (approximately 0.2 to 0.3%) higher, and specific heats were 1 to 6% lower than those by the other path.

The relatively constant difference between the absolute property values as computed by the two paths over the temperature range from 1625° to 2200° F implies error in base properties along one or both of the two paths. There are, of course, sources of error along both the liquid and the monomeric gas paths. The properties by the gas path are dependent on the value selected for the heat of vaporization of solid sodium at 0° R ( $\Delta H_0^s$ ), and on the statistical mechanical calculations for the monomer. The value of this heat of vaporization is generally derived from vapor-pressure data. From a third-law analysis of the vapor-pressure data of this Laboratory using the virial equation of state (see section entitled "Experimental Saturation Pressures"), a value of 25.61 kcal/mole was obtained, and this was used for all the thermodynamic calculations in this report. Evans et al. (19) analyzed the vapor-pressure measurements existing at that time and selected a value of 25.908 kcal/mole. If this latter value had been used for the monomeric gas calculations, the magnitudes of the absolute enthalpies by the two paths would be reversed from that shown in Table 10. It is interesting to note that an intermediate value of approximately 25.76 would bring the enthalpies by the two paths into close agreement.

In Table 10 it will be noted that the enthalpy of the superheated vapor at any given pressure, if computed from the liquid base, exhibits an abnormal decrease in slope beginning at 2200° F and becoming pronounced at 2500° F. This is reflected in the specific-heat values which at 2500° F are 9 to 21% lower than those computed by the monomeric gas path. Part of this apparent error in enthalpy as computed along the liquid path may have resulted from the extrapolation of the liquid specific heats above their measured range or to errors in other quantities along the two computational paths. It is believed that a part must also be attributed to errors in the enthalpies of vaporization resulting from small inconsistencies in the virial equation at higher pressures.

Engineering design calculations put prime emphasis on the change in enthalpy or entropy when moving from one state to another rather than on their absolute values; therefore, the choice of path is of minor importance for both these properties. However,

specific heat of the vapor would be expected to be more accurate if computed from the monomeric gas path, since this path is independent of vaporization quantities and does not require an extrapolation of the specific heat of the liquid above its measured range. Therefore, the monomeric gas path has been chosen for computation of all the tabular properties in this report.

### Molecular Reactions in Sodium Vapor and Their Equilibrium Constants

If it is assumed that all molecular species behave as perfect gases, the association of sodium vapor can be represented by a series of independent equilibria of the type



The equilibrium constants are defined by

$$k_n = \frac{V_n}{(V_1)^n p^{n-1}} \quad (23)$$

where  $n$  may be 2, 3, or 4 for the dimeric, trimeric, and tetrameric reactions, respectively.

The existence of the dimeric species has been verified spectroscopically (22), but the higher-molecular-weight species have not been identified. Before equilibrium constants could be reduced from the raw PVT data, an identification of the species higher than the dimer was required. The method employed with sodium was one which has been applied frequently to the study of association in hydrogen-bonded organics (21). The apparent equilibrium constant of dimerization  $k'_2$ , when all association is taken to be dimerization, can be expressed as a power series (21)

$$k'_2 = k_2 + 2k_3p + 3k_4p^2 + 2k_3^2p^3 - 2k_2k_4p^3 + \dots \quad (24)$$

in terms of the pressure and the true equilibrium constants of the association reactions. The apparent dimerization constants at a given temperature may be computed from the raw PVT data, and the relationship of the apparent constants to pressure may be used to predict the higher reactions present in the vapor and to compute their equilibrium constants.

Although the possibility of the coexistence of significant amounts of both trimer and tetramer was recognized, the existence of only one higher-molecular-weight species was believed to be more probable. If PVT data are of sufficiently high precision, a distinction between trimer and tetramer can be made with Eq. (24). If, in a vapor mixture, species of molecular weight higher than the trimer are not present, Eq. (24) (by setting  $k_4 = 0$ ) reduces to

$$k'_2 - 2k_3^2p^3 = k_2 + 2k_3p \quad (25)$$

Likewise, if the trimeric species is taken as insignificant, the same equation reduces to

$$k'_2 + 2k_2k_4p^3 = k_2 + 3k_4p^2 \quad (26)$$

When proper adjustments are made for the small  $p^3$  term in Eqs. (25) and (26), a linear relationship between  $(k'_2 - 2k_3^2 p^3)$  and  $p$  implies the existence of trimer, while a linear relationship between  $(k'_2 + 2k_2 k_4 p^3)$  and  $p^2$  implies the existence of tetramer. Accordingly, the fit of each relationship (Figs. 10 and 11) to the experimental PVT data for sodium at 2525° F was tested. The vertical line for each data point represents the probable error assigned to each equilibrium constant. It will be noted that the tetramer relationship (Eq. (26) and Fig. 11) provides the best fit to the experimental data. This was also true in a similar test made with the PVT data for potassium (1a). Therefore, the assumption that sodium vapor consists of monomeric, dimeric, and tetrameric species is based on evidence from the two alkali metal systems.

Equilibrium constants for the dimeric and tetrameric association reactions of sodium were reduced from the PVT data with Eq. (26) by the same method as that described in the potassium report (1a). The temperature of 2525° F was again chosen as a basis for the adjustment of the experimental data. At this temperature,  $k'_2$  was plotted versus  $(3p^2 - 2k_2 p^3)$  on successive graphical plots until a final curve was obtained for which the intercept was not significantly different from the  $k_2$  estimated from the previous plot. The factor required for each of the nine PVT experiments to correct the average molecular weight of the vapor for the apparent systematic error was computed from the deviation of  $k'_2$  from the best linear curve. The plot of  $k'_2$  versus  $(3p^2 - 2k_2 p^3)$  is not presented, since the equivalent plot of  $(k'_2 + 2k_2 k_4 p^3)$  versus  $p^2$  was presented as Fig. 11. Deviations of experimental points and the probable errors assigned to the points are not altered by the slightly different method of plotting the data.

Assuming all errors to be systematic, the apparent equilibrium constants of dimerization  $k'_2$  for each of the nine experiments were adjusted at all temperatures by the multiplying factor obtained at 2525° F. The adjusted values of  $k'_2$ , identified as  $(k'_2)^*$ , were plotted as a function of  $(3p^2 - 2k_2 p^3)$  for isotherms at 50-degree intervals between 2125° and 2575° F; and the thermodynamic constants for the dimeric and tetrameric reactions were obtained from these plots. The values of each equilibrium constant were effectively fitted for the full temperature range by a simple exponential relationship in  $1/T$ , and the resulting equations are presented in the next section.

A few experimental PVT points were obtained between 1775° and 2125° F. Since dimerization is still significant at these temperatures, the reliability of Eqs. (27) and (28) in this region had to be determined by testing the agreement of extrapolated and experimental points. Experimental values of  $k_2$  for each observed  $k'_2$  below 2125° F were computed with Eq. (26) (values of  $k_4$  were obtained from Eq. (28)) and these values were found to be in satisfactory agreement with those obtained by an extrapolation of Eq. (27).

It should again be recognized that the adjustment procedure was used only as a technique in the reduction of data. The average adjustment factor was  $\pm 0.31\%$  of  $M_n$ , and in no case did a factor exceed 0.8%.

Theoretically the equilibrium constants derived for the dimerization reaction should be independent of the assumptions made regarding imperfections in the vapor, since  $k_2$  for any type of imperfection is the  $\lim k'_2$  as  $p \rightarrow 0$ . For the sodium data this was not true. The intercept or  $k_2$  for each isotherm had to be defined in part by the higher pressure data, since data at pressures below 8 atm were too few and of too low precision. Therefore, the magnitude of the dimerization constant was affected to the extent of several percent by the assumptions regarding gas imperfections.

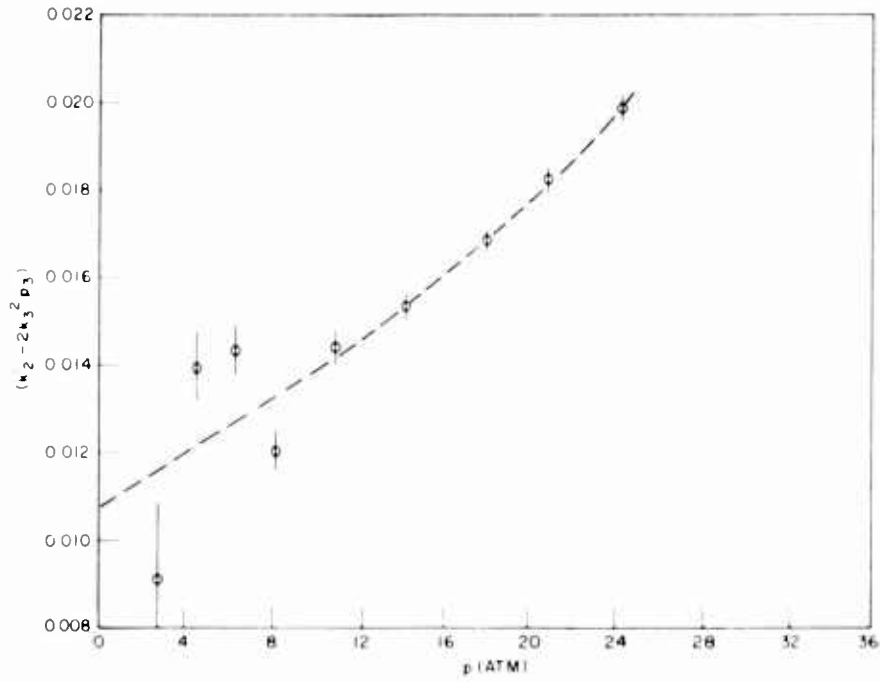


Fig. 10 - Plot of  $(k_2 - 2k_3 p)$  versus  $p$  for sodium at 2525°F (vertical line for each point represents probable error)

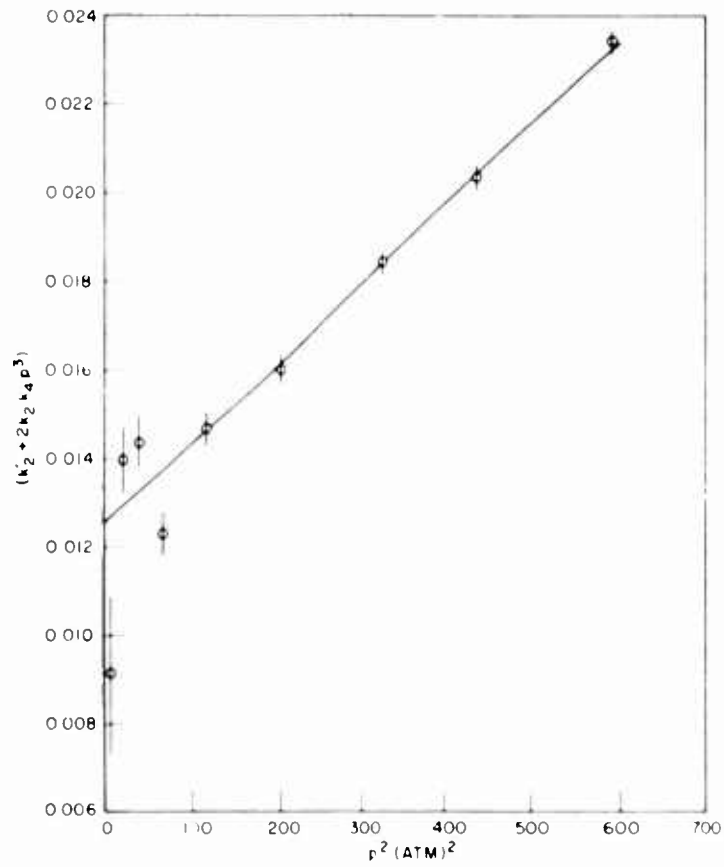


Fig. 11 - Plot of  $(k_2 + 2k_4 p^2)$  versus  $p^2$  for sodium at 2525°F (vertical line for each point represents probable error)

## The Quasi-Chemical Equation of State of Sodium

The second equation of state of sodium vapor consists of the three equations, \*

$$\log k_2 = -4.3249 + \frac{7204.2}{T} \quad (27)$$

$$\log k_4 = -10.6798 + \frac{16,325}{T} \quad (28)$$

$$p\hat{V} = \frac{M_1 R T}{M_d} \quad (29)$$

The observed specific volume data in Table 2, or the corresponding compressibility factors, may be computed from these three equations with an average deviation of  $\pm 0.26\%$ . This equation of state, therefore, is equivalent to the virial form and may also be used to compute other thermodynamic properties.

Compositional Properties of Sodium  
by the Quasi-Chemical Method

Enthalpies of the Dimeric and Tetrameric Reactions in Sodium Vapor - Enthalpies of the two reactions were obtained with the van't Hoff equation

$$\frac{d \ln k}{dT} = \frac{\Delta H^\circ}{RT^2} \quad (30)$$

by substituting the known differentials from Eqs. (27) and (28). The standard enthalpies so obtained are

$$2Na \rightleftharpoons Na_2, \Delta H_2^\circ = -32,948 \text{ Btu lb-mole or } -18.30 \text{ mean kcal/mole}$$

$$4Na \rightleftharpoons Na_4, \Delta H_4^\circ = -74,661 \text{ Btu lb-mole or } -41.48 \text{ mean kcal/mole}$$

Within the precision of the measurements, each reaction enthalpy was constant for the temperature range of the observed equilibrium constant.

The magnitude of the dimerization equilibrium constant has been shown to be dependent upon the choice of the higher-molecular-weight species. On the other hand, the temperature dependency of  $k_2$ , upon which the reaction enthalpy is based, is practically independent of this assumption; and a probable error of  $\pm 0.46$  kcal/mole has been assigned to  $\Delta H_2^\circ$ . The enthalpy of the tetrameric reaction can be influenced by the treatment of imperfections, unless it is assumed that all simple collisions leading to intermolecular attractions can be treated ideally as molecular association. In any event, no assignment of accuracy has been made for the enthalpy of this reaction.

The association enthalpy at absolute zero of the dimeric reaction was calculated by two methods. A value of  $-17.0$  kcal/mole was obtained at an average temperature of  $2250^\circ\text{F}$  with the equation

$$(\Delta H_0^\circ)_2 = \Delta H_2^\circ - \Delta(H^\circ - H_0^\circ)_{2Na}^{Na_2} \quad (31)$$

\*Preliminary equilibrium constants (29) for the dimerization and tetramerization reactions were based on incorrect thermal expansion coefficients for columbium-1% zirconium.

using the observed reaction enthalpy and the computed enthalpy functions of Evans et al. (19). Another value of  $-16.8 \pm 0.05$  kcal/mole (which is an average for the temperature range from  $1800^\circ$  to  $2400^\circ$  F) was obtained with the equation

$$\frac{(\Delta H_0^\circ)_2}{T} = -R \ln k_2 - \Delta \left[ \frac{(F^\circ - H_0^\circ)}{T} \right]_{2Na}^{Na_2} \quad (31A)$$

using the observed equilibrium constants and the computed free-energy functions of Evans. The agreement between the enthalpy constants as computed by the two methods increases the degree of confidence which can be placed in the measured quantity and the computed thermal functions. The value of  $-17.0$  may be compared to the spectroscopic value of  $-17.53$  by Herzberg (22) and to the molecular-beam value of  $-16.91$  by Lewis (23).

Equilibrium Composition of Saturated and Superheated Sodium Vapor - The relative amounts of dimer and tetramer in the equilibrium vapor and the average molecular weight of the vapor at each pressure and temperature state (Appendixes C and D) were computed by a modification of the method of Ritter and Simons (24), which was presented in detail for potassium (1a). The application of this method required a knowledge of the average molecular weight of the vapor and the two equilibrium constants. With equilibrium constants obtained from Eqs. (27) and (28), the average molecular weight of the vapor at a given state was computed from the three equations

$$k_2' = k_2 + 3k_4 p^2 - 2k_2 k_4 p^3 \quad (32)$$

$$k_2' = \frac{(N_2')}{(N_1')^2 p} \quad (33)$$

$$M_v = N_1' M_1 + N_2' (2M_1) \quad (34)$$

Enthalpy of Vaporization of Monomeric Sodium Vapor - This quantity from  $1600^\circ$  to  $2575^\circ$  F is presented in Appendix C and was computed with

$$\Delta h_{v,1} = \Delta h_v - (\Delta h_2)(x_2)_s - (\Delta h_4)(x_4)_s \quad (35)$$

#### Thermodynamic Properties of Sodium by the Quasi-Chemical Method (Monomeric Gas Path)

Enthalpy of Saturated and Superheated Vapor - As with the virial method, the enthalpies of the vapor were computed along isotherms with the enthalpy of the monomeric gas at each temperature as a starting point. Since  $\left(\frac{\partial h}{\partial p}\right)_T = 0$  for a perfect gas, any change in enthalpy must result from the association reactions; and the general equation for the absolute enthalpy is

$$h_i^g = (h^g)^0 + \Delta h_2 x_2 + \Delta h_4 x_4 \quad (36)$$

The last two terms in this equation represent the enthalpy changes contributed by each species in moving from zero to some finite concentration.

Entropy of Saturated and Superheated Vapor - The general entropy equation along a constant temperature line is

$$s_i^g = (s_i^g)^o + \frac{\Delta h_2 x_2}{T} + \frac{\Delta h_4 x_4}{T} - \frac{R \ln p}{M_a} + \frac{x_2 R \ln k_2}{2M_1} + \frac{x_4 R \ln k_4}{4M_1} - \left[ \frac{R(N_1 \ln N_1 + N_2 \ln N_2 + N_4 \ln N_4)}{M_a} \right] \quad (37)$$

### A Comparison of the Thermodynamic Properties by the Virial and the Quasi-Chemical Methods (Monomeric Gas Path)

Enthalpies and entropies of selected vapor states of sodium were computed by the quasi-chemical method for comparison with those by the virial method. These are presented graphically as a partial Mollier diagram (Fig. 12) and compared to the corresponding diagram generated by the virial method. Enthalpy and entropy changes along constant temperature lines as computed by both methods are in good agreement. For example, the maximum enthalpy changes by the quasi-chemical method (from  $p_s$  to 0.2 atm) for temperatures in the measured range of the PVT data (1725° to 2500° F) are an average of only 1.0% different from corresponding changes by the virial method. Similarly, entropy changes by the quasi-chemical method are only 0.3% different from corresponding changes by the virial method.

Although the two equations of state are essentially equivalent, the thermodynamic properties as computed by the virial method have been selected over those by the other method for several reasons: (a) higher confidence in the thermodynamic relationships of the virial method, (b) the appreciable error that may be generated in quantities computed from equilibrium constants and enthalpies of the reactions by the assumption of linear relationships for the variation of  $\log k_i$  with  $1/T$ , and (c) the relative simplicity of the calculation of the specific heat of the vapor by the virial method. All the final thermodynamic properties of sodium in Appendixes A and B and in the Mollier diagram (Fig. 13) were computed by the virial method.

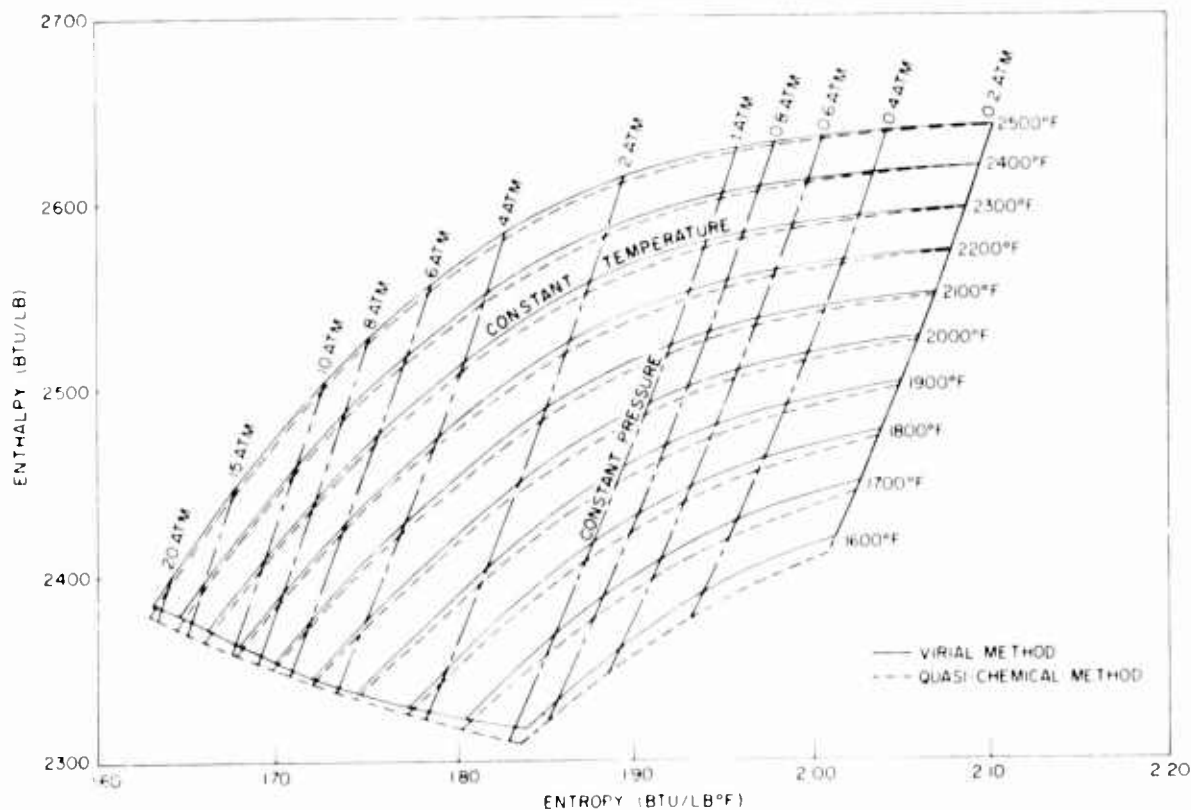
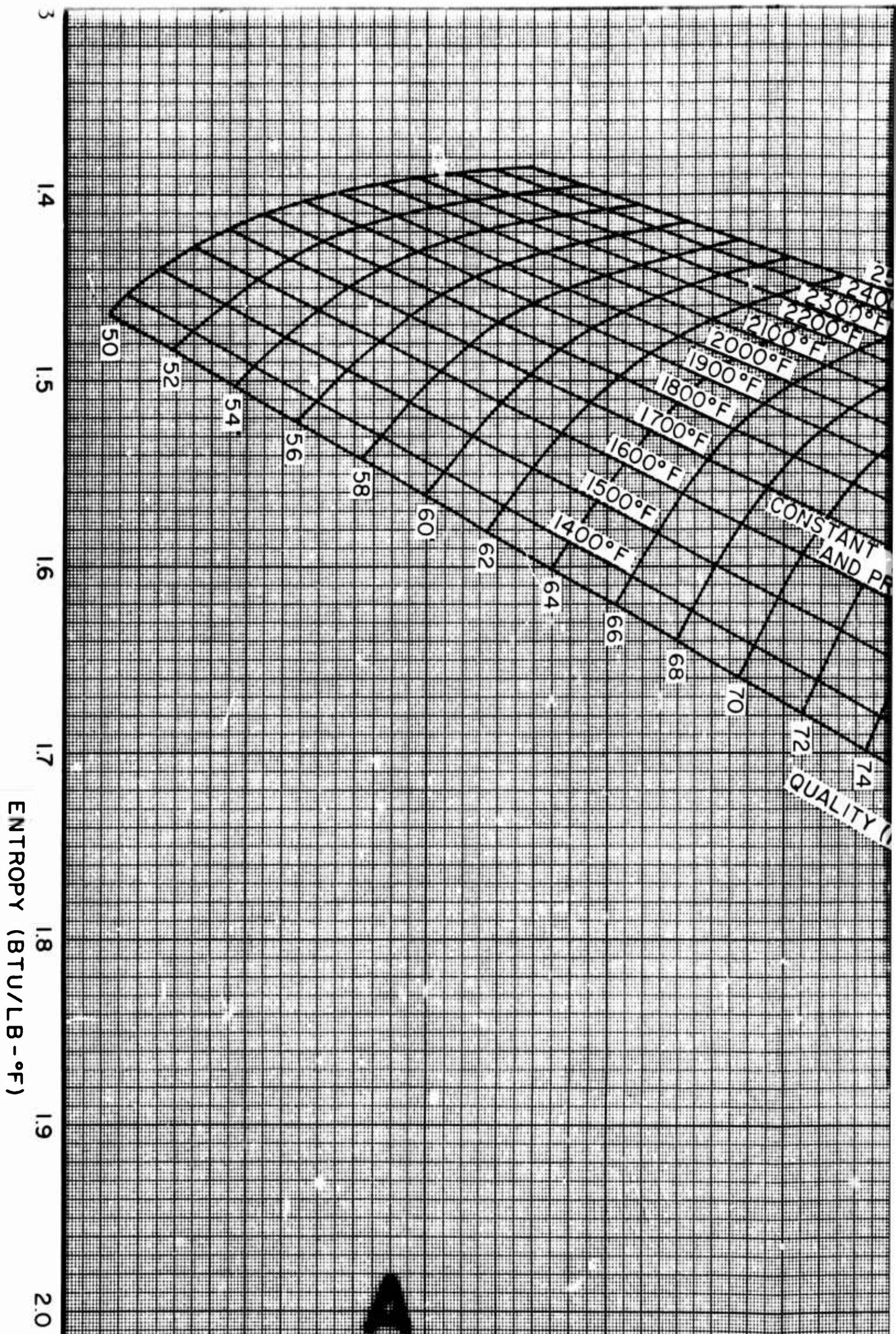
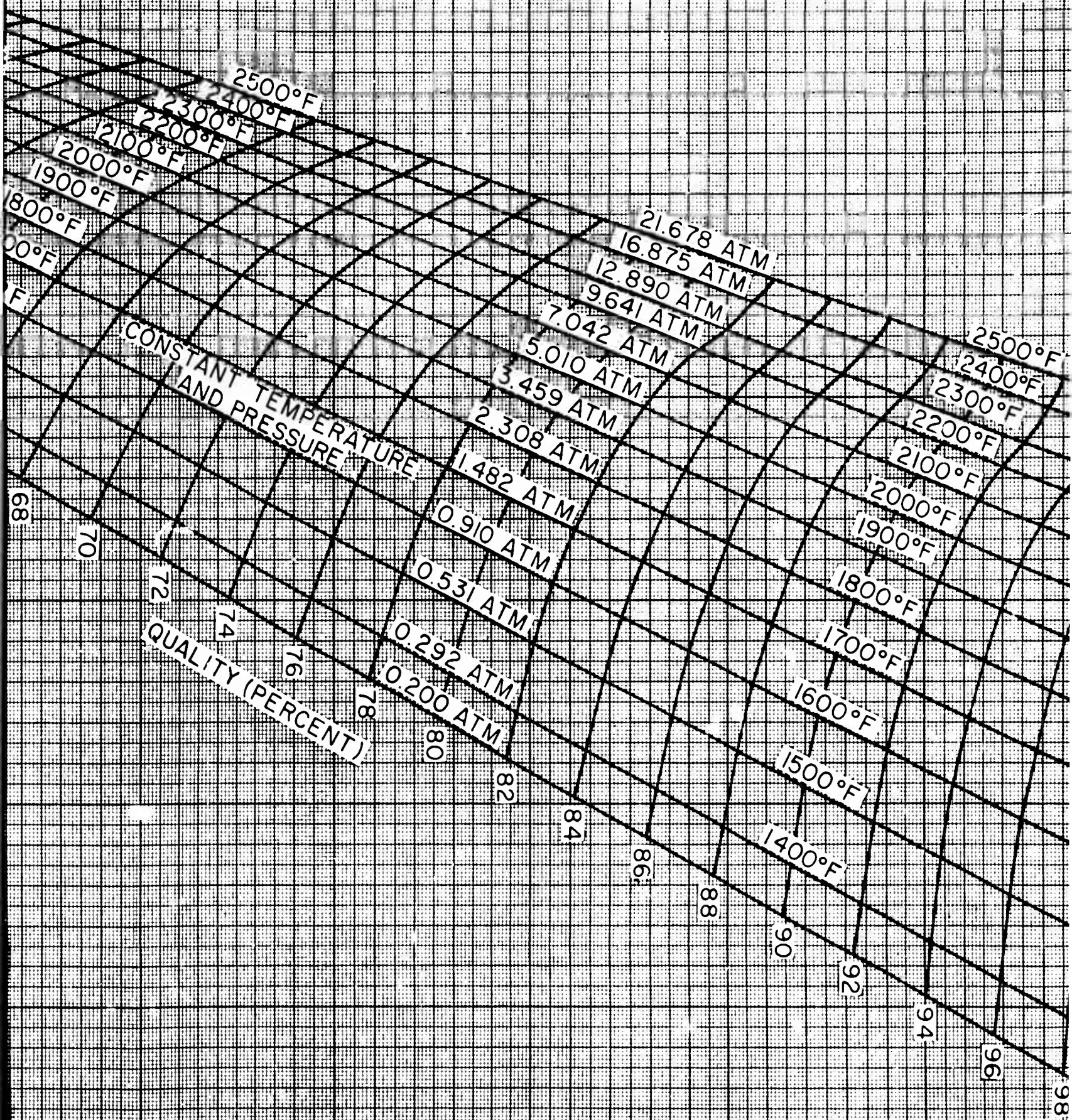


Fig. 12 - Comparison of partial Mollier diagram for sodium by quasi-chemical method with that by virial method

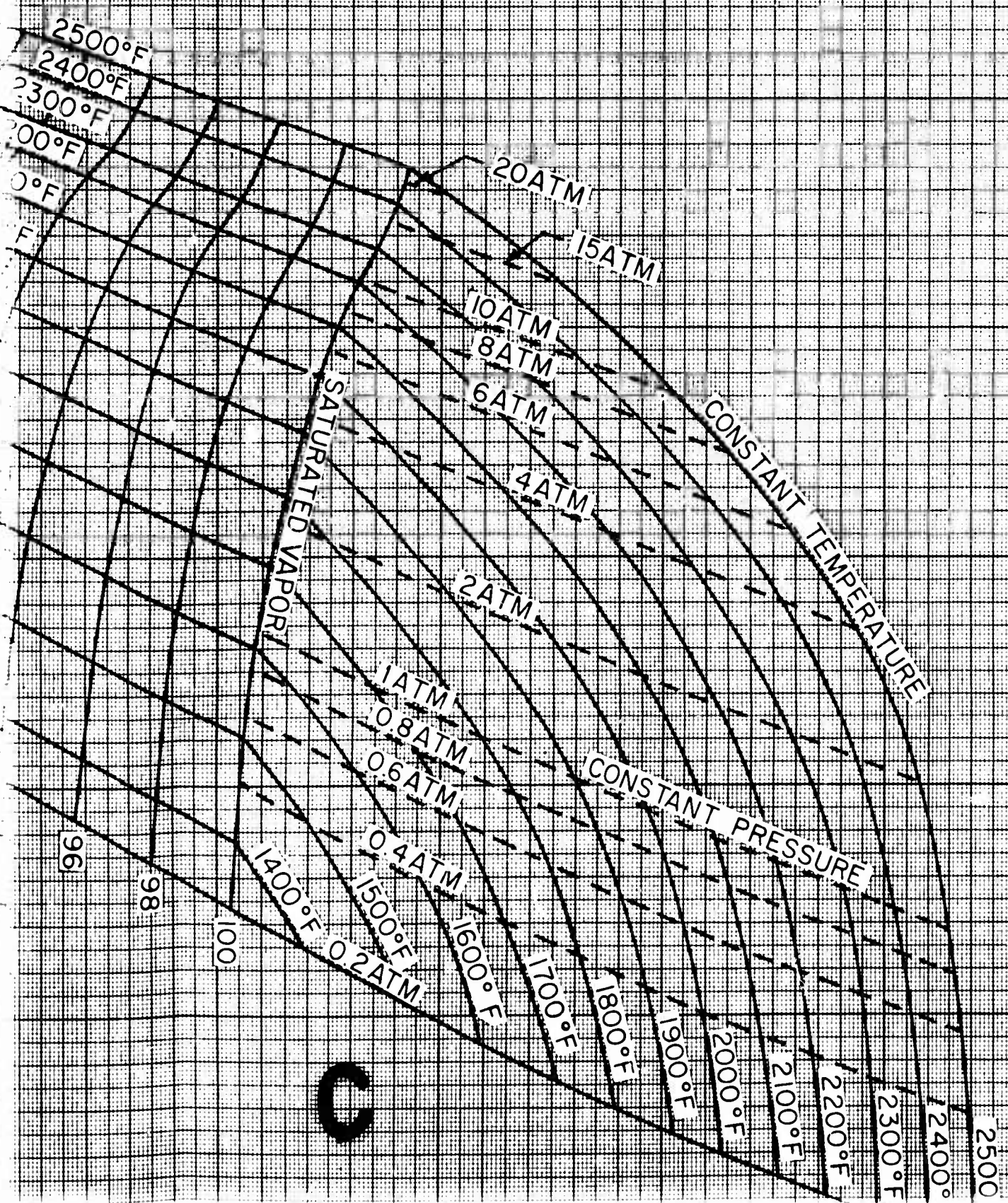




**B**

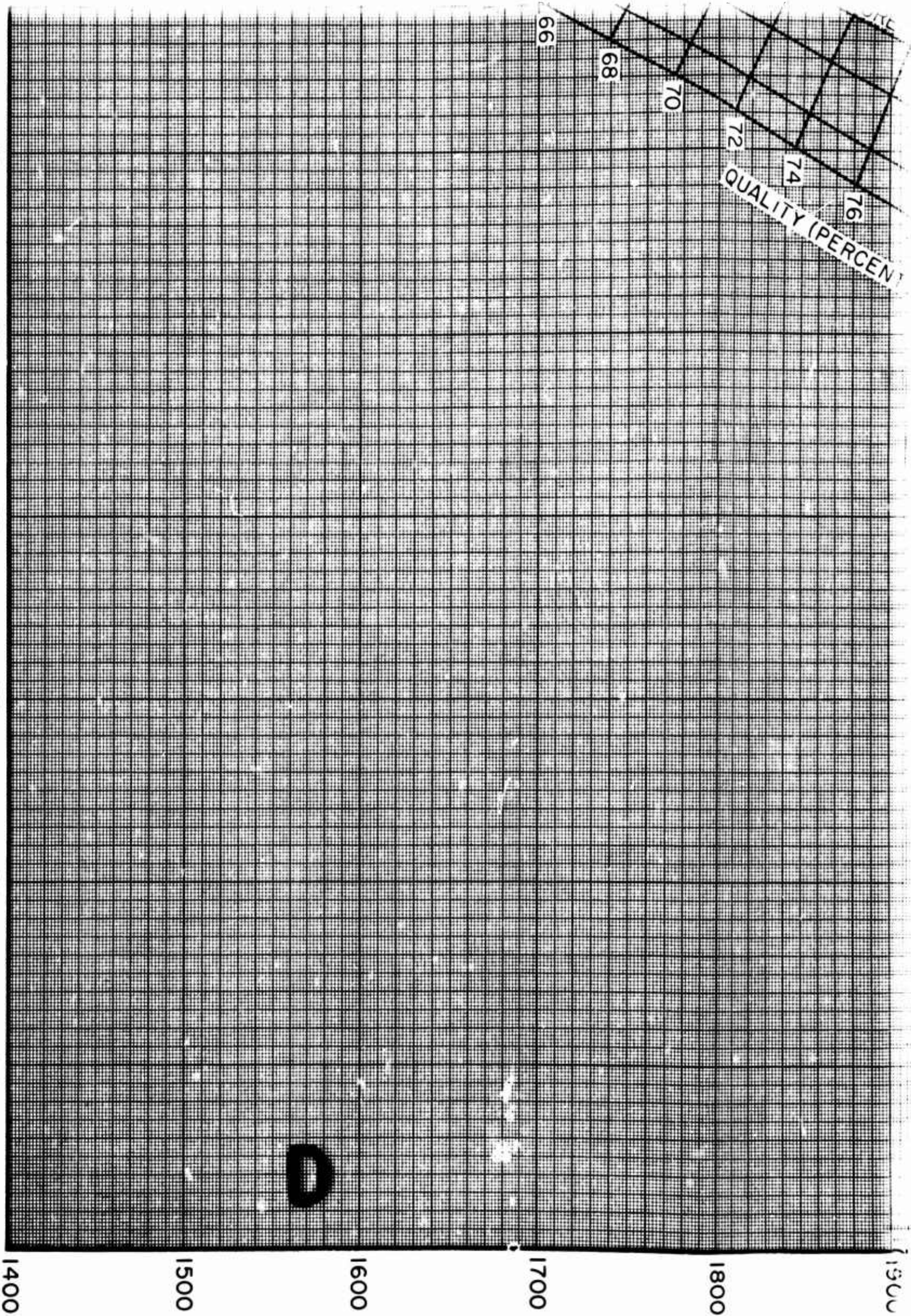
3  
1.4  
1.5  
1.6  
1.7  
1.8  
1.9  
2.0

ENTROPY (BTU/LB-°F)



ENTROPY (BTU/LB-°F)

1.7 1.8 1.9 2.0 2.1 2.2 2.3



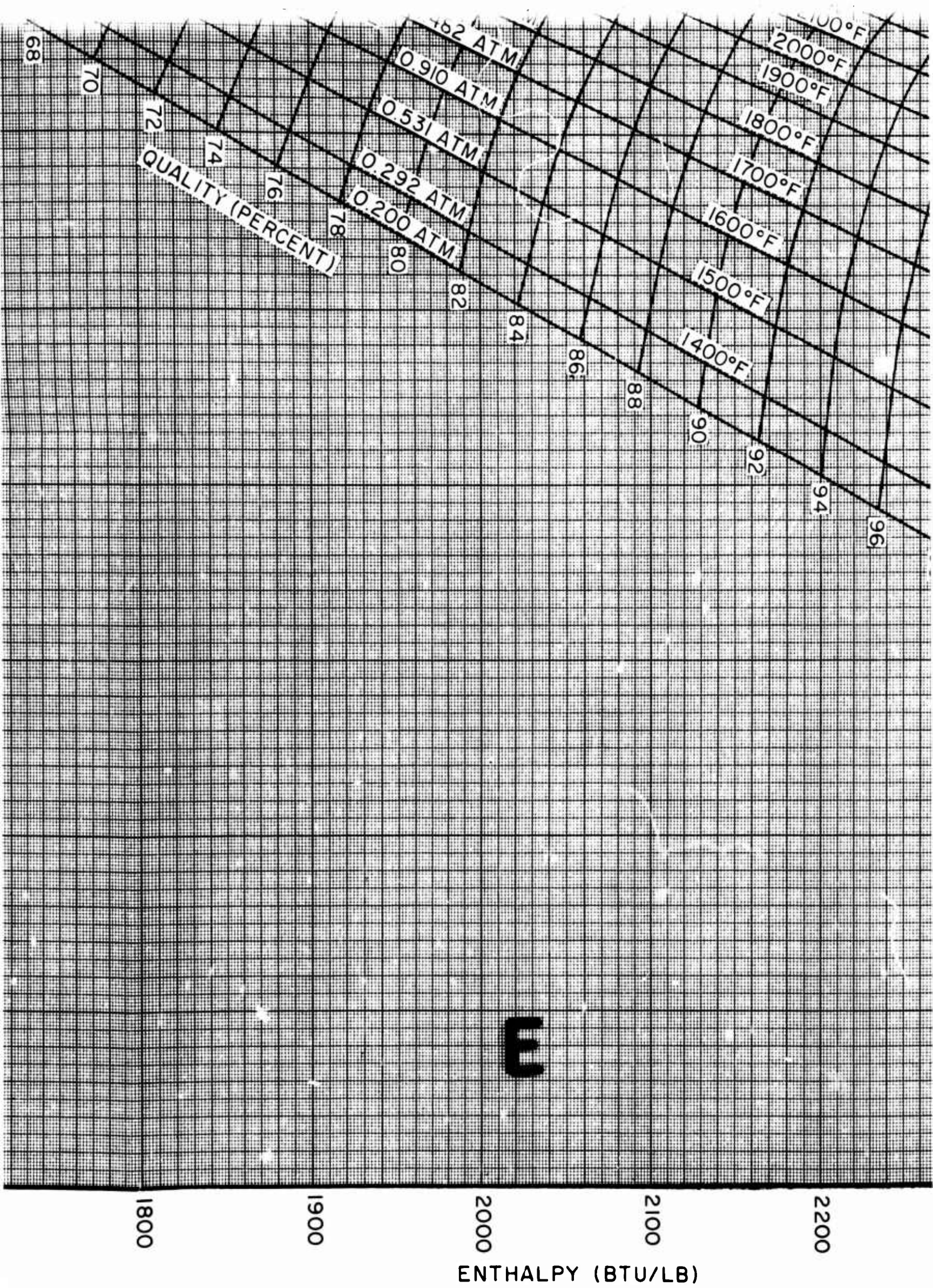
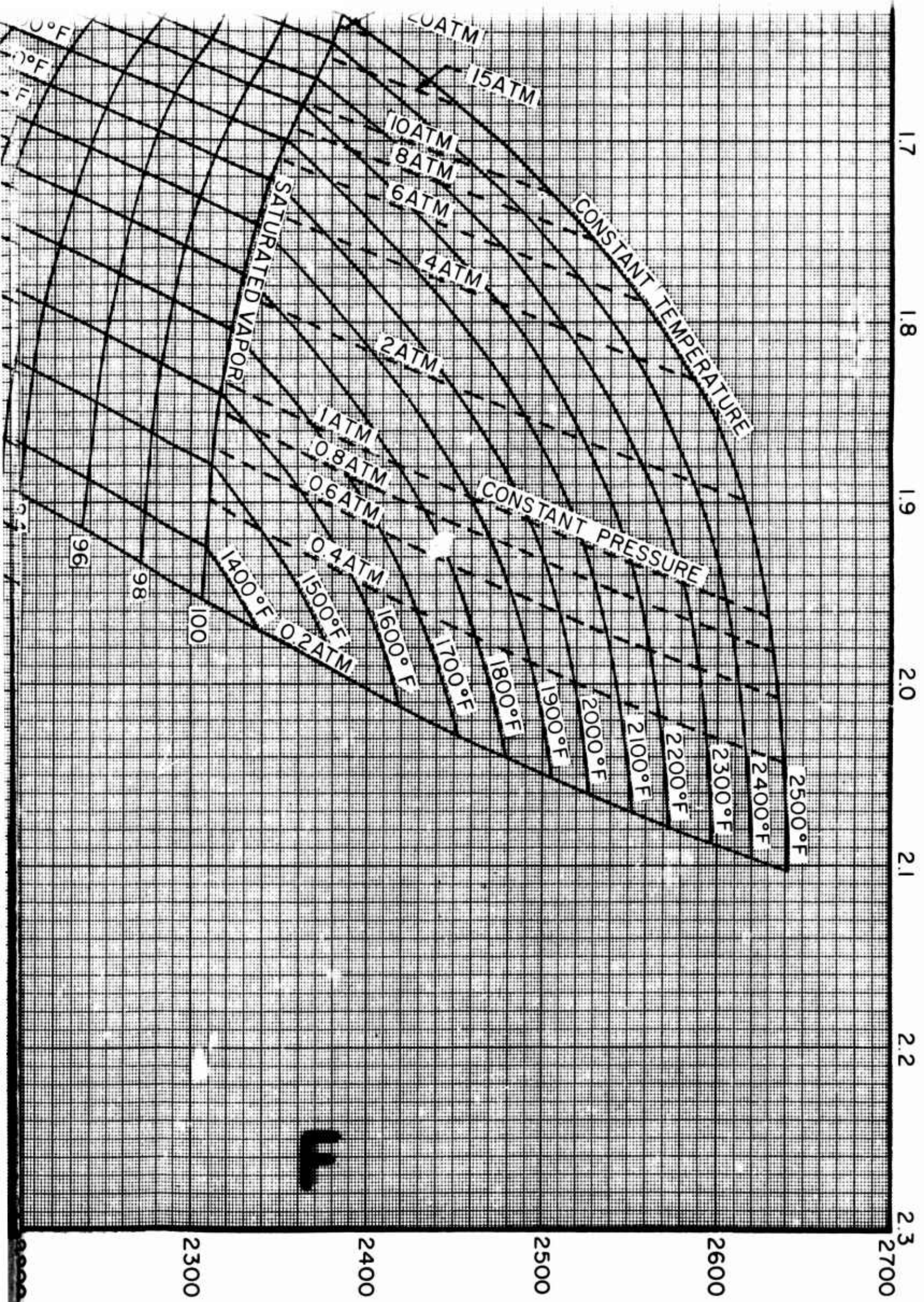


Fig. 13 - Mollier diagram of sodium vapor

ENTROPY (BTU/LB-°F)



**F**

## DISCUSSION OF QUASI-CHEMICAL TREATMENT AND COMPOSITIONAL INFORMATION

The PVT results have been satisfactorily interpreted by a quasi-chemical approach assuming that sodium vapor is an ideal mixture of monomeric, dimeric, and tetrameric species. This physical picture of the vapor is based solely on the thermodynamic analysis of observed PVT results. The existence of the dimeric species has been verified spectroscopically (22), but the tetramer has not been identified by any other type of measurement. It was recognized that other molecular states of the vapor with their corresponding formulas might be equally as effective in a treatment of the data. As a test of this hypothesis, the sodium results were analyzed as an imperfect mixture of monomeric and dimeric species.

The van der Waals equation was chosen to treat the gas imperfections (interactions of atoms or molecules not leading to stable assemblies). This equation of state

$$\left(p + \frac{\tilde{a}_1}{\tilde{V}^2}\right)(\tilde{V} - \tilde{b}_1) = \frac{M_1 RT}{M_a} \quad (38)$$

for an imperfect vapor with a dimer equilibrium was derived by Vukalovich et al. (28). The value of  $\tilde{b}_1$ , which represents the excluded volume correction, can be reliably estimated from the condensed volume (1a). The mixture law used by Vukalovich in deriving the internal pressure term  $\tilde{a}_1/\tilde{V}^2$  is not valid for metal vapors, and  $\tilde{a}_1$  would be expected to vary with both composition and temperature. However, since the dimer content of the vapor is small and the reduced temperature range is short, the coefficient  $\tilde{a}_1$  has been assumed to be a constant. The value of this coefficient cannot be estimated theoretically and must be obtained empirically by fitting Eq. (38) to the PVT data.

The objective was to see whether or not another physical state of the vapor would correlate the PVT results, and no attempt was made to determine exact equational fits. However, it was readily apparent that a value of  $\tilde{a}_1$  for Eq. (38) could be found for which the corresponding dimerization constants were independent of pressure along isotherms over the full temperature range. It was concluded that an effective equation of state could be obtained in terms of the van der Waals relationship and the corresponding equilibrium constants of the dimerization reaction.

A direct implication of this analysis is that several physical states of the vapor, including an imperfect mixture of monomeric, dimeric, and trimeric species, would also satisfy the PVT data. This is not surprising. Although these gas imperfections may in reality result either from the interaction of species or from molecular association, they are all close approaches of atoms or molecules and differ mainly in longevity or average life of contact. This study of molecular models only serves to emphasize that imperfections of either type may be properly treated from the thermodynamic standpoint as interactions or as associated molecules.

All applications of the molecular composition information for the vapor states of sodium (Appendixes C and D) should be made with full realization that all values are based on the most probable model or on the most probable set of assumptions regarding imperfections. If, at a later date, the higher-molecular-weight species is positively identified to be other than the tetramer or if it becomes possible to partition the interaction imperfections from association, the PVT data can be readily reanalyzed using the correct model.

## DISCUSSION OF THERMODYNAMIC AND ENGINEERING PROPERTIES OF SODIUM

The engineering and thermodynamic properties of sodium,\* which are presented in Appendixes A and B and in the large Mollier diagram (Fig. 13), were computed by the virial method and are based on the monomeric gas properties at 1 atm. Two basic relationships, the virial equation of state and the vapor-pressure equation, were used with the thermodynamic equations to derive the superheat and saturation properties. The virial equation was reduced from PVT data covering a pressure range of 1.86 to 25.1 atm and a temperature range of 1758° to 2588° F. The saturated vapor-pressure equation represents data covering a pressure range of 1.00 to 23.82 atm and a temperature range of 1618.6° to 2539° F. Thus the observed data effectively cover all states in Appendixes A and B, and only short extrapolations with Eqs. (1) and (14) are required for the pressure states below 1.86 atm. In contrast to the compositional information, these properties are completely independent of any assumptions made regarding imperfections. They have been examined and evaluated by several tests for internal consistency and by duplicate calculations using two independent equations of state. It is believed that they represent the best values and that they will be satisfactory for any type of calculation required in the design of turbines using sodium as working fluid.

The present study represents the only known PVT measurements of sodium. However, there are a number of publications in which thermodynamic properties of the vapor have been computed from saturation pressures, spectroscopic data, and published thermodynamic functions of the monomeric and dimeric vapors. The properties derived in this report from the PVT study were compared with those derived in two recent publications by Makansi et al. (25) and Weatherford et al. (26), and the overall agreement is good. If we arbitrarily take the NRL data as a reference and compare at each temperature enthalpy and entropy changes from  $p_s$  to 0.3 atm, the enthalpy changes reported by Makansi are 5 to 20% lower and the entropy changes on the average differ by 1.4%. By a similar comparison ( $p_s$  to 0.2 atm), the enthalpy changes reported by Weatherford are an average of 8% higher, and the entropy changes differ by  $\pm 0.6\%$ .

As background for the present study, thermodynamic properties of sodium vapor were computed at NRL (27) using the saturation pressures of Makansi et al. (8) and the thermodynamic functions of Evans et al. (19). If we again take the properties derived from the PVT measurements as a reference and compare at each temperature the enthalpy and entropy changes from  $p_s$  to 0.2 atm, the enthalpy changes estimated previously are an average of 11% higher, and the entropy changes are an average of 3.9% lower than those observed in this report.

Saturation pressures of sodium were measured between 1437° and 2539° F with the null-point apparatus. This method, which is new to the measurement of saturation pressures at high temperatures, has been shown to be capable of high accuracy. The precision and internal consistency of the saturation measurements are attested to by the small variation in  $(\Delta H_0^2)_{p_s}$  as computed for all the vapor-pressure data and by the small deviation ( $\pm 0.37\%$ ) of all measured data from a simple three-term equation. In the previous study on potassium (1a) an equation of the Kirchhoff type was effective in fitting the saturation pressures. This study with sodium reaffirms that an equation of this type is required to describe accurately the dependence of vapor pressure on temperature.

Densities of the condensed phase were measured in the temperature range from 1577° to 2491° F with pycnometers. This method was time consuming since an independent measurement was required at each temperature point, but results of unquestionable accuracy were obtained. With these new measurements and those generated by several

\*Preliminary tables of thermodynamic properties (29) were based on incorrect thermal expansion values for columbium-1% zirconium.

other investigators at lower temperatures, overlapping determinations have been made from the melting point to 2491° F; and the density of liquid sodium is well defined for this full temperature range.

The specific heat of the condensed phase was measured from 212° to 2140° F. Values at intermediate temperatures from 212° to 1200° F were measured under ideal conditions and are in good agreement with the specific-heat data of Ginnings et al. (18). The values at higher temperatures were measured under less ideal conditions with relatively high probable errors, but they do tend to substantiate an extension of the specific-heat data of Ginnings. A more accurate knowledge of this property above 2200° F is needed.

The liquid metal program at this Laboratory is only a small part of the total national effort in this area. The internal consistency and the confidence limits of the properties of sodium, potassium, and cesium can be more fully evaluated as additional properties are measured for the three metals. Particularly important in this respect would be reliable determinations of the heat of vaporization, the specific heat of liquid and vapor, and the electrical conductivity of the vapor. A direct determination of the heat of vaporization would help to evaluate the thermodynamic computation of this quantity from the Clapeyron equation. Similarly, a direct determination of the specific heat of the vapor would test the values computed from the virial equation of state, and a determination of the electrical conductivity would provide additional information on the degree of ionization of the vapor.

#### ACKNOWLEDGMENTS

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## NOMENCLATURE AND UNITS

$B$	second virial coefficient, cu ft/mole
$C$	third virial coefficient, (cu ft) <sup>2</sup> /(mole) <sup>2</sup>
$D$	fourth virial coefficient, (cu ft) <sup>3</sup> /(mole) <sup>3</sup>
$c_p$	specific heat at constant pressure, Btu/lb-°F
$d$	density, lb/cu ft
$f$	free energy, Btu/lb
$F$	free energy, Btu/lb-mole
$h$	enthalpy per unit mass, Btu/lb
$\Delta h$	enthalpy change per unit mass, Btu/lb
$\Delta h_2$	enthalpy change for the formation of a unit mass of dimer from monomer, Btu/lb
$\Delta h_4$	enthalpy change for the formation of a unit mass of tetramer from monomer, Btu/lb
$\Delta h_v$	enthalpy change upon vaporization of a unit mass at equilibrium, Btu/lb
$\Delta h_{v_1}$	enthalpy change upon vaporization of a unit mass of monomer, Btu/lb
$H$	enthalpy per mole, Btu/lb-mole
$\Delta H$	enthalpy change per mole, Btu/lb-mole
$\Delta H_2$	enthalpy change for the formation of one mole of dimer from monomer, Btu/lb-mole
$\Delta H_4$	enthalpy change for the formation of one mole of tetramer from monomer, Btu/lb-mole
$\Delta H_v$	enthalpy change upon vaporization of a mole at equilibrium, Btu/lb-mole
$J$	any unit conversion
$k$	equilibrium constant
$k'_2$	apparent equilibrium constant assuming only diatomic and monatomic species
$M$	molecular weight
$N$	mole fraction
$p$	absolute pressure, atm
$R$	gas constant
$s$	entropy per unit mass, Btu/lb-°F
$\Delta s_v$	entropy change upon vaporization of a unit mass at equilibrium, Btu/lb-°F
$T$	absolute temperature, °R
$t$	temperature, °F
$\tilde{V}$	molal volume (normally per formula weight of monomer), cu ft/lb-mole
$v$	specific volume, cu ft/lb
$z$	compressibility factor, $p\tilde{V}/RT$

## Subscripts

$a$  quantity for equilibrium molecular mixture

- i* quantity for the vapor in a state
- 0* quantity at 0° R
- p* constant pressure change
- s* quantity at saturation
- t* constant temperature change
- 1* quantity for monatomic species
- 2* quantity for diatomic species
- 3* quantity for triatomic species
- 4* quantity for tetratomic species

#### Superscripts

- g* quantity in gas state
- l* quantity in liquid state
- o* standard state, 1 atm for gas
- '* apparent quantity, when assuming only diatomic and monatomic species
- \** adjusted value

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APPENDIX A

SATURATION PROPERTIES OF SODIUM  
(Monomer Gas Base)

$t$	$P_s$	$v^l$	$v^g$	$h^l$	$\Delta h_v$	$h^g$	$\Delta s_v$	$s^l$	$s^g$
1600.	.9100	.02157	64.8536	624.60	1692.35	2316.95	.8216	1.0173	1.0390
1625.	1.0327	.02167	57.6569	632.77	1685.54	2318.31	.8085	1.0212	1.0298
1650.	3.1482	.02177	51.4107	640.92	1678.79	2319.70	.7957	1.0251	1.0209
1675.	1.3174	.02187	45.9722	649.06	1672.09	2321.14	.7833	1.0290	1.0123
1700.	1.4418	.02197	41.2225	657.19	1665.44	2322.63	.7711	1.0327	1.0039
1725.	1.6427	.02207	37.0621	665.31	1658.86	2324.17	.7593	1.0365	1.7958
1750.	1.8430	.02217	33.4073	673.42	1652.34	2325.76	.7478	1.0402	1.7879
1775.	2.0740	.02228	30.1878	681.54	1645.87	2327.41	.7365	1.0438	1.7803
1800.	2.3181	.02238	27.3441	689.64	1639.47	2329.11	.7255	1.0474	1.7729
1825.	2.5829	.02249	24.8259	697.75	1633.12	2330.88	.7148	1.0510	1.7658
1850.	2.8382	.02260	22.5901	705.86	1626.83	2332.70	.7043	1.0545	1.7589
1875.	3.1365	.02270	20.6003	713.98	1620.59	2334.57	.6941	1.0580	1.7521
1900.	3.4854	.02281	18.8251	722.11	1614.40	2336.50	.6842	1.0614	1.7456
1925.	3.8957	.02292	17.2378	730.25	1608.24	2338.49	.6744	1.0649	1.7393
1950.	4.1791	.02303	15.8152	738.40	1602.12	2340.52	.6649	1.0683	1.7331
1975.	4.5400	.02314	14.5375	746.58	1596.03	2342.60	.6555	1.0716	1.7272
2000.	5.0197	.02326	13.3875	754.78	1589.95	2344.73	.6464	1.0750	1.7214
2025.	5.4494	.02337	12.3507	763.01	1583.88	2346.89	.6375	1.0783	1.7157
2050.	5.9104	.02348	11.4127	771.28	1577.80	2349.09	.6287	1.0816	1.7103
2075.	6.4445	.02360	10.5637	779.59	1571.72	2351.31	.6201	1.0849	1.7050
2100.	7.0424	.02372	9.7935	787.95	1565.61	2353.56	.6116	1.0881	1.6998
2125.	7.6354	.02384	9.0933	796.35	1559.46	2355.81	.6033	1.0914	1.6947
2150.	8.2453	.02395	8.4557	804.82	1553.26	2358.08	.5952	1.0946	1.6898
2175.	8.9335	.02408	7.8739	813.35	1546.99	2360.34	.5872	1.0979	1.6850
2200.	9.6408	.02420	7.3423	821.94	1540.65	2362.59	.5793	1.1011	1.6804
2225.	10.3804	.02432	6.8556	830.62	1534.20	2364.82	.5715	1.1043	1.6758
2250.	11.1789	.02444	6.4092	839.38	1527.64	2367.02	.5638	1.1076	1.6713
2275.	12.0422	.02457	5.9992	848.23	1520.95	2369.17	.5562	1.1108	1.6670
2300.	12.8903	.02469	5.6220	857.17	1514.10	2371.28	.5486	1.1140	1.6627
2325.	13.8143	.02482	5.2744	866.23	1507.09	2373.32	.5411	1.1173	1.6585
2350.	14.7854	.02495	4.9536	875.39	1499.88	2375.27	.5338	1.1205	1.6544
2375.	15.8155	.02508	4.6570	884.69	1492.45	2377.14	.5265	1.1238	1.6503
2400.	16.8752	.02521	4.3825	894.11	1484.78	2378.89	.5192	1.1271	1.6463
2425.	17.9901	.02534	4.1279	903.68	1476.84	2380.52	.5120	1.1304	1.6423
2450.	19.1493	.02548	3.8914	913.40	1468.61	2382.01	.5047	1.1337	1.6384
2475.	20.3902	.02561	3.6715	923.30	1460.03	2383.33	.4975	1.1371	1.6346
2500.	21.6770	.02575	3.4666	933.37	1451.09	2384.46	.4903	1.1405	1.6307
2525.	23.0154	.02589	3.2754	943.64	1441.74	2385.38	.4830	1.1439	1.6269
2550.	24.4103	.02602	3.0967	954.13	1431.93	2386.06	.4758	1.1474	1.6231
2575.	25.8434	.02616	2.9294	964.85	1421.62	2386.47	.4685	1.1509	1.6193

**APPENDIX B**  
**THERMODYNAMIC PROPERTIES OF SODIUM VAPOR**  
**(Monomer Gas Base)**

$t$	$p$	$v^g$	$z$	$h^g$	$s^g$	$c_p^g$
1600.	.9100	64,6536	.90212	2316.95	1.83896	.6704
1600.	.8000	74,6537	.91288	2331.76	1.8562	.6264
1600.	.6000	101,7693	.93334	2359.77	1.89281	.5365
1600.	.4000	156,1641	.95480	2388.98	1.94008	.4362
1600.	.2000	319,6150	.97708	2419.13	2.01263	.3285
1625.	1.0327	57,6569	.89916	2318.31	1.82978	.6690
1625.	1.0000	59,7274	.90200	2322.21	1.83415	.6583
1625.	.8000	76,1466	.91997	2346.91	1.86356	.5860
1625.	.6000	103,6181	.93890	2372.76	1.89908	.5034
1625.	.4000	158,6546	.95864	2399.58	1.94520	.4128
1625.	.2000	324,1464	.97905	2427.19	2.01652	.3164
1650.	1.1682	51,4107	.89624	2319.70	1.82088	.6669
1650.	1.0000	60,9556	.90964	2338.15	1.84175	.6174
1650.	.8000	77,5971	.92638	2361.09	1.87033	.5498
1650.	.6000	105,4189	.94390	2384.97	1.90490	.4742
1650.	.4000	161,1734	.96207	2409.64	1.94999	.3923
1650.	.2000	328,6233	.98081	2434.96	2.02023	.3058
1675.	1.3176	49,9722	.89334	2321.14	1.81225	.6643
1675.	1.0000	62,1495	.91659	2353.12	1.84880	.5803
1675.	.8000	79,0081	.93218	2374.43	1.87661	.5174
1675.	.6000	107,1767	.94840	2396.50	1.91033	.4483
1675.	.4000	163,6061	.96516	2419.22	1.95451	.3743
1675.	.2000	333,0520	.98238	2442.49	2.02378	.2965
1700.	1.4814	41,2225	.89047	2322.63	1.80389	.6611
1700.	1.0000	63,3115	.92292	2357.20	1.85536	.5466
1700.	.8000	80,3835	.93743	2386.99	1.88246	.4884
1700.	.6000	108,8959	.95246	2407.41	1.91541	.4254
1700.	.4000	165,5978	.96793	2428.38	1.95877	.3584
1700.	.2000	337,4389	.98380	2449.80	2.02718	.2883
1725.	1.6620	37,0621	.88763	2324.17	1.79579	.6573
1725.	1.0000	64,4439	.92868	2380.48	1.86148	.5163
1725.	.8000	81,7266	.94219	2398.87	1.88793	.4626
1725.	.6000	110,5803	.95612	2417.79	1.92019	.4051
1725.	.4000	168,3530	.97043	2437.16	1.96281	.3444
1725.	.2000	341,7860	.98507	2456.91	2.03046	.2811
1750.	1.8590	33,4073	.88483	2325.76	1.78794	.6530
1750.	1.0000	65,5492	.93392	2393.04	1.86719	.4889
1750.	.8000	83,0403	.94650	2410.14	1.89306	.4395
1750.	.6000	112,2335	.95944	2427.69	1.92469	.3870
1750.	.4000	170,6755	.97269	2445.61	1.96666	.3319
1750.	.2000	346,1001	.98622	2463.86	2.03362	.2748
1775.	2.0740	30,1878	.88206	2327.41	1.78032	.6482
1775.	2.0000	31,4293	.88557	2332.24	1.78526	.6396
1775.	1.0000	66,6297	.93869	2404.95	1.87255	.4644
1775.	.8000	84,3274	.95042	2420.87	1.89789	.4189
1775.	.6000	113,8587	.96244	2437.16	1.92896	.3710
1775.	.4000	172,9687	.97473	2453.76	1.97033	.3209
1775.	.2000	350,3840	.98726	2470.66	2.03668	.2691
1800.	2.3081	27,3441	.87932	2329.11	1.77295	.6430
1800.	2.0000	32,0457	.89294	2347.85	1.79221	.6094
1800.	1.0000	67,6876	.94305	2416.27	1.87759	.4422
1800.	.8000	85,5905	.95398	2431.11	1.90245	.4005

## APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^g$	$z$	$h^g$	$s^g$	$c_p^g$
2000.	5.0000	13.4166	.85863	2345.00	1.72163	.5911
2000.	4.0000	17.2135	.88130	2375.74	1.75090	.5626
2000.	3.0000	23.6232	.90710	2410.81	1.78739	.5070
2000.	2.0000	36.5545	.93576	2449.70	1.83551	.4273
2000.	1.0000	75.5434	.96688	2491.79	1.90968	.3284
2000.	.8000	95.0582	.97336	2500.53	1.93194	.3068
2000.	.6000	127.5979	.97991	2509.37	1.95981	.2847
2000.	.4000	192.6913	.98654	2518.29	1.99789	.2622
2000.	.2000	397.9986	.99324	2527.31	2.06085	.2393
2025.	5.4694	12.3502	.85589	2346.89	1.71575	.5842
2025.	5.0000	13.6285	.86532	2359.61	1.72753	.5768
2025.	4.0000	17.5096	.88744	2399.57	1.75649	.5437
2025.	3.0000	23.9987	.91224	2423.24	1.79242	.4877
2025.	2.0000	37.0736	.93950	2460.18	1.83975	.4117
2025.	1.0000	76.4658	.96888	2499.89	1.91296	.3196
2025.	.8000	96.1837	.97497	2508.11	1.93501	.2996
2025.	.6000	129.0557	.98114	2516.42	1.96266	.2793
2025.	.4000	194.8123	.98737	2524.80	2.00052	.2585
2025.	.2000	392.1060	.99365	2533.26	2.06326	.2374
2050.	5.9606	11.4127	.85336	2349.09	1.71028	.5773
2050.	5.0000	13.6985	.87175	2373.83	1.73323	.5614
2050.	4.0000	17.8016	.89325	2402.93	1.76184	.5251
2050.	3.0000	24.3680	.91706	2435.20	1.79721	.4696
2050.	2.0000	37.5349	.94297	2470.29	1.84379	.3973
2050.	1.0000	77.3820	.97072	2507.78	1.91612	.3116
2050.	.8000	97.2998	.97646	2515.52	1.93797	.2931
2050.	.6000	130.5039	.98226	2523.34	1.96543	.2743
2050.	.4000	196.9235	.98812	2531.22	2.00309	.2552
2050.	.2000	396.2036	.99404	2539.18	2.06563	.2357
2075.	6.4845	10.5637	.85083	2351.31	1.70496	.5705
2075.	6.0000	11.5286	.85916	2362.44	1.71500	.5664
2075.	5.0000	14.1361	.87791	2387.67	1.73872	.5453
2075.	4.0000	18.0894	.89874	2415.83	1.76696	.5071
2075.	3.0000	24.7315	.92155	2446.73	1.80178	.4527
2075.	2.0000	38.0890	.94619	2480.06	1.84767	.3842
2075.	1.0000	78.2498	.97242	2515.47	1.91917	.3043
2075.	.8000	98.4074	.97784	2522.77	1.94085	.2872
2075.	.6000	131.9435	.98331	2530.14	1.96813	.2698
2075.	.4000	199.0259	.98882	2537.56	2.00561	.2522
2075.	.2000	400.2922	.99439	2545.05	2.06796	.2342
2100.	7.3424	9.7935	.84829	2353.56	1.69978	.5639
2100.	7.0000	9.8604	.84895	2354.43	1.70056	.5637
2100.	6.0000	11.7276	.86546	2376.45	1.72058	.5536
2100.	5.0000	14.3711	.88378	2401.10	1.74399	.5290
2100.	4.0000	18.3729	.90391	2428.29	1.77185	.4898
2100.	3.0000	25.0893	.92576	2457.85	1.80614	.4369
2100.	2.0000	38.5862	.94918	2489.51	1.85138	.3722
2100.	1.0000	79.1700	.97400	2523.00	1.92212	.2977
2100.	.8000	99.5071	.97911	2529.89	1.94364	.2819
2100.	.6000	133.3751	.98427	2536.83	1.97076	.2658
2100.	.4000	201.1202	.98947	2543.83	2.00807	.2494
2100.	.2000	404.3726	.99471	2550.89	2.07025	.2328
2125.	7.6356	9.0933	.84573	2355.81	1.69474	.5574
2125.	7.0000	10.0338	.85526	2368.41	1.70600	.5544
2125.	6.0000	11.9251	.87152	2390.12	1.72590	.5399
2125.	5.0000	14.6031	.88937	2414.12	1.74905	.5128
2125.	4.0000	18.6523	.90878	2440.33	1.77653	.4733
2125.	3.0000	25.4418	.92968	2468.58	1.81032	.4222
2125.	2.0000	39.0771	.95196	2498.68	1.85494	.3611
2125.	1.0000	80.0832	.97545	2530.36	1.92499	.2917

APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^{\theta}$	$s$	$h^{\theta}$	$u^{\theta}$	$c_p^{\theta}$
2125.	.8000	100.5997	.98028	2536.87	1.94636	.2770
2125.	.6000	134.7995	.97516	2543.43	1.97332	.2621
2125.	.4000	203.2071	.99007	2550.04	2.01048	.2469
2125.	.2000	408.4455	.99501	2556.69	2.07251	.2315
2150.	8.2454	6.4557	.84315	2358.08	1.68983	.5513
2150.	8.0000	8.7742	.84681	2362.86	1.69404	.5509
2150.	7.0000	10.2005	.86140	2392.14	1.71128	.5435
2150.	6.0000	12.1208	.87734	2403.44	1.73102	.5257
2150.	5.0000	14.8322	.89467	2416.74	1.75391	.4970
2150.	4.0000	18.9277	.91336	2451.96	1.78101	.4577
2150.	3.0000	25.7893	.93335	2478.97	1.81432	.4086
2150.	2.0000	39.5623	.95454	2507.58	1.85837	.3509
2150.	1.0000	80.9698	.97681	2537.59	1.92777	.2862
2150.	.8000	101.6857	.98137	2543.74	1.94900	.2726
2150.	.6000	136.2171	.98598	2549.94	1.97583	.2587
2150.	.4000	205.2872	.99062	2556.18	2.01285	.2446
2150.	.2000	412.5115	.99529	2562.47	2.07473	.2304
2175.	8.9735	7.8739	.84054	2360.34	1.68504	.5454
2175.	8.0000	8.9225	.85294	2376.53	1.69926	.5426
2175.	7.0000	10.3690	.86732	2395.58	1.71641	.5315
2175.	6.0000	12.3144	.88290	2416.40	1.73597	.5112
2175.	5.0000	15.0583	.89969	2438.97	1.75858	.4816
2175.	4.0000	19.1992	.91767	2463.22	1.78530	.4430
2175.	3.0000	26.1321	.93679	2489.02	1.81815	.3959
2175.	2.0000	40.0420	.95695	2516.23	1.86107	.3416
2175.	1.0000	81.8505	.97806	2544.68	1.93047	.2812
2175.	.8000	102.7656	.98239	2550.50	1.95158	.2685
2175.	.6000	137.6285	.98674	2556.37	1.97828	.2556
2175.	.4000	207.3610	.99113	2562.27	2.01517	.2426
2175.	.2000	416.5712	.99555	2568.21	2.07692	.2294
2200.	9.6408	7.3423	.83789	2362.59	1.68036	.5400
2200.	9.0000	7.9393	.84580	2372.81	1.68921	.5393
2200.	8.0000	9.0701	.85891	2389.98	1.70434	.5328
2200.	7.0000	10.5552	.87303	2408.71	1.72137	.5189
2200.	6.0000	12.5059	.88820	2429.00	1.74073	.4969
2200.	5.0000	15.2813	.90444	2450.83	1.76306	.4669
2200.	4.0000	19.4669	.92172	2474.12	1.78942	.4291
2200.	3.0000	26.4705	.94000	2498.77	1.82183	.3842
2200.	2.0000	40.5166	.95919	2524.66	1.86485	.3330
2200.	1.0000	82.7257	.97923	2551.65	1.93311	.2766
2200.	.8000	103.8399	.98333	2557.17	1.95410	.2648
2200.	.6000	139.0344	.98745	2562.72	1.98068	.2528
2200.	.4000	209.4292	.99161	2568.31	2.01745	.2407
2200.	.2000	420.6251	.99579	2573.94	2.07909	.2284
2225.	10.3488	6.8556	.83520	2364.82	1.67580	.5349
2225.	10.0000	7.1604	.83969	2370.56	1.68069	.5350
2225.	9.0000	8.0705	.85177	2386.19	1.69422	.5315
2225.	8.0000	9.2169	.86468	2403.17	1.70927	.5220
2225.	7.0000	10.7019	.87849	2421.52	1.72616	.5059
2225.	6.0000	12.6951	.89324	2441.25	1.74531	.4828
2225.	5.0000	15.5017	.90893	2462.32	1.76736	.4528
2225.	4.0000	19.7310	.92553	2484.68	1.79337	.4161
2225.	3.0000	26.8047	.94300	2508.24	1.82538	.3733
2225.	2.0000	40.9867	.96129	2532.89	1.86793	.3251
2225.	1.0000	83.5958	.98031	2558.51	1.93567	.2724
2225.	.8000	104.9091	.98420	2563.74	1.95656	.2614
2225.	.6000	140.4350	.98811	2569.01	1.98303	.2502
2225.	.4000	211.4920	.99205	2574.31	2.01969	.2389
2225.	.2000	424.6757	.99601	2579.63	2.08122	.2275
2250.	11.1789	6.4092	.83245	2367.02	1.67133	.5304

## APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^g$	$z$	$h^g$	$u^g$	$c_p^g$
2250.	11.0000	6,5287	.83440	2369.48	1,67340	.5305
2250.	10.0000	7,2784	.84564	2383.86	1,68562	.5287
2250.	9.0000	8,2011	.85757	2399.37	1,69910	.5223
2250.	8.0000	9,3626	.87025	2416.08	1,71406	.5105
2250.	7.0000	10,8659	.88373	2434.00	1,73079	.4929
2250.	6.0000	12,8821	.89803	2453.14	1,74972	.4691
2250.	5.0000	15,7190	.91317	2473.47	1,77149	.4394
2250.	4.0000	19,9917	.92910	2494.93	1,79717	.4039
2250.	3.0000	27,1349	.94581	2517.44	1,82879	.3632
2250.	2.0000	41,4523	.96324	2540.92	1,87091	.3179
2250.	1.0000	84,4612	.98132	2565.27	1,93818	.2685
2250.	.8000	105,9736	.98501	2570.24	1,95897	.2583
2250.	.6000	141,8307	.98873	2575.23	1,98534	.2479
2250.	.4000	213,5500	.99246	2580.26	2,02190	.2374
2250.	.2000	428,7174	.99622	2585.31	2,08332	.2267
2275.	12.0022	5,9992	.82963	2369.17	1,66696	.5263
2275.	12.0000	6,0063	.82976	2369.33	1,66709	.5263
2275.	11.0000	6,6358	.84034	2382.68	1,67825	.5255
2275.	10.0000	7,3960	.85145	2396.98	1,69044	.5210
2275.	9.0000	8,3310	.86319	2412.30	1,70385	.5122
2275.	8.0000	9,5071	.87560	2428.69	1,71869	.4987
2275.	7.0000	11,0281	.88872	2446.16	1,73526	.4799
2275.	6.0000	13,0668	.90258	2464.71	1,75397	.4559
2275.	5.0000	15,9336	.91717	2484.30	1,77547	.4267
2275.	4.0000	20,2492	.93247	2504.88	1,80083	.3925
2275.	3.0000	27,4616	.94845	2526.41	1,83209	.3539
2275.	2.0000	41,9140	.96506	2548.79	1,87380	.3112
2275.	1.0000	85,3223	.98226	2571.94	1,94063	.2650
2275.	.8000	107,0334	.98577	2576.66	1,96133	.2554
2275.	.6000	143,2221	.98930	2581.40	1,98761	.2457
2275.	.4000	215,6035	.99285	2586.17	2,02407	.2359
2275.	.2000	432,7565	.99641	2590.97	2,08540	.2260
2300.	12.8403	5,6220	.82674	2371.28	1,66268	.5229
2300.	12.0000	6,1045	.83569	2382.44	1,67186	.5222
2300.	11.0000	5,7428	.84614	2395.74	1,68300	.5188
2300.	10.0000	7,5130	.85709	2409.90	1,69515	.5121
2300.	9.0000	8,4599	.86861	2424.98	1,70847	.5016
2300.	8.0000	9,6502	.88073	2441.01	1,72318	.4867
2300.	7.0000	11,1886	.89349	2458.00	1,73957	.4673
2300.	6.0000	13,2492	.90689	2475.94	1,75806	.4432
2300.	5.0000	16,1455	.92095	2494.81	1,77930	.4147
2300.	4.0000	20,5036	.93563	2514.56	1,80435	.3819
2300.	3.0000	27,7848	.95091	2535.14	1,83526	.3452
2300.	2.0000	42,3719	.96677	2556.49	1,87660	.3050
2300.	1.0000	86,1794	.98314	2578.53	1,94303	.2618
2300.	.8000	108,0896	.98648	2583.01	1,96364	.2528
2300.	.6000	144,6094	.98983	2587.52	1,98983	.2437
2300.	.4000	217,6529	.99320	2592.06	2,02621	.2346
2300.	.2000	436,7914	.99659	2596.61	2,08746	.2253
2325.	13.8143	5,2744	.82376	2373.32	1,65848	.5201
2325.	13.0000	5,6581	.83159	2382.97	1,66629	.5192
2325.	12.0000	6,2026	.84150	2395.43	1,67655	.5164
2325.	11.0000	6,8493	.85180	2408.61	1,68765	.5110
2325.	10.0000	7,6294	.86255	2422.58	1,69972	.5025
2325.	9.0000	8,5878	.87382	2437.38	1,71294	.4905
2325.	8.0000	9,7919	.88564	2453.02	1,72751	.4747
2325.	7.0000	11,3472	.89802	2469.53	1,74373	.4549
2325.	6.0000	13,4295	.91098	2486.87	1,76200	.4311
2325.	5.0000	16,3548	.92451	2505.04	1,78298	.4034
2325.	4.0000	20,7551	.93860	2523.99	1,80775	.3720

APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^0$	$z$	$A^0$	$s^0$	$c_p^0$
2325.	3.0000	28.1047	.95323	2543.67	1.83934	.3372
2325.	2.0000	42.8263	.96836	2564.04	1.87933	.2993
2325.	1.0000	87.0328	.98397	2585.03	1.94537	.2588
2325.	.6000	109.1419	.98714	2589.30	1.96591	.2504
2325.	.4000	145.9928	.99033	2593.59	1.99202	.2419
2325.	.2000	219.6964	.99354	2577.90	2.02832	.2333
2325.	.1000	440.8225	.99676	2602.24	2.08948	.2247
2350.	14.7654	4.9536	.82069	2375.27	1.65435	.5181
2350.	14.0000	5.2779	.82795	2394.13	1.66139	.5167
2350.	13.0000	5.7488	.83740	2395.89	1.67091	.5139
2350.	12.0000	6.3004	.84716	2408.25	1.68113	.5093
2350.	11.0000	6.9553	.85728	2421.28	1.69218	.5023
2350.	10.0000	7.7449	.86782	2435.02	1.70417	.4924
2350.	9.0000	8.7146	.87883	2449.50	1.71727	.4794
2350.	8.0000	9.9321	.89033	2464.75	1.73170	.4630
2350.	7.0000	11.5041	.90233	2480.75	1.74774	.4430
2350.	6.0000	13.6076	.91485	2497.50	1.76580	.4196
2350.	5.0000	16.5617	.92788	2514.99	1.78654	.3928
2350.	4.0000	21.0039	.94140	2533.17	1.81103	.3627
2350.	3.0000	28.4217	.95540	2552.01	1.84132	.3297
2350.	2.0000	43.2775	.96986	2571.46	1.88198	.2940
2350.	1.0000	87.8827	.98473	2591.47	1.94767	.2560
2350.	.6000	110.1906	.98776	2595.53	1.96813	.2482
2350.	.4000	147.3728	.99080	2599.62	1.99418	.2402
2350.	.2000	221.7404	.99385	2603.72	2.03040	.2322
2350.	.1000	444.8499	.99692	2607.85	2.09149	.2241
2375.	15.8055	4.6570	.81750	2377.14	1.65029	.5168
2375.	15.0000	4.9534	.82470	2385.82	1.65707	.5148
2375.	14.0000	5.3623	.83377	2396.99	1.66595	.5118
2375.	13.0000	5.8397	.84307	2408.66	1.67543	.5074
2375.	12.0000	6.3977	.85265	2420.89	1.68561	.5013
2375.	11.0000	7.0636	.86258	2433.72	1.69658	.4930
2375.	10.0000	7.8595	.87289	2447.20	1.70848	.4820
2375.	9.0000	8.8401	.88363	2461.35	1.72147	.4683
2375.	8.0000	10.0739	.89480	2476.18	1.73575	.4515
2375.	7.0000	11.6592	.90643	2491.68	1.75161	.4316
2375.	6.0000	13.7837	.91851	2507.86	1.76947	.4087
2375.	5.0000	16.7663	.93105	2524.68	1.78998	.3828
2375.	4.0000	21.2591	.94404	2542.13	1.81421	.3541
2375.	3.0000	28.7359	.95745	2560.16	1.84421	.3228
2375.	2.0000	43.7257	.97126	2578.74	1.88456	.2892
2375.	1.0000	88.7294	.98545	2597.84	1.94993	.2535
2375.	.8000	111.2362	.98834	2601.71	1.97032	.2461
2375.	.6000	148.7494	.99123	2605.60	1.99630	.2387
2375.	.4000	223.7791	.99414	2609.52	2.03246	.2317
2375.	.2000	448.8741	.99706	2613.44	2.09347	.223
2400.	16.8750	4.3825	.81419	2378.89	1.64629	.516
2400.	16.0000	4.6653	.82178	2387.96	1.65323	.5134
2400.	15.0000	5.0294	.83054	2398.64	1.66157	.5099
2400.	14.0000	5.4464	.83945	2409.71	1.67042	.5056
2400.	13.0000	5.9292	.84858	2421.25	1.67986	.5000
2400.	12.0000	6.4944	.85798	2433.31	1.68997	.4927
2400.	11.0000	7.1651	.86770	2445.92	1.70087	.4833
2400.	10.0000	7.9731	.87777	2459.12	1.71267	.4715
2400.	9.0000	8.9644	.88822	2472.92	1.72553	.4573
2400.	8.0000	10.2081	.89907	2487.32	1.73967	.4403
2400.	7.0000	11.8125	.91032	2502.33	1.75535	.4206
2400.	6.0000	13.9578	.92198	2517.94	1.77301	.3983
2400.	5.0000	16.9666	.93405	2534.13	1.79330	.3734

## APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$c_p^g$	$z$	$h^g$	$u^g$	$c_p^g$
2400.	4.0000	21.4938	.94652	2550.88	1.81728	.3460
2400.	3.0000	29.0474	.95936	2568.15	1.84701	.3164
2400.	2.0000	44.1711	.97257	2585.92	1.88708	.2847
2400.	1.0000	89.5732	.98613	2604.14	1.95214	.2511
2400.	.6000	112.2787	.98888	2607.84	1.97248	.2442
2400.	.4000	150.1231	.99164	2611.55	1.99839	.2372
2400.	.2000	225.8147	.99441	2615.28	2.03448	.2302
2400.	.1000	452.8452	.99720	2619.05	2.09543	.2231
2425.	17.9961	4.1279	.81073	2380.52	1.64234	.5169
2425.	17.0000	4.4152	.81916	2390.49	1.64981	.5126
2425.	16.0000	4.7397	.82765	2400.74	1.65767	.5084
2425.	15.0000	5.1081	.83623	2411.31	1.66598	.5039
2425.	14.0000	5.5301	.84497	2422.27	1.67479	.4985
2425.	13.0000	6.0186	.85392	2433.65	1.68417	.4919
2425.	12.0000	6.5905	.86312	2445.52	1.69422	.4836
2425.	11.0000	7.2687	.87262	2457.88	1.70503	.4734
2425.	10.0000	8.0856	.88244	2470.78	1.71673	.4611
2425.	9.0000	9.0875	.89261	2484.21	1.72947	.4465
2425.	8.0000	10.3439	.90313	2498.19	1.74345	.4295
2425.	7.0000	11.9641	.91402	2512.72	1.75897	.4102
2425.	6.0000	14.1300	.92527	2527.78	1.77644	.3885
2425.	5.0000	17.1689	.93689	2543.36	1.79651	.3646
2425.	4.0000	21.7353	.94886	2559.43	1.82026	.3385
2425.	3.0000	29.3565	.96117	2575.98	1.84974	.3104
2425.	2.0000	44.6138	.97381	2592.98	1.88954	.2805
2425.	1.0000	90.4142	.98676	2610.39	1.95432	.2490
2425.	.6000	113.3184	.98939	2613.92	1.97459	.2425
2425.	.4000	151.4939	.99202	2617.47	2.00045	.2359
2425.	.2000	227.6475	.99467	2621.03	2.03648	.2293
2425.	.1000	455.9134	.99733	2624.60	2.09737	.2227
2450.	19.1493	3.8714	.80712	2382.01	1.63844	.5185
2450.	19.0000	3.9329	.80853	2383.64	1.63962	.5175
2450.	18.0000	4.1939	.81681	2393.35	1.64676	.5121
2450.	17.0000	4.4855	.82506	2403.24	1.65421	.5073
2450.	16.0000	4.8137	.83335	2413.38	1.66204	.5024
2450.	15.0000	5.1864	.84176	2423.82	1.67030	.4971
2450.	14.0000	5.6134	.85032	2434.63	1.67906	.4908
2450.	13.0000	6.1075	.85908	2445.84	1.68838	.4833
2450.	12.0000	6.6855	.86808	2457.49	1.69835	.4742
2450.	11.0000	7.3715	.87736	2469.59	1.70908	.4634
2450.	10.0000	8.1971	.88692	2482.17	1.72066	.4507
2450.	9.0000	9.2093	.89680	2495.24	1.73327	.4360
2450.	8.0000	10.4783	.90700	2508.80	1.74711	.4192
2450.	7.0000	12.1142	.91753	2522.85	1.76246	.4003
2450.	6.0000	14.3004	.92838	2537.37	1.77975	.3793
2450.	5.0000	17.3671	.93956	2552.37	1.79962	.3563
2450.	4.0000	21.9746	.95106	2567.81	1.82315	.3315
2450.	3.0000	29.6632	.96287	2583.67	1.85239	.3049
2450.	2.0000	45.0541	.97497	2599.94	1.89194	.2766
2450.	1.0000	91.2526	.98735	2616.59	1.95646	.2470
2450.	.6000	114.3556	.98986	2619.96	1.97668	.2409
2450.	.4000	152.8622	.99238	2623.35	2.00248	.2347
2450.	.2000	229.8777	.99491	2626.75	2.03846	.2285
2450.	.1000	460.9290	.99745	2630.16	2.09929	.2223
2475.	20.3562	3.6715	.80334	2393.33	1.63458	.5213
2475.	20.0000	3.7593	.80659	2397.06	1.63721	.5184
2475.	19.0000	3.9970	.81470	2396.51	1.64403	.5120
2475.	18.0000	4.2607	.82274	2406.08	1.65111	.5065
2475.	17.0000	4.5554	.83079	2415.85	1.65852	.5012
2475.	16.0000	4.8874	.83889	2425.85	1.66631	.4957

APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^g$	$z$	$h^g$	$s^g$	$c_p^g$
2475.	15.0000	5.2643	.84712	2436.16	1.67452	.4896
2475.	14.0000	5.6961	.85549	2446.80	1.68322	.4826
2475.	13.0000	6.1957	.86407	2457.82	1.69248	.4744
2475.	12.0000	6.7833	.87286	2469.23	1.70237	.4647
2475.	11.0000	7.4734	.88190	2481.06	1.71300	.4535
2475.	10.0000	8.3075	.89121	2493.32	1.72448	.4406
2475.	9.0000	9.3299	.90080	2506.02	1.73696	.4259
2475.	8.0000	10.6112	.91068	2519.16	1.75066	.4093
2475.	7.0000	12.2626	.92086	2532.74	1.76585	.3909
2475.	6.0000	14.4690	.93133	2546.75	1.78296	.3706
2475.	5.0000	17.5635	.94209	2561.18	1.80263	.3486
2475.	4.0000	22.2119	.95314	2576.01	1.82596	.3249
2475.	3.0000	29.9578	.96447	2591.23	1.85498	.2997
2475.	2.0000	45.4921	.97606	2606.81	1.89429	.2730
2475.	1.0000	92.0886	.98791	2622.74	1.95856	.2451
2475.	.8000	115.3903	.99031	2625.97	1.97873	.2394
2475.	.6000	154.2279	.99272	2629.20	2.00448	.2336
2475.	.4000	231.9054	.99514	2632.45	2.04041	.2278
2475.	.2000	464.9420	.99756	2635.72	2.10119	.2219
2500.	21.6779	3.4666	.79936	2384.46	1.63074	.5254
2500.	21.0000	3.6030	.80485	2390.72	1.63506	.5195
2500.	20.0000	3.8206	.81281	2399.94	1.64159	.5122
2500.	19.0000	4.0606	.82067	2409.24	1.64835	.5060
2500.	18.0000	4.3270	.82849	2418.67	1.65538	.5002
2500.	17.0000	4.6249	.83634	2428.29	1.66275	.4944
2500.	16.0000	4.9606	.84421	2438.16	1.67048	.4884
2500.	15.0000	5.3417	.85231	2448.30	1.67864	.4816
2500.	14.0000	5.7782	.86050	2458.76	1.68728	.4740
2500.	13.0000	6.2832	.86887	2469.56	1.69646	.4653
2500.	12.0000	6.8741	.87745	2480.73	1.70627	.4553
2500.	11.0000	7.5743	.88626	2492.27	1.71680	.4438
2500.	10.0000	8.4168	.89531	2504.21	1.72817	.4307
2500.	9.0000	9.4492	.90462	2516.54	1.74053	.4161
2500.	8.0000	10.7428	.91419	2529.27	1.75409	.3998
2500.	7.0000	12.4095	.92402	2542.40	1.76913	.3819
2500.	6.0000	14.6360	.93412	2555.91	1.78607	.3624
2500.	5.0000	17.7581	.94448	2569.80	1.80556	.3413
2500.	4.0000	22.4472	.95510	2584.06	1.82869	.3188
2500.	3.0000	30.2703	.96598	2598.66	1.85750	.2949
2500.	2.0000	45.9279	.97709	2613.60	1.89659	.2697
2500.	1.0000	92.9224	.98844	2628.85	1.96064	.2434
2500.	.8000	116.4228	.99073	2631.93	1.98076	.2380
2500.	.6000	155.5915	.99304	2635.03	2.00646	.2325
2500.	.4000	233.9308	.99535	2638.14	2.04234	.2271
2500.	.2000	468.9528	.99767	2641.26	2.10307	.2216
2525.	23.0156	3.2754	.79517	2385.38	1.62693	.5310
2525.	23.0000	3.2781	.79530	2385.53	1.62702	.5308
2525.	22.0000	3.4617	.80331	2394.60	1.63313	.5208
2525.	21.0000	3.6618	.81113	2403.62	1.63940	.5126
2525.	20.0000	3.8813	.81881	2412.67	1.64587	.5056
2525.	19.0000	4.1237	.82644	2421.80	1.65257	.4993
2525.	18.0000	4.3929	.83406	2431.09	1.65956	.4933
2525.	17.0000	4.6940	.84172	2440.56	1.66687	.4871
2525.	16.0000	5.0333	.84946	2450.27	1.67456	.4806
2525.	15.0000	5.4185	.85732	2460.24	1.68265	.4734
2525.	14.0000	5.8597	.86532	2470.50	1.69123	.4653
2525.	13.0000	6.3701	.87350	2481.08	1.70034	.4562
2525.	12.0000	6.9670	.88186	2491.99	1.71006	.4458
2525.	11.0000	7.6742	.89044	2503.25	1.72050	.4342
2525.	10.0000	8.5250	.89923	2514.86	1.73175	.4212

## APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^g$	$z$	$h^g$	$u^g$	$c_p^g$
1A00.	.6000	115.4586	.96517	2446.25	1.93300	.3567
1A00.	.4000	175.2357	.97658	2461.66	1.97385	.3111
1A00.	.2000	354.6409	.98820	2477.32	2.03965	.2641
1A25.	2.5625	24.8259	.87662	2330.88	1.76579	.6374
1A25.	2.0000	32.6494	.89981	2362.73	1.79875	.5806
1A25.	1.0000	68.7248	.94702	2427.08	1.88235	.4223
1A25.	.8000	86.6518	.95723	2440.91	1.90676	.3839
1A25.	.6000	117.0358	.96765	2455.00	1.93685	.3439
1A25.	.4000	177.4791	.97826	2469.33	1.97722	.3024
1A25.	.2000	358.0735	.98905	2483.87	2.04253	.2597
1A50.	2.8362	22.5901	.87394	2332.70	1.75885	.6315
1A50.	2.0000	33.2406	.90619	2376.90	1.80492	.5535
1A50.	1.0000	69.7431	.95065	2437.41	1.88684	.4044
1A50.	.6000	88.0533	.96019	2450.32	1.91086	.3691
1A50.	.4000	118.5924	.96990	2463.45	1.94053	.3325
1A50.	.2000	179.7014	.97979	2476.79	1.98047	.2946
1A50.	.2000	363.0844	.98982	2490.31	2.04533	.2557
1A75.	3.1365	20.6003	.87130	2334.57	1.75213	.6252
1A75.	3.0000	21.6483	.87577	2340.70	1.75811	.6177
1A75.	2.0000	33.8198	.91211	2390.42	1.81075	.5282
1A75.	1.0000	70.7442	.95397	2447.31	1.89111	.3883
1A75.	.8000	89.2569	.96289	2459.38	1.91476	.3558
1A75.	.6000	120.1305	.97196	2471.64	1.94406	.3223
1A75.	.4000	181.9045	.98118	2484.07	1.98360	.2877
1A75.	.2000	367.2757	.99053	2496.66	2.04806	.2522
1A00.	3.4586	18.8251	.86868	2336.50	1.74560	.6187
1A00.	3.0000	22.0562	.88282	2355.85	1.76457	.5944
1A00.	2.0000	34.3874	.91759	2403.32	1.81624	.5046
1A00.	1.0000	71.7296	.95701	2456.84	1.89517	.3738
1A00.	.8000	90.4442	.96536	2468.12	1.91848	.3439
1A00.	.6000	121.6518	.97384	2479.58	1.94744	.3131
1A00.	.4000	184.0903	.98245	2491.18	1.98663	.2814
1A00.	.2000	371.4493	.99117	2502.92	2.05073	.2490
1A25.	3.8057	17.2578	.86609	2338.49	1.73927	.6120
1A25.	3.0000	22.4579	.88947	2370.42	1.77071	.5714
1A25.	2.0000	34.9440	.92267	2415.66	1.82145	.4828
1A25.	1.0000	72.7008	.95980	2466.01	1.89904	.3606
1A25.	.8000	91.6167	.96762	2476.58	1.92205	.3332
1A25.	.6000	123.1578	.97556	2487.30	1.95070	.3049
1A25.	.4000	186.2605	.98361	2498.14	1.98957	.2758
1A25.	.2000	375.6070	.99176	2509.11	2.05334	.2462
1A50.	4.1791	15.8152	.86352	2340.52	1.73313	.6052
1A50.	4.0000	16.5097	.86803	2346.67	1.73896	.6000
1A50.	3.0000	22.8529	.89573	2384.43	1.77655	.5489
1A50.	2.0000	35.4903	.92737	2427.48	1.82638	.4627
1A50.	1.0000	73.6589	.96236	2474.88	1.90273	.3488
1A50.	.8000	92.7758	.96970	2484.79	1.92547	.3235
1A50.	.6000	124.6500	.97714	2494.82	1.95384	.2974
1A50.	.4000	188.4166	.98467	2504.98	1.99242	.2708
1A50.	.2000	379.7502	.99229	2515.24	2.05590	.2436
1A75.	4.5800	14.5375	.86096	2342.60	1.72716	.5982
1A75.	4.0000	16.9134	.87482	2361.44	1.74506	.5816
1A75.	3.0000	23.2413	.90160	2397.88	1.78211	.5274
1A75.	2.0000	36.0269	.93172	2438.81	1.83105	.4442
1A75.	1.0000	74.6051	.96471	2483.46	1.90628	.3381
1A75.	.8000	93.9226	.97161	2492.76	1.92877	.3147
1A75.	.6000	126.1297	.97859	2502.18	1.95687	.2908
1A75.	.4000	190.5598	.98565	2511.69	1.99519	.2663
1A75.	.2000	383.8803	.99279	2521.30	2.05840	.2413
2A00.	5.0097	13.3875	.85842	2344.73	1.72137	.5912

APPENDIX B

THERMODYNAMIC PROPERTIES OF SODIUM VAPOR (cont'd)  
(Monomer Gas Base)

$t$	$p$	$v^g$	$z$	$h^g$	$s^g$	$c_p^g$
2525.	9.0000	9.5673	.90826	2526.82	1.74399	.4067
2525.	8.0000	10.5730	.91752	2539.15	1.75741	.3908
2525.	7.0000	12.5550	.92702	2551.84	1.77230	.3735
2525.	6.0000	14.8014	.93676	2564.87	1.78908	.3547
2525.	5.0000	17.9509	.94674	2578.25	1.80840	.3346
2525.	4.0000	22.6808	.95696	2591.95	1.83135	.3131
2525.	3.0000	30.5710	.96740	2605.98	1.85996	.2904
2525.	2.0000	46.3618	.97806	2620.30	1.89885	.2666
2525.	1.0000	93.7541	.98893	2634.91	1.96268	.2418
2525.	.6000	117.4552	.99113	2637.87	1.98275	.2367
2525.	.5000	156.9529	.99333	2640.83	2.00841	.2316
2525.	.4000	235.9541	.99555	2643.81	2.04424	.2264
2525.	.2000	472.9615	.99777	2646.79	2.10494	.2212
2550.	24.4105	3.0967	.79073	2386.06	1.62312	.5382
2550.	24.0000	3.1629	.79406	2389.77	1.62552	.5330
2550.	23.0000	3.3533	.80196	2398.68	1.63141	.5220
2550.	22.0000	3.5182	.80964	2407.52	1.63744	.5130
2550.	21.0000	3.7200	.81717	2416.34	1.64364	.5054
2550.	20.0000	3.9416	.82461	2425.22	1.65005	.4986
2550.	19.0000	4.1863	.83203	2434.20	1.65671	.4922
2550.	18.0000	4.4583	.83945	2443.33	1.66365	.4859
2550.	17.0000	4.7625	.84693	2452.65	1.67091	.4795
2550.	16.0000	5.1054	.85449	2462.18	1.67853	.4725
2550.	15.0000	5.4947	.86216	2471.97	1.68657	.4649
2550.	14.0000	5.9405	.86997	2482.02	1.69507	.4565
2550.	13.0000	6.4561	.87794	2492.37	1.70410	.4471
2550.	12.0000	7.0590	.88609	2503.02	1.71374	.4366
2550.	11.0000	7.7732	.89443	2513.98	1.72408	.4249
2550.	10.0000	8.6322	.90297	2525.27	1.73523	.4120
2550.	9.0000	9.6843	.91172	2536.88	1.74735	.3978
2550.	8.0000	11.0020	.92069	2548.82	1.76064	.3823
2550.	7.0000	12.6491	.92987	2561.07	1.77538	.3655
2550.	6.0000	14.6853	.93927	2573.65	1.79201	.3474
2550.	5.0000	18.1422	.94888	2586.53	1.81116	.3282
2550.	4.0000	22.9125	.95871	2599.71	1.83393	.3078
2550.	3.0000	30.8698	.96874	2613.18	1.86237	.2863
2550.	2.0000	46.7937	.97897	2626.93	1.90106	.2637
2550.	1.0000	94.5539	.98939	2640.94	1.96469	.2403
2550.	.8000	118.4516	.99150	2643.77	1.98472	.2355
2550.	.6000	158.3123	.99362	2646.61	2.01034	.2307
2550.	.4000	237.9754	.99574	2649.46	2.04613	.2258
2550.	.2000	476.9681	.99786	2652.32	2.10678	.2209
2575.	25.8638	2.9294	.78602	2386.47	1.61932	.5475
2575.	25.0000	3.0575	.79300	2394.20	1.62418	.5350
2575.	24.0000	3.2162	.80078	2402.97	1.62988	.5232
2575.	23.0000	3.3877	.80833	2411.63	1.63570	.5135
2575.	22.0000	3.5740	.81571	2420.25	1.64165	.5053
2575.	21.0000	3.7776	.82299	2428.89	1.64779	.4980
2575.	20.0000	4.0013	.83021	2437.59	1.65415	.4913
2575.	19.0000	4.2485	.83742	2446.41	1.66075	.4848
2575.	18.0000	4.5232	.84466	2455.38	1.66763	.4783
2575.	17.0000	4.8307	.85196	2464.53	1.67484	.4715
2575.	16.0000	5.1771	.85933	2473.89	1.68240	.4643
2575.	15.0000	5.5703	.86682	2483.48	1.69038	.4564
2575.	14.0000	6.0207	.87445	2493.33	1.69881	.4477
2575.	13.0000	6.5414	.88222	2503.43	1.70777	.4381
2575.	12.0000	7.1502	.89015	2513.82	1.71732	.4275
2575.	11.0000	7.8713	.89826	2524.49	1.72756	.4159
2575.	10.0000	8.7384	.90655	2535.46	1.73860	.4031
2575.	9.0000	9.8001	.91503	2546.72	1.75060	.3892
2575.	8.0000	11.1297	.92370	2558.27	1.76376	.3741
2575.	7.0000	12.8418	.93258	2570.12	1.77838	.3579
2575.	6.0000	15.1278	.94165	2582.25	1.79485	.3406
2575.	5.0000	18.3320	.95091	2594.66	1.81385	.3222
2575.	4.0000	23.1428	.96037	2607.35	1.83646	.3028
2575.	3.0000	31.1670	.97001	2620.29	1.86472	.2824
2575.	2.0000	47.2239	.97983	2633.49	1.90323	.2611
2575.	1.0000	95.4118	.98983	2646.93	1.96667	.2389
2575.	.8000	119.5082	.99185	2649.64	1.98667	.2344
2575.	.6000	159.6699	.99388	2652.37	2.01224	.2298
2575.	.4000	239.9948	.99591	2655.10	2.04800	.2253
2575.	.2000	480.9728	.99795	2657.84	2.10861	.2206

APPENDIX C

THE MOLECULAR COMPOSITION OF SATURATED SODIUM  
VAPOR AND ENTHALPIES OF VAPORIZATION

$t$	$P_s$	$(z_2)_s$	$(z_4)_s$	$(M_a)_s$	$\Delta h_v$	$\Delta h_{v_1}$
1600.	.9100	.193900	.003021	25.5220	1692.35	1833.74
1625.	1.0327	.198008	.003493	25.5904	1685.54	1830.27
1650.	1.1482	.202039	.004023	25.6593	1678.79	1826.83
1675.	1.3176	.205989	.004615	25.7288	1672.09	1823.44
1700.	1.4818	.209856	.005274	25.7989	1665.44	1820.10
1725.	1.6420	.213436	.006005	25.8697	1658.86	1816.82
1750.	1.8590	.217327	.006813	25.9412	1652.34	1813.60
1775.	2.0740	.220924	.007702	26.0136	1645.87	1810.44
1800.	2.3081	.224427	.008679	26.0869	1639.47	1807.33
1825.	2.5425	.227830	.009747	26.1612	1633.12	1804.29
1850.	2.8382	.231133	.010913	26.2366	1626.83	1801.32
1875.	3.1365	.234331	.012181	26.3132	1620.59	1798.40
1900.	3.4586	.237422	.013555	26.3910	1614.40	1795.53
1925.	3.8057	.240403	.015040	26.4701	1608.24	1792.72
1950.	4.1791	.243271	.016641	26.5507	1602.12	1789.95
1975.	4.5800	.246024	.018361	26.6327	1596.03	1787.23
2000.	5.0097	.248660	.020205	26.7163	1589.95	1784.53
2025.	5.4694	.251175	.022176	26.8015	1583.88	1781.87
2050.	5.9606	.253568	.024277	26.8884	1577.80	1779.21
2075.	6.4845	.255838	.026510	26.9770	1571.72	1776.57
2100.	7.0424	.257981	.028878	27.0675	1565.61	1773.92
2125.	7.6356	.259997	.031383	27.1598	1559.46	1771.24
2150.	8.2656	.261884	.034025	27.2540	1553.26	1768.54
2175.	8.9335	.263641	.036806	27.3501	1546.99	1765.79
2200.	9.6408	.265267	.039725	27.4481	1540.65	1762.98
2225.	10.3888	.266763	.042783	27.5482	1534.20	1760.09
2250.	11.1789	.268127	.045978	27.6501	1527.64	1757.10
2275.	12.0122	.269360	.049309	27.7541	1520.95	1754.00
2300.	12.8903	.270462	.052774	27.8601	1514.10	1750.76
2325.	13.8143	.271435	.056370	27.9679	1507.09	1747.36
2350.	14.7856	.272279	.060094	28.0778	1499.88	1743.78
2375.	15.8055	.272995	.063943	28.1895	1492.45	1739.99
2400.	16.8752	.273586	.067912	28.3030	1484.78	1735.96
2425.	17.9961	.274053	.071997	28.4184	1476.84	1731.68
2450.	19.1693	.274399	.076193	28.5355	1468.61	1727.09
2475.	20.3962	.274627	.080496	28.6543	1460.03	1722.18
2500.	21.6779	.274739	.084898	28.7748	1451.09	1716.89
2525.	23.0156	.274738	.089395	28.8967	1441.74	1711.19
2550.	24.4105	.274627	.093980	29.0202	1431.93	1705.02
2575.	25.8638	.274411	.098647	29.1450	1421.62	1698.34

APPENDIX D  
MOLECULAR COMPOSITION OF SODIUM VAPOR

$t$	$p$	$x_2$	$x_4$	$M_a$
1600.	.9100	.193900	.003021	25.5220
1600.	.8000	.176493	.002178	25.2602
1600.	.6000	.141460	.001028	24.7602
1600.	.4000	.101271	.000344	24.2226
1600.	.2000	.054702	.000049	23.6372
1625.	1.0327	.196008	.003493	25.5904
1625.	1.0000	.193523	.003222	25.5209
1625.	.8000	.164103	.001822	25.0821
1625.	.6000	.130910	.000853	24.6169
1625.	.4000	.093217	.000283	24.1191
1625.	.2000	.050038	.000040	23.5805
1650.	1.1482	.202039	.004023	25.6593
1650.	1.0000	.180672	.002719	25.3296
1650.	.8000	.152604	.001527	24.9198
1650.	.6000	.121207	.000710	24.4868
1650.	.4000	.085883	.000233	24.0257
1650.	.2000	.045841	.000033	23.5297
1675.	1.3176	.205989	.004615	25.7288
1675.	1.0000	.168671	.002296	25.1545
1675.	.6000	.141947	.001281	24.7717
1675.	.6000	.112288	.000591	24.3688
1675.	.4000	.079205	.000193	23.9414
1675.	.2000	.042059	.000027	23.4841
1700.	1.4818	.209856	.005274	25.7989
1700.	1.0000	.157484	.001942	24.9943
1700.	.8000	.132083	.001077	24.6368
1700.	.6000	.104097	.000494	24.2616
1700.	.4000	.073123	.000160	23.8652
1700.	.2000	.038648	.000022	23.4432
1725.	1.6620	.213636	.006005	25.8697
1725.	1.0000	.147071	.001645	24.8476
1725.	.8000	.122962	.000907	24.5136
1725.	.6000	.096575	.000414	24.1641
1725.	.4000	.067582	.000133	23.7963
1725.	.2000	.035568	.000018	23.4064
1750.	1.8590	.217327	.006813	25.9412
1750.	1.0000	.137391	.001395	24.7134
1750.	.8000	.114532	.000766	24.4012
1750.	.6000	.089669	.000347	24.0755
1750.	.4000	.062531	.000111	23.7338
1750.	.2000	.032782	.000015	23.3732
1775.	2.0740	.220924	.007702	26.0136
1775.	2.0000	.215620	.007050	25.9215
1775.	1.0000	.128399	.001186	24.5904
1775.	.8000	.106747	.000648	24.2985
1775.	.6000	.083329	.000292	23.9948
1775.	.4000	.057924	.000093	23.6772
1775.	.2000	.030260	.000013	23.3432
1800.	2.3081	.224427	.008679	26.0869
1800.	2.0000	.203753	.006114	25.7290
1800.	1.0000	.120052	.001010	24.4776
1800.	.8000	.099558	.000549	24.2046

## APPENDIX D

## MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_4$	$M_a$
1800.	.6000	.077507	.000247	23.9213
1800.	.4000	.053719	.000078	23.6258
1800.	.2000	.027974	.000010	23.3161
1825.	2.5625	.227530	.009747	26.1612
1825.	2.0000	.192509	.005305	25.5508
1825.	1.0000	.112310	.000861	24.3743
1825.	.8000	.092920	.000467	24.1188
1825.	.6000	.072160	.000209	23.8542
1825.	.4000	.049879	.000066	23.5790
1825.	.2000	.025898	.000009	23.2916
1850.	2.8382	.231133	.010913	26.2366
1850.	2.0000	.181875	.004607	25.3861
1850.	1.0000	.105130	.000736	24.2795
1850.	.8000	.086793	.000397	24.0402
1850.	.6000	.067246	.000177	23.7930
1850.	.4000	.046367	.000056	23.5364
1850.	.2000	.024010	.000007	23.2693
1875.	3.1465	.234331	.012181	26.3132
1875.	3.0000	.227784	.010956	26.1875
1875.	2.0000	.171833	.004005	25.2336
1875.	1.0000	.098473	.000631	24.1924
1875.	.8000	.081134	.000339	23.9682
1875.	.6000	.062729	.000151	23.7370
1875.	.4000	.043155	.000047	23.4976
1875.	.2000	.022292	.000006	23.2490
1900.	3.4784	.237422	.013555	26.3910
1900.	3.0000	.216697	.009647	25.9943
1900.	2.0000	.162364	.003485	25.0924
1900.	1.0000	.092301	.000541	24.1124
1900.	.8000	.075908	.000290	23.9022
1900.	.6000	.058574	.000129	23.6858
1900.	.4000	.040212	.000040	23.4622
1900.	.2000	.020726	.000005	23.2306
1925.	3.8057	.240403	.015040	26.4701
1925.	3.0000	.206103	.008498	25.8146
1925.	2.0000	.153445	.003037	24.9618
1925.	1.0000	.086578	.000465	24.0388
1925.	.8000	.071080	.000249	23.8416
1925.	.6000	.054749	.000110	23.6388
1925.	.4000	.037514	.000034	23.4299
1925.	.2000	.019295	.000004	23.2138
1950.	4.1791	.243271	.016641	26.5507
1950.	4.0000	.236865	.015023	26.4160
1950.	3.0000	.195999	.007490	25.6473
1950.	2.0000	.145052	.002649	24.8408
1950.	1.0000	.081271	.000401	23.9711
1950.	.8000	.066617	.000214	23.7659
1950.	.6000	.051226	.000094	23.5958
1950.	.4000	.035038	.000029	23.4003
1950.	.2000	.017968	.000004	23.1985
1975.	4.5400	.246024	.018361	26.6327
1975.	4.0000	.226387	.013368	26.2207
1975.	3.0000	.186379	.006607	25.4917
1975.	2.0000	.137160	.002314	24.7286
1975.	1.0000	.076349	.000347	23.9087
1975.	.8000	.062491	.000184	23.7347
1975.	.6000	.047978	.000081	23.5563
1975.	.4000	.032763	.000025	23.3731
1975.	.2000	.016791	.000003	23.1845
2000.	5.0097	.248660	.020205	26.7163

## APPENDIX D

## MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_4$	$M_a$
2000.	5.0000	.246380	.020116	26.7099
2000.	4.0000	.216310	.011899	26.0383
2000.	3.0000	.177232	.005832	25.3468
2000.	2.0000	.129743	.002024	24.6246
2000.	1.0000	.071782	.000300	23.6512
2000.	.8000	.058672	.000159	23.6875
2000.	.6000	.044982	.000070	23.5200
2000.	.4000	.030671	.000021	23.3482
2000.	.2000	.015694	.000003	23.1717
2025.	5.4694	.251175	.022176	26.8015
2025.	5.0000	.238279	.018043	26.5065
2025.	4.0000	.206641	.010594	25.8680
2025.	3.0000	.168548	.005152	25.2119
2025.	2.0000	.122777	.001773	24.5282
2025.	1.0000	.067542	.000260	23.7981
2025.	.8000	.055137	.000138	23.6441
2025.	.6000	.042215	.000060	23.4866
2025.	.4000	.028745	.000018	23.3254
2025.	.2000	.014687	.000002	23.1599
2050.	5.9606	.253568	.024277	26.8884
2050.	5.0000	.228505	.016185	26.3159
2050.	4.0000	.197377	.009438	25.7090
2050.	3.0000	.160311	.004556	25.0863
2050.	2.0000	.116235	.001556	24.4386
2050.	1.0000	.063605	.000226	23.7491
2050.	.8000	.051862	.000120	23.6040
2050.	.6000	.039659	.000052	23.4558
2050.	.4000	.026969	.000016	23.3043
2050.	.2000	.013761	.000002	23.1491
2075.	6.4845	.255838	.026510	26.9770
2075.	6.0000	.244871	.022245	26.7050
2075.	5.0000	.219070	.014521	26.1374
2075.	4.0000	.188518	.008413	25.5604
2075.	3.0000	.152505	.004034	24.9693
2075.	2.0000	.110094	.001367	24.3555
2075.	1.0000	.059946	.000197	23.7038
2075.	.8000	.048825	.000104	23.5670
2075.	.6000	.037295	.000045	23.4275
2075.	.4000	.025332	.000014	23.2850
2075.	.2000	.012910	.000002	23.1392
2100.	7.0424	.257981	.028878	27.0675
2100.	7.0000	.257143	.028494	27.0450
2100.	6.0000	.235506	.020082	26.5108
2100.	5.0000	.209980	.013033	25.9703
2100.	4.0000	.180057	.007504	25.4215
2100.	3.0000	.145113	.003575	24.8602
2100.	2.0000	.104330	.001203	24.2782
2100.	1.0000	.056545	.000172	23.6618
2100.	.8000	.046008	.000091	23.5327
2100.	.6000	.035106	.000039	23.4013
2100.	.4000	.023819	.000012	23.2671
2100.	.2000	.012125	.000002	23.1301
2125.	7.6356	.259997	.031383	27.1598
2125.	7.0000	.247992	.025865	26.8383
2125.	6.0000	.226426	.018131	26.3285
2125.	5.0000	.201239	.011701	25.8137
2125.	4.0000	.171984	.006699	25.2918
2125.	3.0000	.138117	.003172	24.7585
2125.	2.0000	.098919	.001060	24.2063
2125.	1.0000	.053381	.000151	23.6230

## APPENDIX D

## MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_1$	$M_a$
2125.	.8000	.043393	.000079	23.5011
2125.	.6000	.033078	.000034	23.3770
2125.	.4000	.022420	.000010	23.2506
2125.	.2000	.011401	.000001	23.1216
2150.	8.2656	.261884	.034025	27.2540
2150.	8.0000	.257467	.031681	27.1264
2150.	7.0000	.239067	.023475	26.6437
2150.	6.0000	.217639	.016372	26.1574
2150.	5.0000	.192845	.010511	25.6670
2150.	4.0000	.164291	.005985	25.1704
2150.	3.0000	.131500	.002818	24.6635
2150.	2.0000	.093840	.000936	24.1394
2150.	1.0000	.050436	.000132	23.5870
2150.	.8000	.040962	.000069	23.4718
2150.	.6000	.031197	.000030	23.3546
2150.	.4000	.021125	.000009	23.2354
2150.	.2000	.010732	.000001	23.1138
2175.	8.9135	.263641	.036806	27.3501
2175.	8.0000	.248782	.028890	26.9220
2175.	7.0000	.230383	.021306	26.4607
2175.	6.0000	.209153	.014788	25.9968
2175.	5.0000	.184796	.009447	25.5296
2175.	4.0000	.156966	.005352	25.0569
2175.	3.0000	.125242	.002506	24.5749
2175.	2.0000	.089072	.000828	24.0770
2175.	1.0000	.047693	.000116	23.5535
2175.	.8000	.038703	.000061	23.4446
2175.	.6000	.029451	.000026	23.3339
2175.	.4000	.019925	.000008	23.2213
2175.	.2000	.010113	.000001	23.1067
2200.	9.6408	.265267	.039725	27.4481
2200.	9.0000	.256221	.034246	27.1681
2200.	8.0000	.240290	.026340	26.7292
2200.	7.0000	.221952	.019340	26.2885
2200.	6.0000	.200971	.013362	25.8460
2200.	5.0000	.177087	.008497	25.4007
2200.	4.0000	.149997	.004900	24.9507
2200.	3.0000	.119328	.002232	24.4921
2200.	2.0000	.084595	.000733	24.0190
2200.	1.0000	.045136	.000102	23.5225
2200.	.8000	.036600	.000054	23.4193
2200.	.6000	.027829	.000023	23.3146
2200.	.4000	.018812	.000007	23.2082
2200.	.2000	.009540	.000001	23.1000
2225.	10.3888	.266763	.042783	27.5482
2225.	10.0000	.261875	.039453	27.3860
2225.	9.0000	.247974	.031351	26.9675
2225.	8.0000	.232007	.024015	26.5476
2225.	7.0000	.213782	.017558	26.1266
2225.	6.0000	.193094	.012080	25.7044
2225.	5.0000	.169712	.007648	25.2800
2225.	4.0000	.143369	.004292	24.8512
2225.	3.0000	.113737	.001990	24.4147
2225.	2.0000	.080391	.000651	23.9648
2225.	1.0000	.042750	.000090	23.4936
2225.	.8000	.034641	.000047	23.3959
2225.	.6000	.026320	.000020	23.2967
2225.	.4000	.017779	.000006	23.1961
2225.	.2000	.009009	.000001	23.0938
2250.	11.1789	.268127	.045978	27.6501

APPENDIX D

MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_4$	$x_6$
2250.	11.0000	.266118	.044452	27.5789
2250.	10.0000	.253849	.036252	27.1792
2250.	9.0000	.239895	.028697	26.7781
2250.	8.0000	.223945	.021896	26.3764
2250.	7.0000	.205880	.015946	25.9742
2250.	6.0000	.185520	.010926	25.5713
2250.	5.0000	.162661	.006889	25.1666
2250.	4.0000	.137070	.003850	24.7581
2250.	3.0000	.108455	.001777	24.3423
2250.	2.0000	.076441	.000578	23.9142
2250.	1.0000	.040524	.000080	23.4667
2250.	.8000	.032815	.000042	23.3740
2250.	.6000	.024916	.000018	23.2801
2250.	.4000	.016819	.000005	23.1849
2250.	.2000	.008516	.000001	23.0881
2275.	12.0122	.269360	.049309	27.7541
2275.	12.0000	.269237	.049206	27.7495
2275.	11.0000	.258424	.040982	27.3671
2275.	10.0000	.246058	.033303	26.9835
2275.	9.0000	.232001	.026267	26.5993
2275.	8.0000	.216114	.019967	26.2151
2275.	7.0000	.198248	.014487	25.8309
2275.	6.0000	.178246	.009888	25.4464
2275.	5.0000	.155927	.006210	25.0603
2275.	4.0000	.131085	.003457	24.6707
2275.	3.0000	.103462	.001589	24.2745
2275.	2.0000	.072729	.000515	23.8669
2275.	1.0000	.038444	.000071	23.4416
2275.	.8000	.031112	.000037	23.3537
2275.	.6000	.023607	.000016	23.2647
2275.	.4000	.015925	.000005	23.1744
2275.	.2000	.008058	.000001	23.0828
2300.	12.8903	.270462	.052774	27.8601
2300.	12.0000	.261826	.045503	27.5340
2300.	11.0000	.250835	.037771	27.1665
2300.	10.0000	.238367	.030589	26.7985
2300.	9.0000	.224303	.024043	26.4306
2300.	8.0000	.208520	.018213	26.0631
2300.	7.0000	.190888	.013167	25.6961
2300.	6.0000	.171266	.008955	25.3289
2300.	5.0000	.149499	.005604	24.9605
2300.	4.0000	.125401	.003107	24.5888
2300.	3.0000	.098745	.001423	24.2110
2300.	2.0000	.069240	.000459	23.8227
2300.	1.0000	.036500	.000063	23.4183
2300.	.8000	.029521	.000033	23.3348
2300.	.6000	.022387	.000014	23.2503
2300.	.4000	.015093	.000004	23.1647
2300.	.2000	.007632	.000001	23.0779
2325.	13.8143	.271435	.056370	27.9679
2325.	13.0000	.264321	.049789	27.6819
2325.	12.0000	.254493	.042062	27.3295
2325.	11.0000	.243367	.034804	26.9766
2325.	10.0000	.230841	.028095	26.6237
2325.	9.0000	.216811	.022010	26.2714
2325.	8.0000	.201167	.016617	25.9200
2325.	7.0000	.183797	.011973	25.5692
2325.	6.0000	.164576	.008116	25.2185
2325.	5.0000	.143366	.005061	24.8667
2325.	4.0000	.120004	.002796	24.5120

APPENDIX D  
MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_4$	$M_a$
2325.	3.0000	.094287	.001276	24.1515
2325.	2.0000	.065959	.000410	23.7814
2325.	1.0000	.034682	.000056	23.3965
2325.	.8000	.028035	.000029	23.3172
2325.	.6000	.021248	.000012	23.2369
2325.	.4000	.014317	.000004	23.1556
2325.	.2000	.007236	.000000	23.0733
2350.	14.7856	.272279	.060094	28.0778
2350.	14.0000	.266083	.053828	27.8129
2350.	13.0000	.257244	.046149	27.4746
2350.	12.0000	.247258	.038871	27.1356
2350.	11.0000	.236038	.032066	26.7968
2350.	10.0000	.223493	.025804	26.4585
2350.	9.0000	.209531	.020153	26.1212
2350.	8.0000	.194058	.015168	25.7850
2350.	7.0000	.176973	.010894	25.4497
2350.	6.0000	.158167	.007361	25.1146
2350.	5.0000	.137518	.004575	24.7786
2350.	4.0000	.114879	.002519	24.4398
2350.	3.0000	.090073	.001145	24.0957
2350.	2.0000	.062872	.000366	23.7427
2350.	1.0000	.032979	.000050	23.3761
2350.	.8000	.026645	.000026	23.3007
2350.	.6000	.020184	.000011	23.2244
2350.	.4000	.013593	.000003	23.1472
2350.	.2000	.006866	.000000	23.0690
2375.	15.8055	.272995	.063943	28.1895
2375.	15.0000	.267246	.057617	27.9286
2375.	14.0000	.259253	.050018	27.6034
2375.	13.0000	.250242	.042762	27.2776
2375.	12.0000	.240137	.035915	26.9518
2375.	11.0000	.228859	.029541	26.6266
2375.	10.0000	.216330	.023704	26.3024
2375.	9.0000	.202469	.018458	25.9795
2375.	8.0000	.187193	.013851	25.6578
2375.	7.0000	.170413	.009918	25.3372
2375.	6.0000	.152032	.006681	25.0168
2375.	5.0000	.131943	.004140	24.6957
2375.	4.0000	.110015	.002272	24.3720
2375.	3.0000	.086089	.001029	24.0433
2375.	2.0000	.059966	.000328	23.7064
2375.	1.0000	.031384	.000044	23.3571
2375.	.8000	.025344	.000023	23.2853
2375.	.6000	.019190	.000010	23.2127
2375.	.4000	.012916	.000003	23.1393
2375.	.2000	.006521	.000000	23.0650
2400.	16.8752	.273586	.067912	28.3030
2400.	16.0000	.267920	.061156	28.0304
2400.	15.0000	.260655	.053661	27.7177
2400.	14.0000	.252482	.046460	27.4042
2400.	13.0000	.243334	.039614	27.0907
2400.	12.0000	.233144	.033180	26.7777
2400.	11.0000	.221843	.027217	26.4656
2400.	10.0000	.209361	.021778	26.1549
2400.	9.0000	.195628	.016911	25.8457
2400.	8.0000	.180570	.012654	25.5379
2400.	7.0000	.164110	.009036	25.2311
2400.	6.0000	.146163	.006069	24.9248
2400.	5.0000	.126630	.003749	24.6177
2400.	4.0000	.105397	.002052	24.3082

APPENDIX D  
MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_4$	$M_a$
2400.	3.0000	.082323	.000927	23.9941
2400.	2.0000	.057229	.000295	23.6724
2400.	1.0000	.029889	.000040	23.3393
2400.	.8000	.024126	.000021	23.2709
2400.	.6000	.018259	.000009	23.2018
2400.	.4000	.012284	.000003	23.1319
2400.	.2000	.006199	.000000	23.0613
2425.	17.9961	.274053	.071997	28.4184
2425.	17.0000	.268194	.064450	28.1198
2425.	16.0000	.261557	.057076	27.8187
2425.	15.0000	.254107	.049956	27.5169
2425.	14.0000	.245786	.043144	27.2149
2425.	13.0000	.236534	.036691	26.9134
2425.	12.0000	.226291	.030653	26.6127
2425.	11.0000	.214996	.025078	26.3134
2425.	10.0000	.202589	.020014	26.0155
2425.	9.0000	.189008	.015500	25.7194
2425.	8.0000	.174188	.011568	25.4247
2425.	7.0000	.158060	.008238	25.1312
2425.	6.0000	.140549	.005518	24.8381
2425.	5.0000	.121567	.003400	24.5443
2425.	4.0000	.101013	.001855	24.2482
2425.	3.0000	.078760	.000835	23.9479
2425.	2.0000	.054651	.000265	23.6405
2425.	1.0000	.028485	.000035	23.3226
2425.	.8000	.022983	.000018	23.2574
2425.	.6000	.017387	.000008	23.1915
2425.	.4000	.011692	.000002	23.1250
2425.	.2000	.005898	.000000	23.0578
2450.	19.1693	.274399	.076193	28.5355
2450.	19.0000	.273547	.074924	28.4868
2450.	18.0000	.268137	.067509	28.1980
2450.	17.0000	.262046	.060268	27.9078
2450.	16.0000	.255224	.053247	27.6170
2450.	15.0000	.247620	.046494	27.3259
2450.	14.0000	.239181	.040056	27.0351
2450.	13.0000	.229854	.033982	26.7452
2450.	12.0000	.219587	.028319	26.4565
2450.	11.0000	.208326	.023112	26.1693
2450.	10.0000	.196019	.018399	25.8838
2450.	9.0000	.182610	.014213	25.6001
2450.	8.0000	.168043	.010581	25.3180
2450.	7.0000	.152256	.007516	25.0369
2450.	6.0000	.135182	.005022	24.7563
2450.	5.0000	.116745	.003086	24.4751
2450.	4.0000	.096851	.001679	24.1918
2450.	3.0000	.075390	.000754	23.9044
2450.	2.0000	.052221	.000238	23.6105
2450.	1.0000	.027168	.000032	23.3070
245.	.8000	.021912	.000017	23.2448
2450.	.6000	.016569	.000007	23.1820
2450.	.4000	.011138	.000002	23.1186
2450.	.2000	.005616	.000000	23.0545
2475.	20.3962	.274627	.080496	28.6543
2475.	20.0000	.272807	.077590	28.5444
2475.	19.0000	.267807	.070341	28.2659
2475.	18.0000	.262193	.063242	27.9861
2475.	17.0000	.255919	.056333	27.7055
2475.	16.0000	.248939	.049659	27.4248
2475.	15.0000	.241208	.043261	27.1442

## APPENDIX D

## MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$x_2$	$x_4$	$M_0$
2475.	14.0000	.232679	.037185	26.8644
2475.	13.0000	.223305	.031473	26.5857
2475.	12.0000	.213040	.026167	26.3085
2475.	11.0000	.201838	.021304	26.0330
2475.	10.0000	.189651	.016920	25.7593
2475.	9.0000	.176432	.013040	25.4875
2475.	8.0000	.162129	.009684	25.2172
2475.	7.0000	.146690	.006862	24.9480
2475.	6.0000	.130053	.004574	24.6793
2475.	5.0000	.112150	.002803	24.4099
2475.	4.0000	.092900	.001522	24.1386
2475.	3.0000	.072201	.000682	23.8635
2475.	2.0000	.049930	.000215	23.5823
2475.	1.0000	.025930	.000029	23.2923
2475.	.8000	.020905	.000015	23.2329
2475.	.6000	.015802	.000006	23.1730
2475.	.4000	.010616	.000002	23.1125
2475.	.2000	.005352	.000000	23.0515
2500.	21.6779	.274739	.084898	28.7748
2500.	21.0000	.271892	.080040	28.5934
2500.	20.0000	.267253	.072957	28.3246
2500.	19.0000	.262056	.066005	28.0545
2500.	18.0000	.256261	.059219	27.7837
2500.	17.0000	.249828	.052637	27.5127
2500.	16.0000	.242716	.046300	27.2418
2500.	15.0000	.234884	.040247	26.9715
2500.	14.0000	.226291	.034518	26.7023
2500.	13.0000	.216896	.029151	26.4345
2500.	12.0000	.206657	.024182	26.1683
2500.	11.0000	.195535	.019644	25.9040
2500.	10.0000	.183487	.015566	25.6416
2500.	9.0000	.170471	.011970	25.3810
2500.	8.0000	.156443	.008869	25.1220
2500.	7.0000	.141355	.006271	24.8641
2500.	6.0000	.125152	.004170	24.6065
2500.	5.0000	.107774	.002550	24.3484
2500.	4.0000	.089147	.001381	24.0885
2500.	3.0000	.069181	.000617	23.8249
2500.	2.0000	.047767	.000194	23.5558
2500.	1.0000	.024765	.000026	23.2785
2500.	.8000	.019960	.000013	23.2218
2500.	.6000	.015082	.000006	23.1646
2500.	.4000	.010131	.000002	23.1069
2500.	.2000	.005104	.000000	23.0486
2525.	23.0156	.274738	.089395	28.8967
2525.	23.0000	.274681	.089285	28.8927
2525.	22.0000	.270834	.082286	28.6346
2525.	21.0000	.266512	.075369	28.3749
2525.	20.0000	.261682	.068566	28.1140
2525.	19.0000	.256309	.061909	27.8525
2525.	18.0000	.250357	.055432	27.5906
2525.	17.0000	.243789	.049170	27.3289
2525.	16.0000	.236569	.043161	27.0677
2525.	15.0000	.228660	.037440	26.8075
2525.	14.0000	.220027	.032043	26.5485
2525.	13.0000	.210633	.027003	26.2911
2525.	12.0000	.200442	.022353	26.0356
2525.	11.0000	.189418	.018120	25.7820
2525.	10.0000	.177524	.014326	25.5303
2525.	9.0000	.164724	.010994	25.2804

APPENDIX D

MOLECULAR COMPOSITION OF SODIUM VAPOR (cont'd.)

$t$	$p$	$r_2$	$r_4$	$M_n$
2525.	5.0000	.150978	.008129	25.0320
2525.	7.0000	.136243	.005735	24.7848
2525.	6.0000	.120470	.003805	24.5379
2525.	5.0000	.103606	.002322	24.2904
2525.	4.0000	.085983	.001254	24.0412
2525.	3.0000	.066322	.000559	23.7886
2525.	2.0000	.045725	.000175	23.5309
2525.	1.0000	.023670	.000023	23.2655
2525.	.8000	.019070	.000012	23.2113
2525.	.6000	.014405	.000005	23.1567
2525.	.4000	.009673	.000002	23.1016
2525.	.2000	.004872	.000000	23.0459
2550.	24.4105	.274627	.093980	29.0202
2550.	24.0000	.273265	.091164	28.9182
2550.	23.0000	.269658	.084340	28.6686
2550.	22.0000	.265617	.077588	28.4175
2550.	21.0000	.261112	.070935	28.1654
2550.	20.0000	.256111	.064411	27.9126
2550.	19.0000	.250582	.058046	27.6594
2550.	18.0000	.244494	.051872	27.4064
2550.	17.0000	.237814	.045923	27.1538
2550.	16.0000	.230509	.040230	26.9021
2550.	15.0000	.222547	.034828	26.6516
2550.	14.0000	.213895	.029747	26.4025
2550.	13.0000	.204523	.025018	26.1552
2550.	12.0000	.194398	.020668	25.9098
2550.	11.0000	.183488	.016720	25.6664
2550.	10.0000	.171762	.013194	25.4249
2550.	9.0000	.159187	.010104	25.1852
2550.	8.0000	.145728	.007455	24.9470
2550.	7.0000	.131346	.005249	24.7098
2550.	6.0000	.115998	.003475	24.4730
2550.	5.0000	.099635	.002116	24.2356
2550.	4.0000	.082197	.001141	23.9966
2550.	3.0000	.063614	.000507	23.7544
2550.	2.0000	.043797	.000159	23.5074
2550.	1.0000	.022638	.000021	23.2534
2550.	.8000	.018233	.000011	23.2015
2550.	.6000	.013769	.000005	23.1492
2550.	.4000	.009243	.000001	23.0966
2550.	.2000	.004654	.000000	23.0434
2575.	25.8738	.274411	.098647	29.1450
2575.	25.0000	.271780	.092868	28.9377
2575.	24.0000	.268387	.086215	28.6962
2575.	23.0000	.264595	.079625	28.4533
2575.	22.0000	.260377	.073122	28.2094
2575.	21.0000	.255706	.066733	27.9648
2575.	20.0000	.250553	.060485	27.7199
2575.	19.0000	.244890	.054408	27.4751
2575.	18.0000	.238687	.048530	27.2307
2575.	17.0000	.231915	.042883	26.9871
2575.	16.0000	.224546	.037497	26.7446
2575.	15.0000	.216550	.032400	26.5035
2575.	14.0000	.207901	.027620	26.2640
2575.	13.0000	.198568	.023185	26.0264
2575.	12.0000	.188526	.019117	25.7907
2575.	11.0000	.177745	.015436	25.5570
2575.	10.0000	.166198	.012157	25.3252
2575.	9.0000	.153856	.009292	25.0952
2575.	8.0000	.140687	.006843	24.8666
2575.	7.0000	.126656	.004808	24.6390
2575.	6.0000	.111726	.003178	24.4117
2575.	5.0000	.095852	.001931	24.1839
2575.	4.0000	.078980	.001039	23.9544
2575.	3.0000	.061047	.000461	23.7221
2575.	2.0000	.041974	.000144	23.4852
2575.	1.0000	.021665	.000019	23.2419
2575.	.8000	.017445	.000010	23.1923
2575.	.6000	.013170	.000004	23.1423
2575.	.4000	.008838	.000001	23.0919
2575.	.2000	.004448	.000000	23.0410

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13 ABSTRACT  An experimental program is in progress at this Laboratory to measure various thermophysical properties of sodium, potassium, and cesium. A final reporting of the experimental results for sodium (saturation and superheat properties of the vapor, density and specific heat of the liquid) is presented together with a thermodynamic treatment of the data. Two equations of state are advanced, one virial and one quasi-chemical; and additional saturation and superheat properties of the vapor are derived from these equations. Either of two paths can be used to compute thermodynamic properties, the monomeric gas path or the liquid path; but results obtained by the former procedure are believed to be more accurate. Enthalpy, entropy, specific volume, specific heat, and compositional information (weight fraction of dimer, weight fraction of tetramer, and average molecular weight) are tabulated for some 700 selected vapor states in the temperature range from 1625° to 2575° F and in the pressure range from 0.2 to 25 atm.		

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sodium Thermophysical properties Compressibility data Saturated vapor Superheated vapor High-temperature properties Monomeric gas path Liquid path Virial equation of state Quasi-chemical equation of state Thermodynamic properties Association Liquid metals						

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