

Argonne National Laboratory  
9700 South Cass Avenue  
Argonne, Illinois 60439

THERMODYNAMIC AND TRANSPORT PROPERTIES  
OF SODIUM LIQUID AND VAPOR

by

J. K. Fink and L. Leibowitz\*

Reactor Engineering Division

January 1995

---

\*Chemical Technology Division

## TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT .....	xvii
INTRODUCTION .....	1
References .....	3
1. THERMODYNAMIC PROPERTIES .....	4
1.1 Enthalpy and Heat Capacity .....	4
1.1.1 Enthalpy .....	4
Summary .....	4
Discussion .....	6
Liquid .....	6
Vapor .....	10
Uncertainty .....	12
1.1.2 Heat Capacity .....	13
Summary .....	13
Heat Capacity at Constant Pressure, $C_p$ .....	13
Heat Capacity at Constant Volume, $C_v$ .....	17
Discussion .....	18
Heat Capacity at Constant Pressure, $C_p$ .....	18
$C_p$ Liquid .....	19
$C_p$ Vapor .....	22
$C_v$ Liquid .....	25
$C_v$ Vapor .....	25
Uncertainties .....	26
$C_p$ Liquid .....	26
$C_v$ Liquid .....	27
$C_p$ Vapor .....	27
$C_v$ Vapor .....	28
Polynomial Approximation .....	29
References .....	30
1.2 Vapor Pressure, Boiling Point, and Enthalpy of Vaporization .....	55
1.2.1 Vapor Pressure .....	55
Summary .....	55
Discussion .....	55
Uncertainty .....	60
Polynomial Approximation .....	61

## TABLE OF CONTENTS

(contd)

	<u>Page</u>
1.2.2 Boiling Point .....	63
Recommendation .....	63
Discussion .....	63
1.2.3 Enthalpy of Vaporization .....	65
Summary .....	65
Discussion .....	67
Uncertainty .....	69
References .....	71
 1.3 Density and Thermal Expansion .....	86
1.3.1 Density .....	86
Summary .....	86
Discussion .....	88
Liquid Density .....	88
Vapor Density .....	91
Uncertainty .....	92
Polynomial Approximations .....	94
Liquid Density .....	94
Vapor Density .....	94
1.3.2 Thermal Expansion .....	96
Summary .....	96
Discussion .....	99
Thermal-Expansion Coefficient for Liquid Sodium .....	99
Thermal-Expansion Coefficient for Sodium Vapor .....	102
Uncertainty .....	104
References .....	106
 1.4 Compressibility and Speed of Sound .....	122
1.4.1 Adiabatic Compressibility .....	122
Summary .....	122
Discussion .....	123
Adiabatic Compressibility of Liquid Sodium .....	123
Adiabatic Compressibility of Sodium Vapor .....	126
Uncertainty .....	132
Adiabatic Compressibility of Liquid Sodium .....	132
Adiabatic Compressibility of Sodium Vapor .....	132
1.4.2 Isothermal Compressibility .....	133
Summary .....	133
Discussion .....	136
Isothermal Compressibility of Liquid Sodium .....	136
Isothermal Compressibility of Sodium Vapor .....	137

## TABLE OF CONTENTS

(contd)

	<u>Page</u>
Uncertainty .....	138
Isothermal Compressibility of Liquid Sodium .....	138
Isothermal Compressibility of Sodium Vapor .....	139
1.4.3 Speed of Sound .....	140
Summary .....	140
Discussion .....	140
Uncertainty .....	143
References .....	144
1.5 Critical Parameters .....	163
Summary .....	163
Discussion .....	163
References .....	168
1.6 Surface Tension .....	170
Summary .....	170
Discussion .....	170
Uncertainty .....	174
References .....	175
 2. TRANSPORT PROPERTIES .....	 181
2.1 Thermal Conductivity .....	181
Summary .....	181
Discussion .....	181
Examination of Existing Recommendations .....	182
Selection of Method of Calculation .....	184
Calculation .....	186
Recommended Equation for Entire Temperature Range .....	189
Uncertainty .....	190
References .....	192
 2.2 Viscosity .....	 207
Summary .....	207
Discussion .....	207
Uncertainty .....	211
References .....	212
 ACKNOWLEDGEMENTS .....	 217

## LIST OF FIGURES

	<u>Page</u>
Fig. 1.1-1 Enthalpy Increments for Liquid Sodium and Vapor and the Average of the Liquid and Vapor Enthalpy Increments. Dotted Lines on Either Side of the Liquid and Vapor Enthalpies Give the Uncertainties, Which Increase Discontinuously to 10% at 2000K .....	32
Fig. 1.1-2 Comparison of Recommended Values for the Enthalpy Increment of Liquid Sodium with Values from Other Assessments .....	33
Fig. 1.1-3 Deviations of Values from Other Assessments from the Recommended Values for the Enthalpy of Liquid Sodium .....	34
Fig. 1.1-4 Comparison of Recommended Values for the Enthalpy Increment of Sodium Vapor with Values from Other Assessments .....	35
Fig. 1.1-5 Deviations of Values from Other Assessments from the Recommended Values for the Enthalpy of Sodium Vapor .....	36
Fig. 1.1-6 Recommended Values for the Heat Capacity at Constant Pressure, $C_p$ , and the Heat Capacity at Constant Volume, $C_v$ , of Liquid Sodium .....	37
Fig. 1.1-7 Recommended Values for the Heat Capacity at Constant Pressure $C_p$ , and the Heat Capacity at Constant Volume, $C_v$ , of Sodium Vapor .....	38
Fig. 1.1-8 Comparison of Heat Capacity at Constant Pressure, Heat Capacity at Constant Volume, Heat Capacity Along the Saturation Curve, and the Temperature Derivative of the Saturation Enthalpy .....	39
Fig. 1.1-9 Deviations of the Heat Capacity Along the Saturation Curve and the Temperature Derivative of the Saturation Enthalpy from the Heat Capacity at Constant Pressure .....	40
Fig. 1.1-10 Comparison of the Recommended Values for the Heat Capacity at Constant Pressure for Liquid Sodium with Values from Other Assessments .....	41

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 1.1-11 Deviations of Values from Other Assessments from the Recommended Values for the Heat Capacity at Constant Pressure of Liquid Sodium .....	42
Fig. 1.1-12 Fit to Quasi-Chemical Values of the Thermal Pressure Coefficient, $\gamma_v$ , and Extrapolation above 1600 K to Agree with $\gamma_a$ at the Critical Point .....	43
Fig. 1.1-13 Comparison of the Recommended Values for the Heat Capacity at Constant Pressure for Sodium Vapor with Values from Other Assessments .....	44
Fig. 1.1-14 Deviations of Values from Other Assessments from the Recommended Values for Heat Capacity at Constant Pressure of Sodium Vapor .....	45
Fig. 1.1-15 Comparison of the Values for the Temperature Derivative of the Vapor Enthalpy from this Calculation with the Fink and Leibowitz Values (F&L) Numerically Calculated Using the Quasi-Chemical Method .....	46
Fig. 1.1-16 Comparison of the Recommended Values for the Heat Capacity at Constant Volume for Liquid Sodium with Values from Other Assessments .....	47
Fig. 1.1-17 Comparison of the Recommended Values for the Heat Capacity at Constant Volume for Sodium Vapor with Values from Other Assessments .....	48
Fig. 1.1-18 Deviations of Values from Other Assessments from the Recommended Values for the Heat Capacity at Constant Volume of Sodium Vapor .....	49
Fig. 1.1-19 Comparison of the Ratio of the Recommended Values for the Heat Capacity at Constant Pressure and Constant Volume for Sodium Vapor with Values of this Ratio from Other Assessments .....	50
Fig. 1.1-20 The Heat Capacity at Constant Pressure for Liquid Sodium with Estimated Uncertainties .....	51

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 1.1-21 The Heat Capacity at Constant Volume for Liquid Sodium with Estimated Uncertainties .....	52
Fig. 1.1-22 The Heat Capacity at Constant Pressure for Sodium Vapor with Estimated Uncertainties .....	53
Fig. 1.1-23 The Heat Capacity at Constant Volume for Sodium Vapor with Estimated Uncertainties .....	54
Fig. 1.2-1 The Vapor Pressure of Saturated Sodium .....	74
Fig. 1.2-2 The Natural Logarithm of Sodium Vapor Pressure as a Function of Inverse Temperature .....	75
Fig. 1.2-3 Deviation of Other Vapor Pressure Equations from the Recommended Equation .....	76
Fig. 1.2-4 Vapor Pressures Calculated from Various Recommended Equations .....	77
Fig. 1.2-5 Deviation of Binder's Vapor Pressure Equation from the Recommended Equation Compared with Deviations from Other Recommendations .....	78
Fig. 1.2-6 Percent Deviation for Two Fits to $\ln P$ Using Eq. (4) .....	79
Fig. 1.2-7 $\chi^2$ of Eq. (4) fits to $\ln P$ Using Two Minimization Techniques .....	80
Fig. 1.2-8 Recommended Values of Enthalpy of Vaporization of Sodium .....	81
Fig. 1.2-9 Comparison of Recommended Equations for Enthalpy of Vaporization of Sodium with Values from Other Assessments .....	82
Fig. 1.2-10 Deviations of Values from Other Assessments from Recommended Values of the Enthalpy of Vaporization of Sodium .....	83
Fig. 1.2-11 Comparison of the Cubic Fit from the Recommended Values for the Enthalpy of Vaporization of Sodium .....	84

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 1.2-12 Deviations of Values from the Cubic Fit from Recommended Values of the Enthalpy of Vaporization of Sodium . . . . .	85
Fig. 1.3-1 Liquid Sodium and Sodium Vapor Densities . . . . .	108
Fig. 1.3-2 Comparison of Recommended Density of Liquid Sodium with Values from Other Assessments . . . . .	109
Fig. 1.3-3 Deviations of Values of the Recommended Values for the Density of Liquid Sodium from Values from Other Assessments . . . . .	110
Fig. 1.3-4 Comparison of Recommended Values for the Density of Sodium Vapor with Values from Other Assessments . . . . .	111
Fig. 1.3-5 Deviations of Recommended Vapor Density Values from Values from Other Assessments . . . . .	112
Fig. 1.3-6 Comparison of the Recommended Values for the Density of Sodium Vapor with Values from the SASS Approximation Equation . . . . .	113
Fig. 1.3-7 Deviations of the SASS Equation for Sodium Vapor Density from the Recommended Values . . . . .	114
Fig. 1.3-8 Recommended Values for the Instantaneous Volumetric Thermal-Expansion Coefficient of Liquid Sodium . . . . .	115
Fig. 1.3-9 Recommended Values for the Instantaneous Volumetric Thermal-Expansion Coefficient for Sodium Vapor . . . . .	116
Fig. 1.3-10 Comparison of Recommended Values for the Instantaneous Volumetric Thermal-Expansion Coefficient of Liquid Sodium with Values from Other Assessments . . . . .	117
Fig. 1.3-11 Percent Deviations of the Recommended Thermal-Expansion Coefficient for Liquid Sodium from Values from Other Assessments . . . . .	118

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 1.3-12 The Thermal-Pressure Coefficient ( $\gamma_v$ ) and the Temperature Derivative of the Vapor Pressure Along the Saturation Curve ( $\gamma_o$ ) .....	119
Fig. 1.3-13 Comparison of the Recommended Values for the Instantaneous Volumetric Thermal-Expansion Coefficient of Sodium Vapor with Values from Fink and Leibowitz .....	120
Fig. 1.3-14 Percent Deviations of the Recommended Values of the Thermal-Expansion Coefficient of Sodium Vapor from Values from Fink and Leibowitz .....	121
Fig. 1.4-1 Recommended Values for the Adiabatic Compressibility of Liquid Sodium .....	145
Fig. 1.4-2 Recommended Values for the Adiabatic Compressibility of Sodium Vapor .....	146
Fig. 1.4-3 Comparison of the Recommended Values for the Adiabatic Compressibility of Liquid Sodium with Values from Other Assessments .....	147
Fig. 1.4-4 Deviations of the Recommended Values for the Adiabatic Compressibility of Liquid Sodium from Values from Other Assessments .....	148
Fig. 1.4-5 The Thermal Pressure Coefficient ( $\gamma_v$ ) and the Temperature Derivative of the Vapor Pressure Along the Saturation Curve ( $\gamma_o$ ) .....	149
Fig. 1.4-6 Comparison of the Recommended Values for the Adiabatic Compressibility of Sodium Vapor with Values from Fink and Leibowitz .....	150
Fig. 1.4-7 Deviations of the Adiabatic Compressibility of Sodium Vapor Calculated by Fink and Leibowitz from Recommended Values .....	151

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 1.4-8 Comparison of the Recommended Values for the Ratio of the Heat Capacities and Compressibilities of Sodium Vapor with Values from Fink and Leibowitz and from Bystrov et al .....	152
Fig. 1.4-9 Deviations of the Values of the Heat Capacity Ratios for Sodium Vapor Calculated by Fink and Leibowitz and by Bystrov et al. from Recommended Values .....	153
Fig. 1.4-10 Recommended Values for the Isothermal Compressibility of Liquid Sodium .....	154
Fig. 1.4-11 Recommended Values for the Isothermal Compressibility of Sodium Vapor .....	155
Fig. 1.4-12 Comparison of the Recommended Values for the Isothermal Compressibility of Liquid Sodium with Values from Other Assessments .....	156
Fig. 1.4-13 Percent Deviations of the Recommended Values for the Isothermal Compressibility of Liquid Sodium from Values from Other Assessments .....	157
Fig. 1.4-14 Comparison of Recommended Values for the Isothermal Compressibility of Sodium Vapor with Values from Fink and Leibowitz .....	158
Fig. 1.4-15 Percent Deviations of the Recommended Values for the Isothermal Compressibility of Sodium Vapor from Values from Fink and Leibowitz .....	159
Fig. 1.4-16 Recommended Values for the Speed of Sound in Liquid Sodium .....	160
Fig. 1.4-17 Comparison of the Recommended Values for the Speed of Sound in Liquid Sodium with Values from Other Assessments .....	161

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 1.4-18 Percent Deviations of the Recommended Values for the Speed of Sound in Liquid Sodium from Values from Other Assessments .....	162
Fig. 1.6-1 Surface Tension of Liquid Sodium .....	177
Fig. 1.6-2 Deviations of Recommended Values for the Surface Tension of Sodium from Values Given by Goldman .....	178
Fig. 1.6-3 Comparison of Recommended Values for the Surface Tension of Sodium with Values of Goldman and of Bystrov et al .....	179
Fig. 1.6-4 Deviations of Other Assessments from the Recommended Values For the Surface Tension of Sodium .....	180
Fig. 2.1-1 Thermal Conductivity of Liquid Sodium .....	194
Fig. 2.1-2 Recommended Values for the Thermal Conductivity of Liquid Sodium from Five Assessments .....	195
Fig. 2.1-3 Comparison of Data from Thermal Conductivity Measurements with Values from Cook and Fritsch, CINDAS, and Bystrov et al .....	196
Fig. 2.1-4 Comparison of Data from Thermal Conductivity Measurements and Resistivity Data Converted to Conductivity by CINDAS with Values from Quadratic Fit to Electrical Resistivities Converted to Thermal Conductivity by CINDAS .....	197
Fig. 2.1-5 Comparison of Data from Thermal Conductivity Measurements and Resistivity Data Converted to Conductivity using Eq. (6) with Values from Cook and Fritsch, CINDAS, and the Calculation in this Assessment .....	198
Fig. 2.1-6 Comparison of Values for the Electrical Resistivity from Cook and Fritsch, CINDAS, and Alekseev and Iakubov .....	199
Fig. 2.1-7 Quadratic Least Squares Fit to the Thermoelectric Potential of Pt Relative to Na given by Bonilla et al. ....	200

## LIST OF FIGURES

(cont'd)

	<u>Page</u>
Fig. 2.1-8 Linear Fit to the Absolute Thermoelectric Power of Pt. Equations from Experiments are Included for Comparison .....	201
Fig. 2.1-9 The Negative of the Absolute Thermoelectric Power for Na and for Pt and Values given by Cook and Fritsch for Na. The Thermoelectric Power of Pt Relative to Na ( $dE/dT$ ) is Included in the Figure .....	202
Fig. 2.1-10 Thermal Conductivity of Sodium Vapor .....	203
Fig. 2.1-11 Constrained Cubic Fit to Calculated Values of the Thermal Conductivity of Liquid Sodium, Calculated Values, and Vapor Thermal Conductivities .....	204
Fig. 2.1-12 Comparison of Recommended Values for the Thermal Conductivity of Sodium with Calculated Values and Values from Other Assessments .....	205
Fig. 2.1-13 Deviations of Values from Other Assessments from Recommended Values of the Thermal Conductivity of Liquid Sodium .....	206
Fig. 2.2-1 Viscosity of Liquid Sodium .....	214
Fig. 2.2-2 Comparison of Recommended Values for the Viscosity of Liquid Sodium with Values from Fink and Leibowitz .....	215
Fig. 2.2-3 Deviations of Values given by Fink and Leibowitz from Recommended Values of the Viscosity of Liquid Sodium .....	216

## LIST OF TABLES

	<u>Page</u>
1.1-1      Sodium Enthalpy Increment, $H(T) - H(s, 298.15 \text{ K})$ .....	5
1.1-2      Estimated Uncertainty in the Recommended Values for Enthalpy of Liquid Sodium .....	7
1.1-3      Estimated Uncertainty in the Recommended Values for Enthalpy of Sodium Vapor .....	8
1.1-4      The Enthalpy and Heat Capacity of Solid and Liquid Sodium Per Mole of Sodium .....	9
1.1-5      Heat Capacity of Liquid Sodium .....	14
1.1-6      Heat Capacity of Sodium Vapor .....	15
1.1-7      Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Pressure of Liquid Sodium .....	16
1.1-8      Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Volume of Liquid Sodium .....	16
1.1-9      Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Pressure of Sodium Vapor .....	17
1.1-10     Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Volume of Sodium Vapor .....	18
1.2-1      Vapor Pressure of Saturated Sodium .....	56
1.2-2      Estimated Uncertainty in Values of Sodium Vapor Pressure Calculated from Eq. (1) .....	57
1.2-3      Vapor Pressure Data Fit by Browning and Potter .....	57
1.2-4      Measured Boiling Point of Sodium .....	64
1.2-5      Boiling Points of Sodium Recommended in Assessments .....	65
1.2-6      Enthalpy of Vaporization of Sodium .....	66
1.2-7      Estimated Uncertainty in Values of the Enthalpy of Vaporization of Sodium Calculated from Eq. (7) .....	67

**LIST OF TABLES**  
(cont'd)

	<u>Page</u>
1.3-1      Sodium Density .....	87
1.3-2      Estimated Uncertainties in the Recommended Values for the Density of Liquid Sodium .....	88
1.3-3      Estimated Uncertainties in the Recommended Values for the Density of Sodium Vapor .....	89
1.3-4      Instantaneous Volumetric Thermal-Expansion Coefficients of Liquid Sodium and Sodium Vapor .....	97
1.3-5      Estimated Uncertainties in the Recommended Values for the Instantaneous Volumetric Thermal-Expansion Coefficient for Liquid Sodium .....	98
1.3-6      Estimated Uncertainties in the Recommended Values for the Instantaneous Volumetric Thermal-Expansion Coefficient for Sodium Vapor .....	98
1.4-1      Adiabatic Compressibility of Sodium .....	123
1.4-2      Estimated Uncertainties in the Recommended Values for the Adiabatic Compressibility of Liquid Sodium .....	124
1.4-3      Estimated Uncertainties in the Recommended Values for the Adiabatic Compressibility of Sodium Vapor .....	124
1.4-4      Isothermal Compressibility of Sodium .....	134
1.4-5      Estimated Uncertainties in the Recommended Values for the Isothermal Compressibility of Liquid Sodium .....	135
1.4-6      Estimated Uncertainties in the Recommended Values for the Isothermal Compressibility of Sodium Vapor .....	135
1.4-7      Speed of Sound in Liquid Sodium .....	141
1.4-8      Estimated Uncertainties in the Recommended Values for the Speed of Sound in Liquid Sodium .....	142

**LIST OF TABLES**  
(cont'd)

	<u>Page</u>
1.5-1 Recommended Values of Critical Parameters .....	163
1.5-2 Critical Parameters Recommended in Assessments .....	164
1.6-1 Surface Tension of Liquid Sodium .....	171
1.6-2 Uncertainties in the Recommended Values for the Surface Tension of Liquid Sodium .....	172
1.6-3 Surface Tension Data Analyzed by Goldman .....	173
2.1-1 Thermal Conductivity of Liquid Sodium .....	182
2.1-2 Estimated Uncertainties in the Recommended Values for the Thermal Conductivity of Liquid Sodium .....	183
2.2-1 Recommended Values for the Dynamic Viscosity of Liquid Sodium .....	208
2.2-2 Estimated Uncertainty in Values for the Viscosity of Sodium Calculated from Eq. (1) .....	209
2.2-3 Sodium Viscosity Data Assessed by Shpil'rain et al .....	210



**THERMODYNAMIC AND TRANSPORT PROPERTIES  
OF SODIUM LIQUID AND VAPOR**

by

J. K. Fink and L. Leibowitz

**ABSTRACT**

The data on thermodynamic and transport properties of sodium have been reviewed to obtain thermodynamically consistent equations for the thermodynamic and transport properties of saturated sodium liquid and vapor. The recently published Russian recommendations and results of equation of state calculations on thermophysical properties of sodium have been included in this critical assessment. Thermodynamic properties of sodium liquid and vapor that have been assessed include: enthalpy, heat capacity at constant pressure, heat capacity at constant volume, vapor pressure, boiling point, enthalpy of vaporization, density, thermal expansion, adiabatic and isothermal compressibility, speed of sound, critical parameters, and surface tension. Transport properties of liquid sodium that have been assessed include: viscosity and thermal conductivity. For each property, recommended values and their uncertainties are graphed and tabulated as functions of temperature. Detailed discussions of the analyses and determinations of the recommended equations include comparisons with recommendations given in other assessments and explanations of consistency requirements. The rationale and methods used in determining the uncertainties in the recommended values are also discussed.

