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183

A PRELIMINARY COLLATION OF THE  
THERMODYNAMIC AND TRANSPORT PROPERTIES OF CESIUM

H.W. Hoffman and T.T. Robin, Jr.

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H. W. Hoffman and T. T. Robin, Jr.

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OAK RIDGE NATIONAL LABORATORY  
Oak Ridge, Tennessee  
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CONVERSION FACTORS

## DENSITY EQUIVALENTS

$\text{g/cm}^3$	$\text{lb}_m/\text{in.}^3$	$\text{lb}_m/\text{ft}^3$
1	0.03613	62.43
27.68	1	1728
0.01602	0.0005787	1

## ENERGY EQUIVALENTS

Joules = $10^7$ ergs	Cal	Btu	kw·hr
1	0.2390	0.0009484	$2.778 \times 10^{-7}$
4.184	1	0.00397	$1.162 \times 10^{-6}$
1054.4	252	1	$2.930 \times 10^{-4}$
$3.6 \times 10^8$	$8.606 \times 10^5$	3413	1

HEAT CAPACITY-ENTROPY EQUIVALENTS

$$1 \text{ cal/g} \cdot \text{mole} \cdot ^\circ\text{C} = 1 \text{ Btu/lb}_m \cdot \text{mole} \cdot ^\circ\text{F}$$

$$1 \text{ cal/g} \cdot ^\circ\text{C} = 1 \text{ Btu/lb}_m \cdot ^\circ\text{F}$$

## ENTHALPY/MASS EQUIVALENTS

cal/g	Btu/lb <sub>m</sub>	Joules/kg <sub>m</sub>
1	1.8	4184
0.5556	1	2324.4
$2.390 \times 10^{-4}$	$4.302 \times 10^{-4}$	1

## PRESSURE EQUIVALENTS

dynes/cm <sup>2</sup>	kg <sub>f</sub> /m <sup>2</sup>	atm	mm of Hg at 0°C (torr)	lb <sub>f</sub> /in. <sup>2</sup>
1	0.010197	$9.869 \times 10^{-7}$	$7.501 \times 10^{-4}$	$1.450 \times 10^{-5}$
92.07	1	$9.678 \times 10^{-5}$	0.073556	$1.422 \times 10^{-3}$
$1.0133 \times 10^6$	10,323	1	760	14.696
$1.333 \times 10^3$	13.5951	0.001316	1	0.01934
$6.895 \times 10^4$	703.1	0.06804	51.715	1

## THERMAL CONDUCTIVITY EQUIVALENTS

cal/sec·cm·°C	watts/cm·°C	Btu/hr·ft·°F	Btu/sec·ft·°F
1	4.184	241.92	0.06720
0.2390	1	57.82	0.1606
$4.1336 \times 10^{-3}$	0.01729	1	$2.7778 \times 10^{-4}$
14.88	62.26	3600	1

## THERMAL DIFFUSIVITY EQUIVALENTS

cm <sup>2</sup> /sec	m <sup>2</sup> /sec	ft <sup>2</sup> /sec	ft <sup>2</sup> /hr
1	$10^{-4}$	$1.0764 \times 10^{-3}$	3.8747
$10^4$	1	10.764	$3.8747 \times 10^4$
929.02	0.092902	1	3600
0.25806	$2.5806 \times 10^{-5}$	$2.7778 \times 10^{-4}$	1

## VISCOSITY EQUIVALENTS

centipoise	lb <sub>m</sub> /ft·sec	lb <sub>m</sub> /ft·hr
1	$6.7197 \times 10^{-4}$	2.4191
1488.2	1	3600
0.41338	$2.7778 \times 10^{-4}$	1

## SURFACE TENSION EQUIVALENTS

dynes/cm	kg <sub>f</sub> /m	lb <sub>f</sub> /ft
1	$1.0197 \times 10^{-4}$	$6.8521 \times 10^{-5}$
9807	1	0.6730
$1.4572 \times 10^4$	1.486	1

A PRELIMINARY COLLATION OF THE  
THERMODYNAMIC AND TRANSPORT PROPERTIES OF CESIUM

H. W. Hoffman and T. T. Robin, Jr.

ABSTRACT

This memorandum constitutes a preliminary collation of the thermodynamic and transport properties of saturated liquid and vapor cesium. It is intended to provide a convenient and consistent source of properties for those involved in the design and evaluation of power systems based on thermodynamic cycles involving cesium as the working fluid.

Included in this compilation are the thermodynamic properties - physical constants and critical state conditions, sonic velocities, PVT relationships (vapor pressure, density, and compressibility), enthalpy, heat capacity, latent heat of vaporization, and entropy, and surface tension - and the transport properties - viscosity, thermal conductivity, and electrical resistivity. A preliminary evaluation of the data available indicates the need for additional measurements of both the thermodynamic and transport properties. Thus, for liquid enthalpy, the differences between the tabulated relations, while small, are sufficient to affect significantly thermodynamic cycle calculations. To a lesser extent, further data on the PVT characteristics would be useful, since these data are the base for the calculation of vapor enthalpies; only Ewing et al. predict vapor pressures for temperatures above 1950°F. Achener alone reports measurements of the latent heat of vaporization; the remaining "investigators" derive this quantity, with only Ewing showing reasonable agreement with the experimental values. The surface tension has been obtained only by Tepper to date; experiments by others are in progress, and evaluation of need for further studies must await the outcome of these current investigations. In respect to the transport properties, serious disagreements exist for vapor viscosities and thermal conductivities; and the need for additional measurements is evident. Some variation, though not as significant, exists for the liquid viscosities and conductivities.

The results of Ewing et al. are currently recommended for the thermodynamic properties in that these constitute an internally consistent set. A later revision of this memorandum will include a more detailed evaluation of this data set in relation to similar consistent sets by Heimel and by Achener et al. Values for superheated vapor and the nuclear properties of cesium will also be included in the final collection.

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## INTRODUCTION

The alkali liquid metals have been proposed as the coolant and thermodynamic medium in space power applications utilizing nuclear reactor or isotopic heat sources. These fluids are also of interest in the fast-breeder reactor program where they serve as the core coolant. The work summarized herein is a part of Phase I of an analytical comparison being carried out at the Oak Ridge National Laboratory for the National Aeronautics and Space Administration under AEC Interagency Agreement 40-98-66, NASA Order W-12,353, on the relative merits of cesium and potassium as working fluids for Rankine-cycle space power plants.

The thermal properties of the alkali metals are necessary both for cycle analyses and for the correlation and interpretation of experimental heat-transfer data. This report compiles the thermodynamic and transport properties of only one of these fluids - cesium; a subsequent addition will cover potassium. A preliminary evaluation of the available data is included. A final report issued at the conclusion of this program will contain (1) a set of recommended equations, and (2) an indication of areas in which further experimental measurements are necessary.

The thermodynamic and transport properties of saturated liquid and vapor cesium are presented in the sections which follow. The data are given in two forms: (1) graphs of the specific property over the temperature span 1100 to 2500°R constituting a preliminary set of values recommended for design calculations; and (2) tabulations of available equations for each property including temperature range, reported error, indication of the method of measurement, the investigator and the date of the investigation, and the reference. Each of the two data sections is preceded by a

brief discussion of the properties within that section and a preliminary evaluation and justification of the recommended data. These discussions include - particularly in the section on transport properties - comments on properties which are not given in ensuing data tabulation; the primary purpose for this has been to provide a reasonably complete perspective on cesium properties. Further, little detail is included in these comments; for further elaboration reference should be made to the original sources.

While the application of this collection is in the design of nuclear systems utilizing cesium as the reactor coolant and/or thermodynamic medium, no information on nuclear properties is included. The possibility of such data appearing in a final version of this report will be considered.

For the thermodynamic properties, the results of Ewing et al.<sup>1</sup> have been recommended; the basis for this choice is discussed further in the section immediately following. Subsequent to the initial writing of this memorandum, Achener et al.<sup>35</sup> issued a report in which, using their measurements as a basis, a self-consistent set of thermodynamic properties was also developed. A brief comparison of the two property sets indicates some differences. The significance of these differences has not yet been evaluated but will be included in the final version of this memorandum.

Superheat values for cesium vapor are not included in this initial cesium properties summary. These should be obtained by reference to Appendix B of Ref. 1; for the convenience of users of this data collection, tabulations or plots of properties of superheated cesium vapor may be appended to the final report.

## THERMODYNAMIC PROPERTIES

### Introduction

The thermodynamic properties characterize a substance with respect to equilibrium states. In this category, we include the critical state conditions and sonic velocity, the PVT relationships (vapor pressure, density, compressibility), the enthalpy, heat capacity, latent heats of phase change, and entropy, and the surface tension.

Ewing and co-workers<sup>1</sup> and Heimel<sup>15</sup> have both generated internally consistent sets for the thermodynamic properties employing approximately the same procedures. The former list saturation values between 1250 and 2350°F (limiting their analysis to pressures between about 1 atm and 34 atm), while the latter tabulates saturation properties over the span -280°F to 2240°F. In the common range, there are some generally small differences between the two data sets. Ewing et al. have also calculated superheat values (Appendix B, Ref. 1) for cesium vapor between 1250 and 2550°F (to a maximum pressure of 34 atm) using as the starting point for a particular property the absolute value of that property for either the saturated liquid or the monomeric gas. In general, the agreement between values calculated by either path was quite good (see Ref. 1, p. 21). This is discussed further in a following section on enthalpy and entropy. Because of the wider range, the Ewing et al. results are currently recommended.

One further comment is necessary. It is known that the vapors of many metals do not behave as normal gases because the molecular weights of such vapors change as conditions change. This is generally believed to

arise from variations in the relative amounts of monomer, dimer, trimer, etc. species in the vapor. Since a certain amount of energy is tied up in these polymeric states, it is necessary to account for these vapor species composition effects in calculating the thermodynamic properties of the vapor. When this is done, the properties are known as equilibrium properties. On the other hand, when processes occur rapidly, equilibrium between the several vapor species may not be achieved; e.g., as in the nozzle expansion of a vapor. Calculations are then made on the basis of a fixed vapor composition and the properties are known as frozen properties. Generally, under conditions of shifting equilibrium, bracketing calculations are made using the extremes of equilibrium properties and frozen properties.

#### Physical Constants and Critical Properties

A brief tabulation of some of the physical constants for cesium are given in Fig. 1; nuclear properties are omitted but will be included later. The critical properties of a fluid ( $T_c$ ,  $P_c$ , and  $v_c$ ) are important in the design of vapor compressors and turbines and useful in the estimation of the transport properties. Further, some generalization of the properties of different substances is possible through the use of the reduced state concept (ratio of the existing state to the critical state).

No experimental values are available for the critical properties of cesium; all values listed in Table 1 were estimated through a variety of methods. As a result, no recommendation as to best values is given. Critical temperatures range from 1838 to 2157°K (the extremes of the estimates by Tepper et al.<sup>17</sup>) with a mean of 2055°K, critical pressures vary from 140 to 170 atm, and critical volumes from 0.311 to 0.380 liter/g-mole.

### Sonic Velocities

The equilibrium and frozen sonic velocities for saturated vapor are shown in Fig. 2. The curves plotted were taken from the calculations of Shapiro and Meisl<sup>31</sup> as reported by Weatherford et al.<sup>26</sup> Values based on experimental measurements are not available.

### PVT Relationships

Vapor Pressure. Six vapor pressure equations are shown in Table 2. Some early data has been omitted due to unavailability of the references at this time; these may be included in the final version of this memorandum. The recommended equation, that of Ewing et al.,<sup>1</sup> is shown as Eq. (3) in Table 2 and plotted in Fig. 3.

The six tabulated vapor pressure equations show the following comparison at the three listed temperatures:

<u>Equation</u>	Vapor Pressure (psia)		
	<u>850°F</u>	<u>1700°F</u>	<u>2300°F</u>
(1)	1.01	99.5	462.7
(2)	0.98	100.4	472.2
(3)	1.01	100.8	452.2
(4)	1.05	105.3	493.7
(5)	0.84	65.3	252.9
(6)	1.05	103.6	449.1

The relation of Taylor and Langmuir<sup>14</sup> [Eq. (5)] deviates significantly over the entire temperature range from the other five expressions; Bonilla's<sup>13</sup> results are somewhat higher. Tepper,<sup>12</sup> Achener,<sup>2</sup> and Ewing<sup>1</sup> are in close agreement except at 2300°F which exceeds the upper temperature limit of the data of the first two. While the lower limit of Ewing's<sup>1</sup> data

is 1236°F as compared to 850°F for Tepper,<sup>12</sup> 893°F for Achener, 754°F for Bonilla, and 85°F for Heimel,<sup>15</sup> the agreement in the calculated vapor pressure remains reasonable.

To determine the effect of vapor pressure on thermodynamic cycle calculations, the equations of Tepper and of Ewing were used in an ideal Rankine-cycle calculation. Turbine inlet conditions were assumed as 2250°F and 293.92 psia; the exhaust condition was 58.78 psia. Using Eq. (1), the cycle efficiency was found to be 20.007% with an exhaust quality of 0.86897. Correspondingly, Eq. (3) gave a cycle efficiency of 19.981% with 0.87080 exhaust quality. Thus, the effect of the particular vapor pressure equation elected (using relationships in fair agreement) on the engineering cycle calculations does not appear large.

Density. For liquid cesium, the equation of Ewing et al.<sup>1</sup> [Table 3, Eq. (3); and Fig. 4] is recommended. This equation represents the best fit to the experimental data obtained by Ewing, Achener,<sup>2,3</sup> and Tepper et al.<sup>5</sup> over the temperature range from the melting point to 2300°F.

For cesium vapor, Ewing et al.<sup>1</sup> [Table 4, Eq. (1); and Fig. 5] is recommended. The virial equation of Ewing predicts experimental data to within  $\pm 0.43\%$ ; the empirical equation of Tepper et al.<sup>17</sup> correlates their data with a maximum deviation of 7.99%. Saturation values only are plotted in Fig. 5.

Compressibility. The compressibility,  $z = p\tilde{V}/RT$ , is often a useful quantity in calculations. The calculated values of Ewing et al.<sup>1</sup> are again recommended.  $z$  is plotted in Fig. 6 for cesium vapor at saturation conditions only; values for superheated vapor are to be found in Appendix B of Ref. 1.

### Enthalpy and Entropy

Enthalpy. The five equations shown for the liquid enthalpy in Table 5 agree reasonably with respect to enthalpy differences over the range 1000 to 2500°R. The Ewing et al.<sup>1</sup> relationship [Table 5, Eq. (4); and Fig. 7] is recommended at this time.

Equation (4) is based on the absolute properties of solid cesium at 77.0°F as measured by Hultgren et al.<sup>28</sup> and the data of Lemmon et al.<sup>4</sup> for the latent heat of fusion. An anomaly in the heat-content curve for the liquid exists between 77 and 570°F, and the enthalpy change as obtained by Lemmon et al. was used for this region. A constant value for the specific heat of the liquid of 0.05683 Btu/lb<sub>m</sub>·°F was used above 570°F (see discussion on  $c_p$ ). The values tabulated by Ewing (Appendixes A and B, Ref. 1) were based on monomeric gas path calculations — as discussed below — rather than on Eq. (4) by subtracting at each temperature the enthalpy of vaporization. The resulting differences in enthalpy were small (0.1 to 2.0%).

The enthalpy of saturated vapor is plotted in Fig. 8. Ewing et al.<sup>1</sup> obtained the vapor enthalpy by computation along isotherms using their PVT equation. Thus, for the monomeric gas,

$$H_g^T = H_g^0 + \frac{RT}{M_1} \left\{ \frac{1}{V} \left[ B - T \left( \frac{dB}{dT} \right) \right] + \frac{1}{V^2} \left[ C - \frac{T}{2} \left( \frac{dC}{dT} \right) \right] + \frac{1}{V^3} \left[ D - \frac{T}{3} \left( \frac{dD}{dT} \right) \right] + \frac{1}{V^4} \left[ E - \frac{T}{4} \left( \frac{dE}{dT} \right) \right] \right\} ,$$

where  $M_1$  is the molecular weight of monomer (132.91) and the remaining quantities are as shown in Table 4, Eq. (1). The reference value for the

monomeric gas at 1 atm (relative to the solid crystal at 0°R) is given by:

$$H_g^0 = 252.18 + 0.037361 T + 240 e^{-31,290/T},$$

where H is in units of Btu/lb<sub>m</sub> and T, in °R. This equation is based on the standard properties of Evans et al.<sup>33</sup> over the temperature range 0 to 3100°F and on the enthalpy of vaporization to 0°R (18.62 mean kcal/mole) as derived by Ewing.<sup>1</sup> It is noted that the value for  $H_g^0$  used by Ewing differs somewhat from that employed by Heimel.<sup>15</sup>

Latent Heat of Vaporization. The equation of Ewing et al.<sup>1</sup> is recommended; this is shown as Eq. (2) in Table 6 and is plotted in Fig. 9. This relation was derived by differentiation of the vapor pressure equation [Eq. (3), Table 2] and substitution into the Clausius-Clapeyron equation. A value of  $v_l$  at each temperature was obtained from Eq. (3), Table 3, and of  $v_g$  from the virial equation of state [Eq. (1), Table 4].

Of the four equations presented, only that of Achener<sup>2</sup> is based on experimental measurements. The other three equations — Ewing et al.,<sup>1</sup> Tepper et al.,<sup>17</sup> and Dillon<sup>16</sup> — obtain the latent heat of vaporization by the procedure discussed above. Only Ewing shows good agreement (1 to 3%) with the Achener data.

Entropy. Again, Ewing et al.<sup>1</sup> is recommended [Table 7, Eq. (2); and Fig. 10]. As discussed with respect to the enthalpy, the values tabulated by Ewing for the entropy of the saturated liquid were based on the properties of the monomeric gas at 1 atm; these are the values plotted in Fig. 9. Equation (2) was used in comparison calculations with the properties of the saturated liquid as the starting point; note that this entropy is given relative to the solid at 0°R. The resulting differences in entropy were small (0 to 0.8%).

The discussion on the vapor entropy follows that given above for the vapor enthalpy. Thus, for the monomeric gas,

$$S_g^T = S_g^O - \frac{R}{M_1} \left\{ \ln p - \ln \frac{p\tilde{V}}{RT} + \frac{B}{\tilde{V}} + \frac{T}{\tilde{V}} \left( \frac{dB}{dT} \right) + \frac{C}{2\tilde{V}^2} + \frac{T}{2\tilde{V}^2} \left( \frac{dC}{dT} \right) + \frac{D}{3\tilde{V}^3} + \frac{T}{3\tilde{V}^3} \left( \frac{dD}{dT} \right) + \frac{E}{4\tilde{V}^4} + \frac{T}{4\tilde{V}^4} \left( \frac{dE}{dT} \right) \right\},$$

where

$$S_g^O = 0.037361 \ln T + 0.080604 + 0.371 e^{-29,598/T},$$

for  $p$  in atm,  $T$  in  $^{\circ}R$ ,  $\tilde{V}$  in  $\text{ft}^3/\text{lb-mole}$ , and  $S$  in  $\text{Btu}/\text{lb}_m \cdot ^{\circ}F$ . Vapor enthalpies tabulated by Ewing et al. (Appendix A, Ref. 1) for saturated vapor are plotted in Fig. 11.

The entropy of vaporization at each saturation point is obtained by dividing the appropriate enthalpy of vaporization by the absolute temperature.

Specific Heat. Six equations are given in Table 8 for the specific heat of saturated liquid. With the exception of Ewing et al.<sup>1</sup> [Eq. (5)], these were obtained by differentiation of derived heat content equations. Ewing's value of  $0.05683 \text{ Btu}/\text{lb}_m \cdot ^{\circ}F$  was obtained through a trial-and-error procedure to provide internal third law consistency with their PVT data. Note that this value lies intermediate to those of Tepper et al.<sup>12</sup> and Lemmon et al.<sup>4</sup> and, further, that an anomaly exists in  $c_{p,l}$  in the temperature range between  $212$  and  $572^{\circ}F$  (see Lemmon et al., Ref. 4, p. 12). Ewing et al. is recommended (Fig. 12).

The specific heat of cesium vapor (Table 9) was determined by Ewing et al.<sup>1</sup> following the procedure outlined above for enthalpy and entropy.

For this property, however, values based on the saturated liquid were 5.3 to 31% lower than those calculated by the monomeric gas path. The latter values are plotted in Fig. 13. Shapiro and Meisl<sup>31</sup> report the frozen specific heat of saturated vapor to be  $0.0371 \text{ Btu/lb}_m \cdot ^\circ\text{F}$ .

To evaluate the effect of liquid  $c_p$  on cycle efficiencies, an ideal Rankine cycle was assumed; and calculations were made for two different values of  $c_{p,l} = 0.05683 \text{ Btu lb}_m \cdot ^\circ\text{F}$  (as recommended by Ewing et al.<sup>1</sup>) and  $0.0600 \text{ Btu/lb}_m \cdot ^\circ\text{F}$  (as reported by Lemmon et al.<sup>4</sup>). The Ewing relations were used for all vapor conditions. The turbine inlet conditions were taken to be  $2250^\circ\text{F}$  and  $293.92 \text{ psia}$ ; the turbine exhaust was at  $58.78 \text{ psia}$ . For the first case, the cycle efficiency was determined to be  $19.981\%$  with a turbine exhaust quality of  $0.870800$ ; the second case yielded an efficiency of  $24.011\%$  and an exhaust quality of  $0.829166$ . These differences are sufficiently significant to suggest the need for further experimental measurements on the enthalpy of liquid cesium.

#### Surface Tension

The interfacial tensions (solid-liquid and vapor-liquid) of the alkali liquid metals are of importance in situations where free liquid surfaces exist, where liquid transfer is by capillary action (heat pipes), and where heat transfer occurs by boiling. The only currently available data for cesium are those of Tepper et al.<sup>17</sup> as shown in Table 10 and in Fig. 14. Achener<sup>34</sup> is currently studying lithium and sodium and plans measurements with cesium. Cooke (ORNL) has also started experiments with cesium to obtain data to about  $2000^\circ\text{F}$ . All three investigators are using the maximum bubble pressure technique.

## Fig. 1. Cesium: Physical Constants

Chemical Formula:	Cs
Molecular Weight:	132.91
Melting Temperature:	83.1°F
Boiling Temperature:	1236°F (1 atm)

Table 1. Critical Properties

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
<u>Temperature (°K)</u>							
$T_c = 2057$			$\pm 40^\circ\text{K}$		Error based on data at 1650°C	Dillon et al. (1965)	16,27
$T_c = 2000$						Morris (1964)	7
$T_c = 2150$						Grosse (1960)	8
$T_c = 1996$						Hochman, Bonilla (1964)	18
$T_c = 1838 \text{ to } 2157$					Five methods used for estimating	Tepper et al. (1965)	17
<u>Pressure (atm)</u>							
$P_c = 145$					Equation of Sawhney and Bonilla using $T_c$ of Dillon et al.	Dillon et al. (1965)	16,27
						Sawhney, Bonilla (1962)	13
$P_c = 140$						Morris (1964)	7
$P_c = 170$						Grosse (1960)	8
<u>Volume (liter/g-mole)</u>							
$V_c = 0.311$			$\pm 0.008$			Dillon et al. (1965)	16,27
$V_c = 0.380$						Morris (1964)	7
$V_c = 0.316$						Grosse (1960)	8

\*See Table of References.

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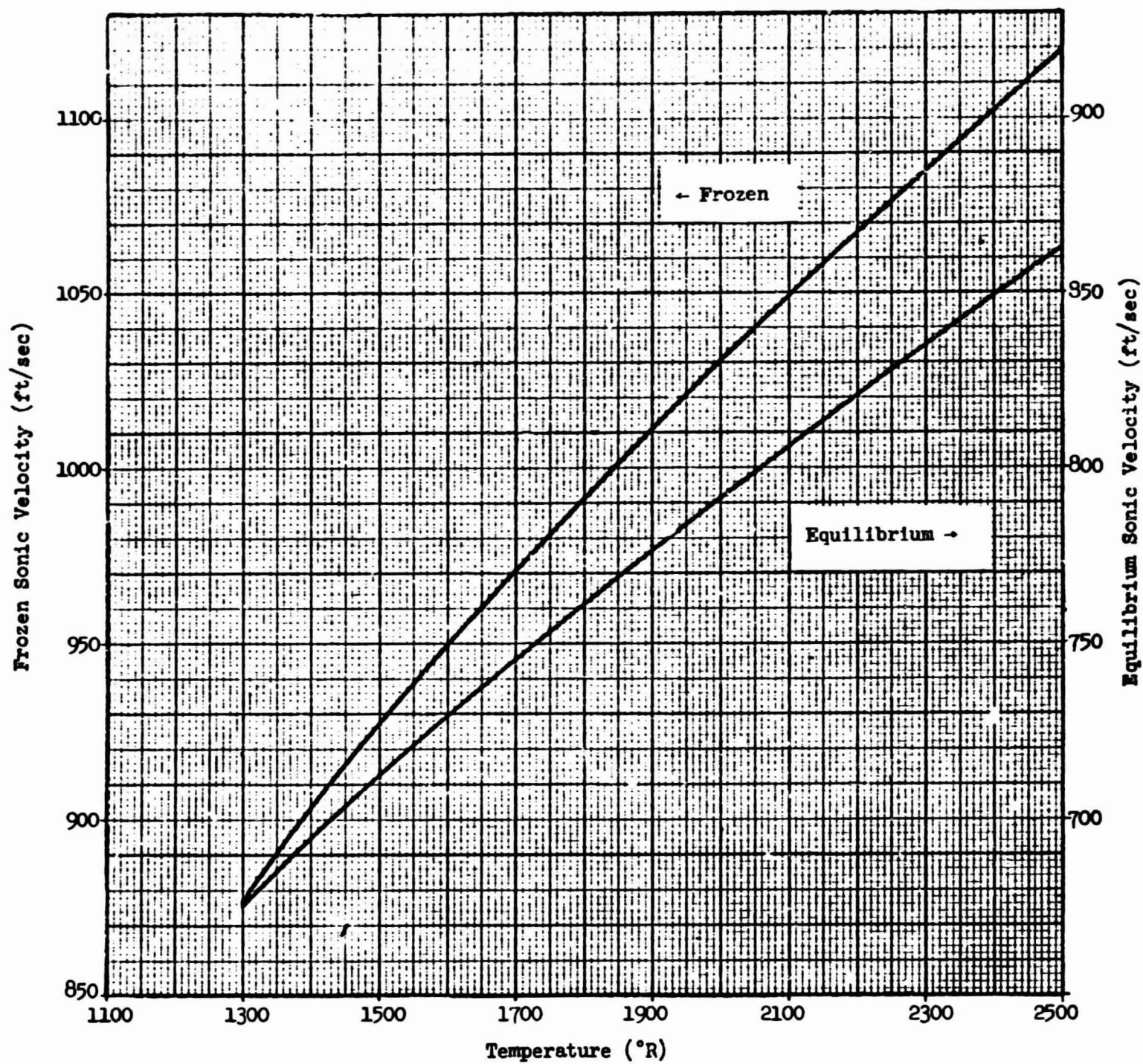


Fig. 2. Cesium: Vapor Sonic Velocity.

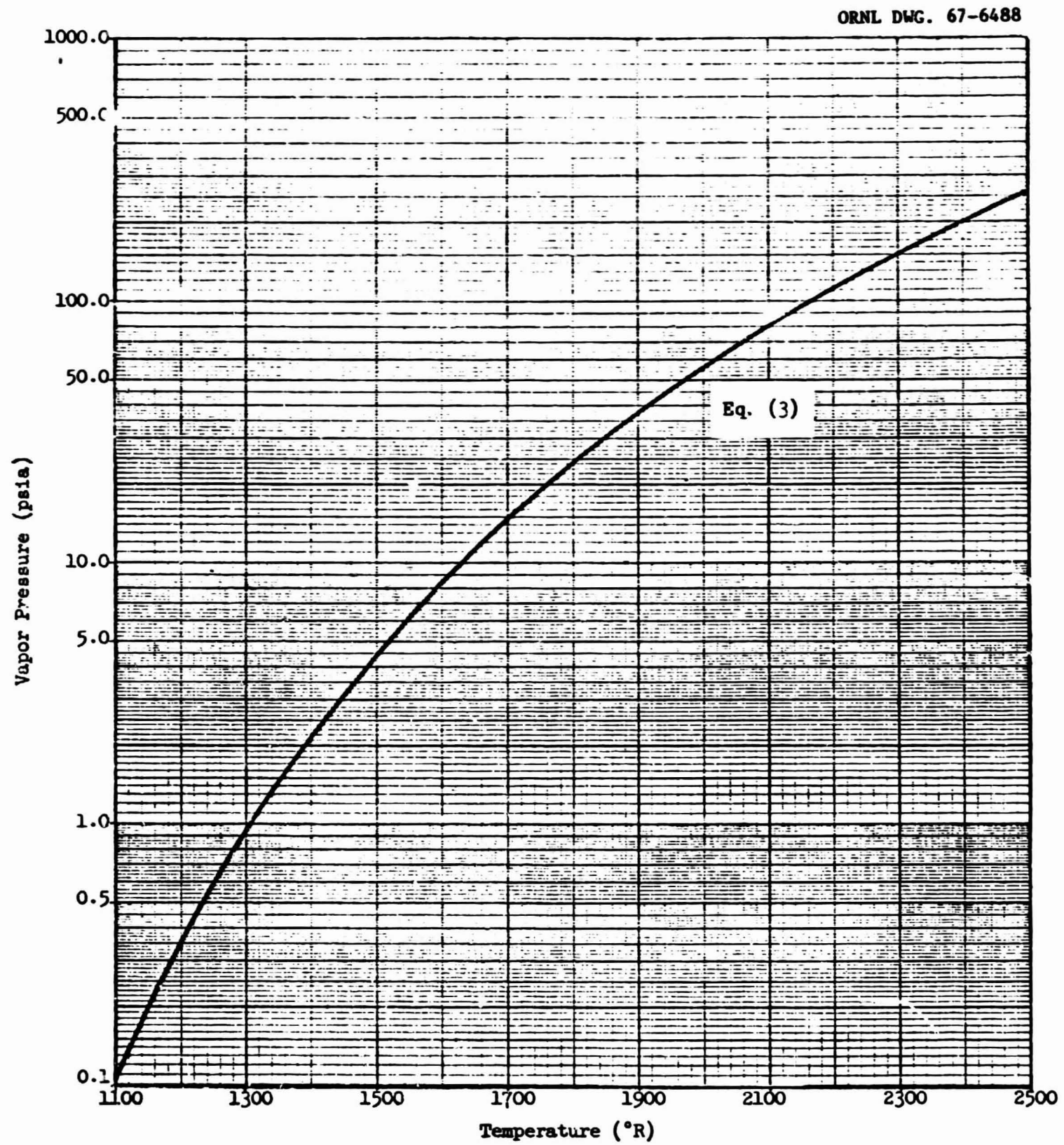


Fig. 3. Cesium: Vapor Pressure.

Table 2. Vapor Pressure

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$\log_{10} P = -\frac{6631.74}{T} + 3.9011$ (P = atm abs; T = °R)	(1)	850-1950	0.72%	Boiling	No mention of super-heat phenomenon or "bumping"; for Rb added Zr-chips to prevent bumping	F. Tepper et al. (1963)	12
$\log_{10} P = -\frac{6680.185}{T} + 5.09475$ (P = psi abs; T = °R)	(2)	893-1600	0.68%	Boiling	No mention of super-heat phenomenon	P. Y. Achener (1964)	2
$\log_{10} P = -\frac{7040.7}{T} + 5.87303 - 0.53290 \log_{10} T$ (P = atm; T = °R)	(3)	1236-2346	±0.35%	Null Point		C. T. Ewing et al. (1965)	1
$\log_{10} P = -\frac{6665.302}{T} + 5.10876$ (P = psi abs; T = °R)	(4)	754-1788	1.44%	Boiling		C. F. Bonilla et al. (1962)	13
$\log_{10} P = -\frac{4041}{T} + 11.0531 - 1.35 \log_{10} T$ (P = mm Hg; T = °K)	(5)	84-1340	300-350°K: 1% 350-600°K: 3% 600-1000°K: 8%	Positive Ion		J. P. Taylor and I. Langmuir (1937)	14
$\log_{10} P = -\frac{4053.30}{T} + 7.04453 - 0.915282 \log_{10} T$ (P = atm; T = °K)	(6)	85-1938	0.5%	Thermodynamic Calculation	Based on zero-degree heat of condensation of the monomer.	S. Heime1 (1965)	15

\*See Table of References.

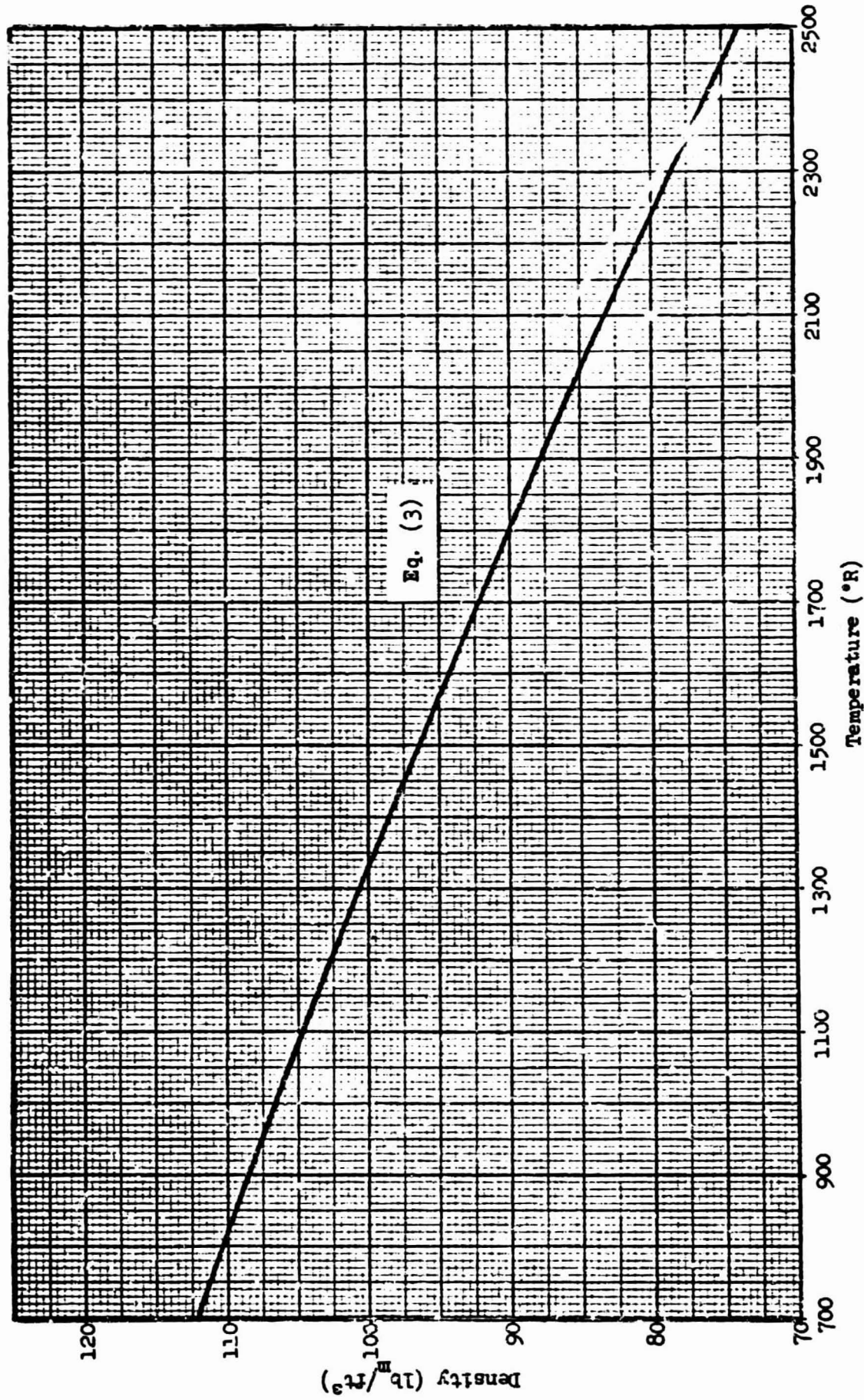


Fig. 4. Cesium: Liquid Density.

Table 3. Density (Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs. *
$\rho = 1.868926 - 0.29211 \left( \frac{T}{1000} \right)$ $- 0.0154436 \left( \frac{T}{1000} \right)^2$ <p>[<math>\rho = \text{g/cc}</math>; <math>T = ^\circ\text{F}</math>]</p>	(1)	100-1950	0.00236 g/cc	Dilatometer (constant wt)		Tepper et al. (1964)	5
$\rho = 1.84/[1 + 1.2755 \times 10^{-4} (T - 82.4)$ $+ 7.656 \times 10^{-8} (T - 82.4)^2]$ <p>[<math>\rho = \text{g/cc}</math>; <math>T = ^\circ\text{F}</math>]</p>	(2)	83-1671	0.6% (0.010 gm/cc)	Pycnometer (constant vol)		Achener (1964)	2,3
$\rho = 124.181 - 1.5970 \times 10^{-2} T$ $- 1.0355 \times 10^{-6} T^2$ <p>[<math>\rho = \text{lb}_m/\text{ft}^3</math>; <math>T = ^\circ\text{R}</math>]</p>	(3)	83-2300	±0.6%	Pycnometer	Equation is best fit to combined NRL, AGN, and MEAR data.	Ewing et al. (1965)	1
Data tabulated as function of temperature		1112-3218		Irradiation	Count of $\gamma$ activity from known isotopes irradiated by thermal neutrons	Dillon et al. (1965)	16,27

\*See Table of References.

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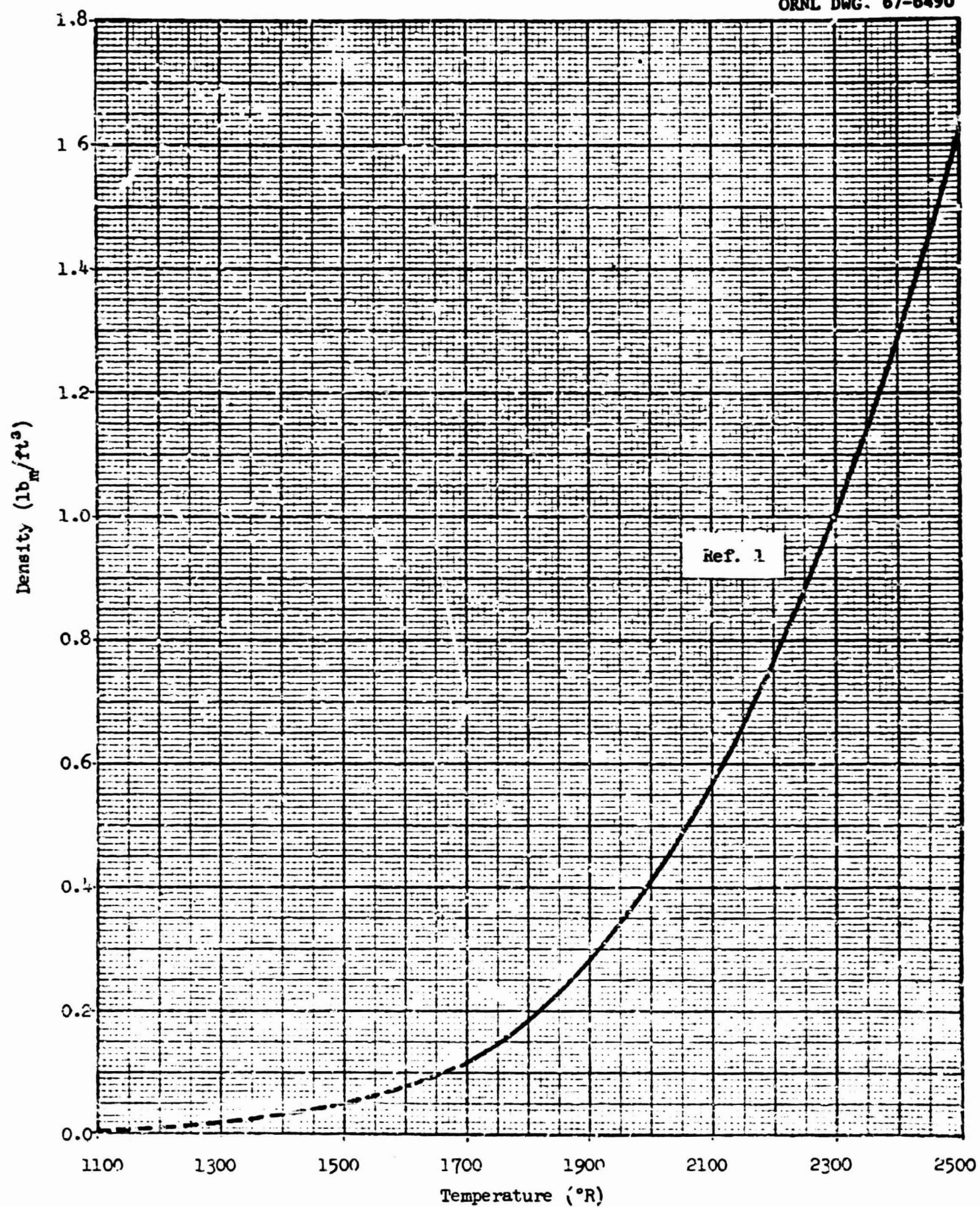


Fig. 5. Cesium: Density, Saturated Vapor.

Table 4. Vapor Density

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs. *
$\frac{P\tilde{V}}{RT} = 1 + \frac{B}{\tilde{V}} + \frac{C}{\tilde{V}^2} + \frac{D}{\tilde{V}^3} + \frac{E}{\tilde{V}^4} + \dots$ $\log_{10}  B  = -3.6200 + \frac{4000}{T} + \log_{10} T$ $B < 0$ $\log C = 3.3551 - \frac{5331.5}{T} + \frac{10.825 \times 10^6}{T^2}$ $C > 0$ $\log  D  = 4.1856 + \frac{880}{T}$ $D < 0$ $E = +600,000$ <p>[P = atm abs; T = °R; <math>\tilde{V}</math> = molal volume, ft<sup>3</sup>/lb-mole] (also tabulated in 25°F increments over temperature range)</p>		1250-2350		PVT-closed chamber with flexible diaphragm as null detector	Virial equation of state developed using graphical evaluation of coefficients	Ewing et al. (1965)	1
$PV = A(T) + B(T)P + C(T)P^2 + D(T)P^3$ $A(T) = 0.09268T - 12.4307$ $B(T) = 5.80719 - \frac{18.2145}{t} + \frac{5.68552}{t^3}$ $C(T) = \frac{2.47250}{t^2} + \frac{0.30167}{t^4} - \frac{1.35708}{t^6}$ $D(T) = \frac{0.02146}{t^2} - \frac{0.46282}{t^4} + \frac{0.27364}{t^6}$ <p>[T = °K; t = 10<sup>-3</sup>T; P = atm; V = liters/g-mole] (also tabulated)</p>		1250-2150		PVT-closed cylinder with movable probe to indicate diaphragm displacement	Empirical equation assuming PV approaches finite value as P → 0	Achener et al.	17

\*See Table of References.

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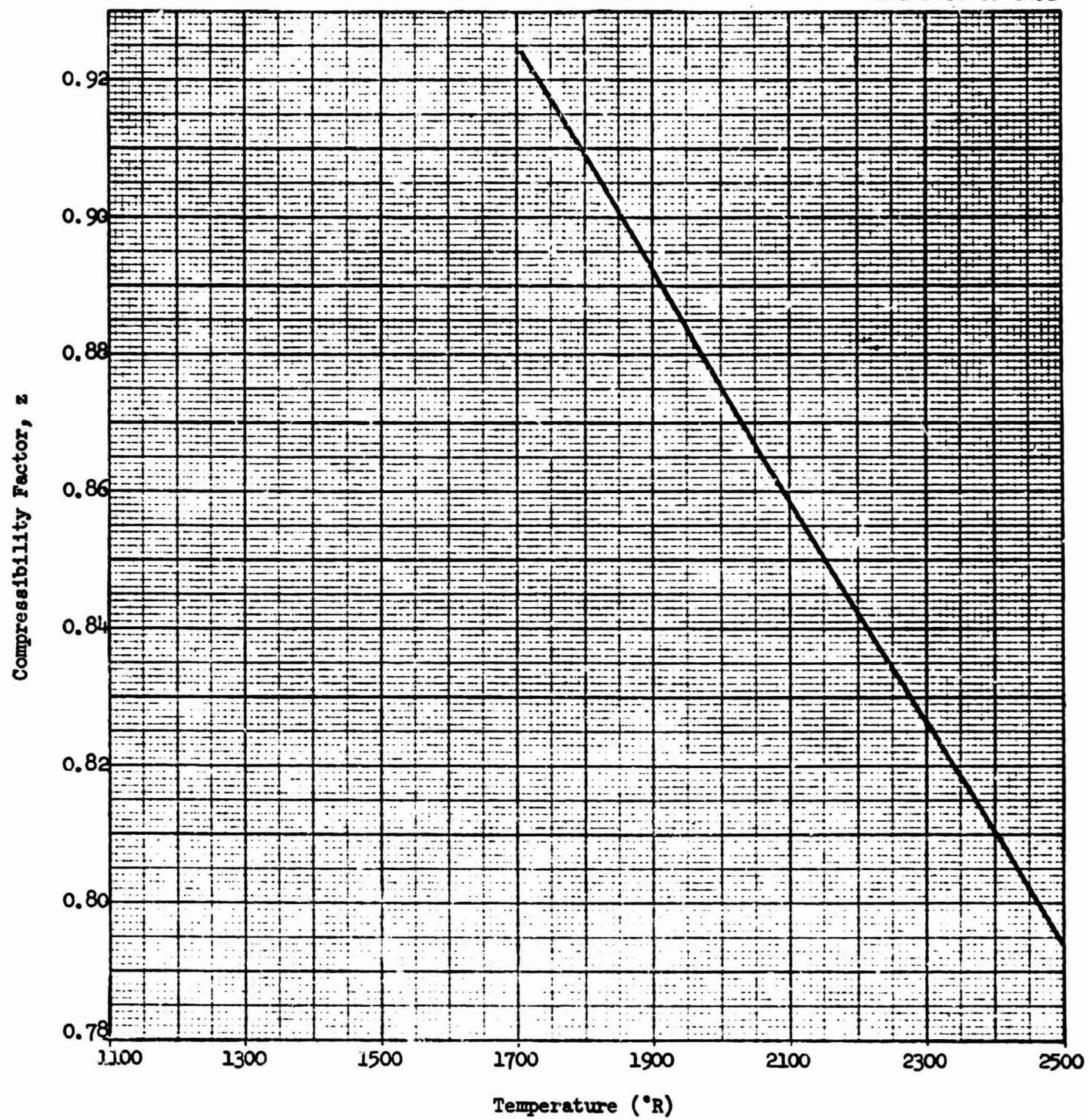


Fig. 6. Cesium: Compressibility, Saturated Vapor.

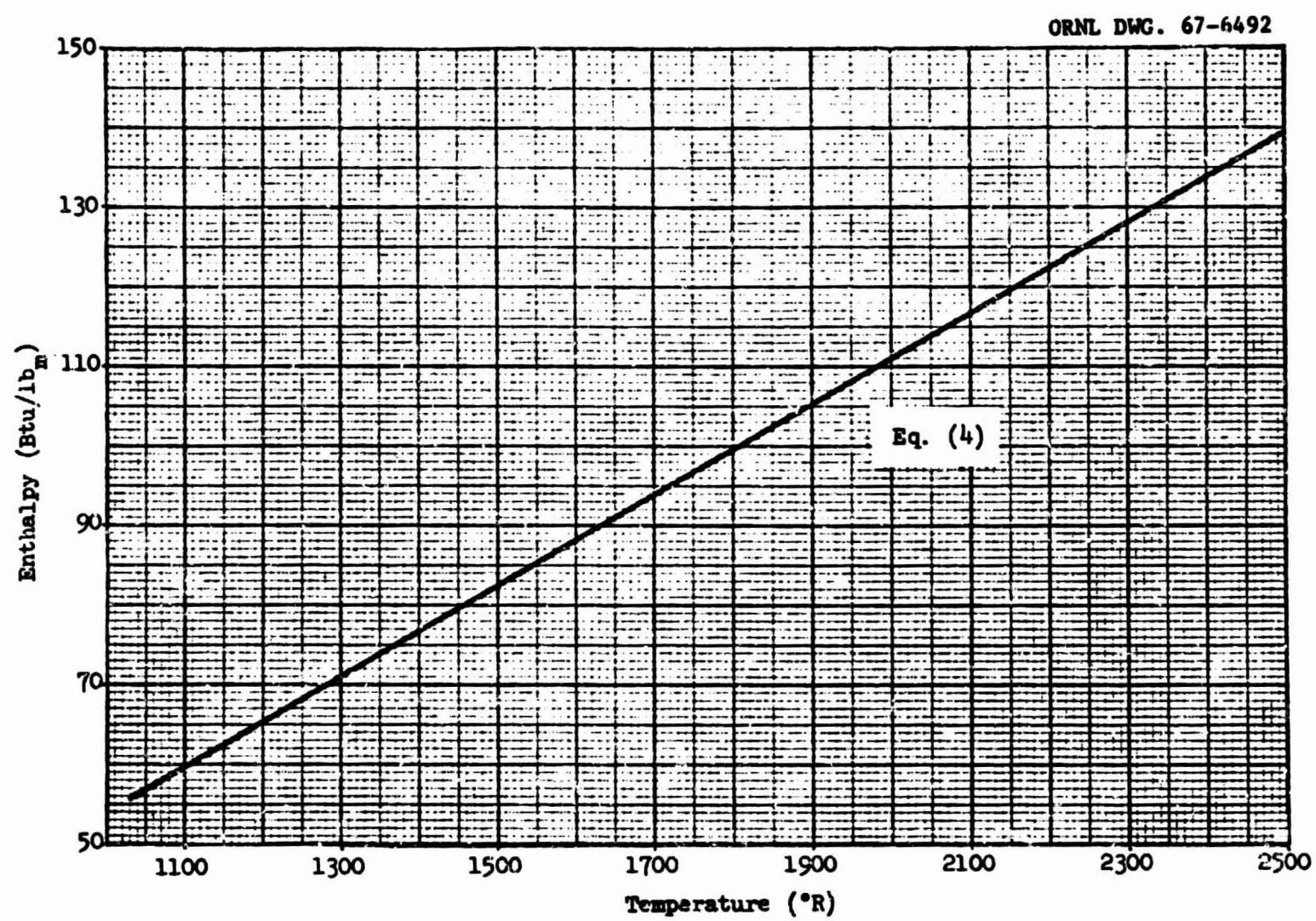


Fig. 7. Cesium: Liquid Enthalpy.

Table 5. Enthalpy (Saturated Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$H_T - H_{298} = -1506 + 7.25 T$ $[H_T = \text{cal/g-atom}; T = ^\circ\text{K}]$	(1)	600-1770	$\pm 1.5\%$	Calorimeter	Not stated whether corrected for vapor condensation; total data range = 170-1770°F, below 600°F an anomaly was observed.	Tepper (1963)	12
$H_T - H_{32} = 2.711 + 0.08543 T - 4.803$ $\times 10^{-5} T^2 + 1.995 \times 10^{-8} T^3$ $[H_T = \text{Btu/lb}_m; T = ^\circ\text{F}]$	(2)	152-1656	0.77 Btu/lb <sub>m</sub>	Calorimeter	Corrected for vaporization	Achener (1964)	2
$H_T - H_O = 3.55 + 0.0554 T$ $H_T - H_O = 0.5 + 0.06 T$ $[H_T = \text{Btu/lb}_m; T = ^\circ\text{R}]$	(3)	86-212 572-2100	~7% (estimate)	Calorimeter	Corrected for vaporization; data in range 212-572°F are anomalous.	Lemmon et al. (1964)	4
$H_T - H_O = -2.6969 + 0.05683 T$ $[H_T = \text{Btu/lb}_m; T = ^\circ\text{R}]$	(4)	>570			Based on a value of C <sub>p</sub> which is consistent with P <sub>3</sub> rd-law calculations of NBS P-V-T data.	Ewing et al. (1965)	1
$H_T - H_{298} = -1704.5 + 7.455 T$ $[H_T = \text{cal/mole}; T = ^\circ\text{K}]$	(5)	600-1770			Corrected equation based on measurements of Ref. 12.	Heimel (1965)	15

\* See Table of References.

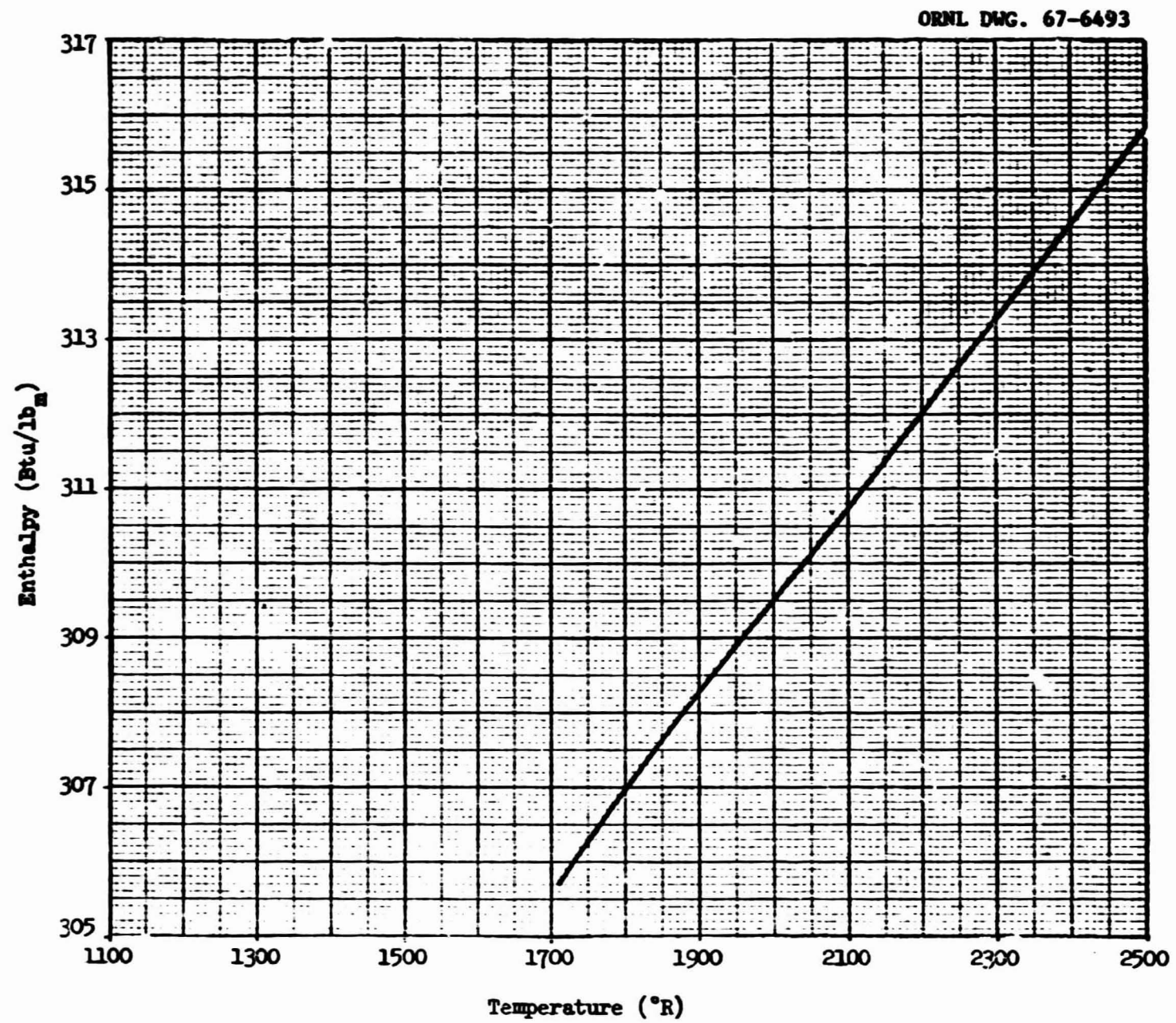


Fig. 8. Cesium: Enthalpy, Saturated Vapor.

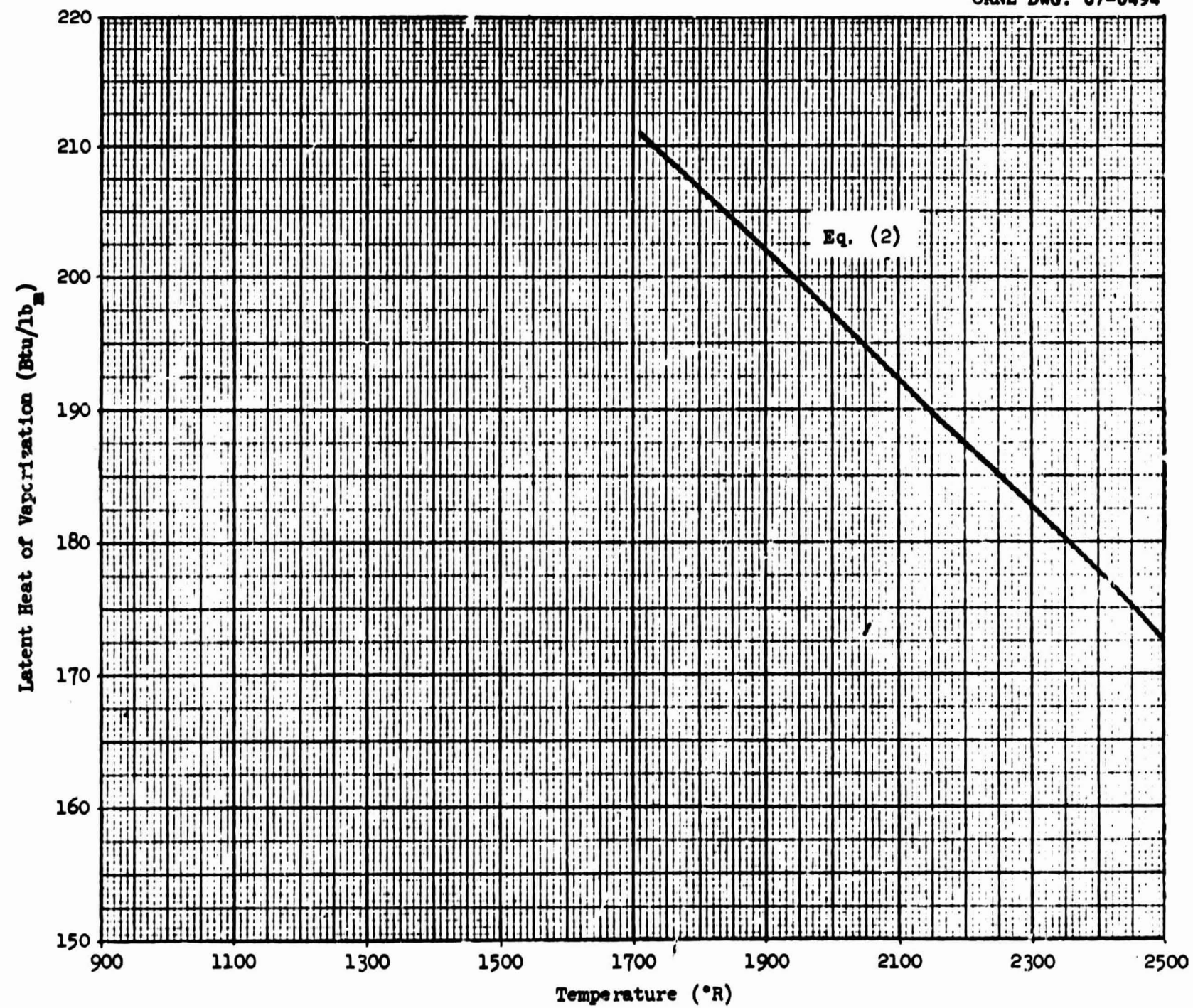


Fig. 9. Cesium: Latent Heat of Vaporization.

Table 6. Latent Heat of Vaporization

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs. *
$h_{fg} = 257.4 - 0.0362 T$ $[h_{fg} = \text{Btu/lb}_m; T = ^\circ\text{F}]$	(1)		0.48%	Direct measurement of heat required to vaporize a given mass of liquid		Achener (1964)	2
$h_{fg} = J P_s \left( \frac{16,211.8}{T} - 0.53290 \right) (v_g - v_l)$ $[h_{fg} = \text{Btu/lb}_m; P_s = \text{atm}; T = ^\circ\text{R}; v = \text{ft}^3/\text{lb}_m]$ (Tabulated in Appendix A, Ref. 1)	(2)			Clausius-Clapeyron equation calculation	$\frac{dP}{dT}$ and $v_g, v_l$ from NRL measurements	Ewing et al. (1965)	1
$h_{fg} = 17,680.3 - 2,699.4 \left( \frac{T}{1000} \right)^2$ $[h_{fg} = \text{cal/g-mole}; T = ^\circ\text{K}]$	(3)			Clausius-Clapeyron	Investigator's P-V-T data	Tepper (1965)	17
$h_{fg} = \frac{2.303 BP}{T} K(v_g - v_l)$ $[h_{fg} = \text{cal/g-mole}; P = \text{atm}; T = ^\circ\text{K};$ $K = 24.218 \text{ cal/liter}\cdot\text{atm};$ $V = \text{liters}; B = 2\text{nd virial coeff}]$	(4)			Clausius-Clapeyron	Second virial coefficient tabulated in reference	Dillon (1965)	16

\* See Table of References.

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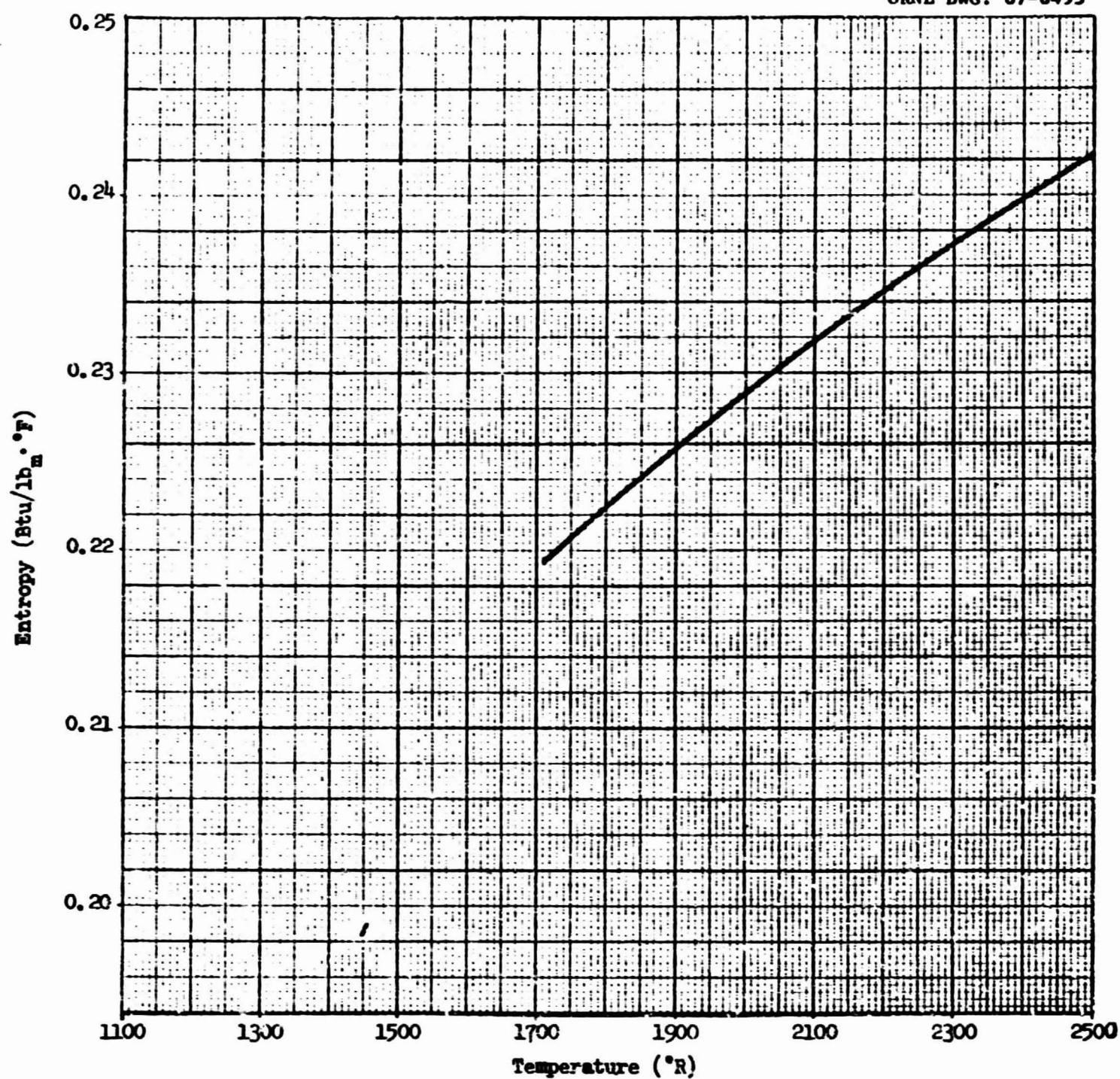


Fig. 10. Cesium: Liquid Entropy.

Table 7. Entropy (Saturated Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$S - S_{537} = -0.8093 + 0.3275 \log_{10} T$ $-1.5107 \times 10^{-4} T + 2.9925 \times 10^{-8} T^2$ $[T = ^\circ R; S = \text{Btu/lb}_m \cdot ^\circ R]$	(1)	152-1656			$S = \int_{537}^T c_{p,l} \frac{dT}{T} + \frac{\Delta H}{T_m}$ $+ \int_{T_m}^T c_{p,g} \frac{dT}{T}$	Achener (1964)	2
$S - S_0 = 0.05683 \ln T - 0.19387$ $[T = ^\circ R; S = \text{Btu/lb}_m \cdot ^\circ F]$	(2)	570-2400			Based on $c_{p,l} = 0.05683$ which gave good degree of internal consistency in P-V-T data; error in P-V-T data would affect $c_{p,l}$ and hence S.	Ewing et al. (1965)	1

\*See Table of References.

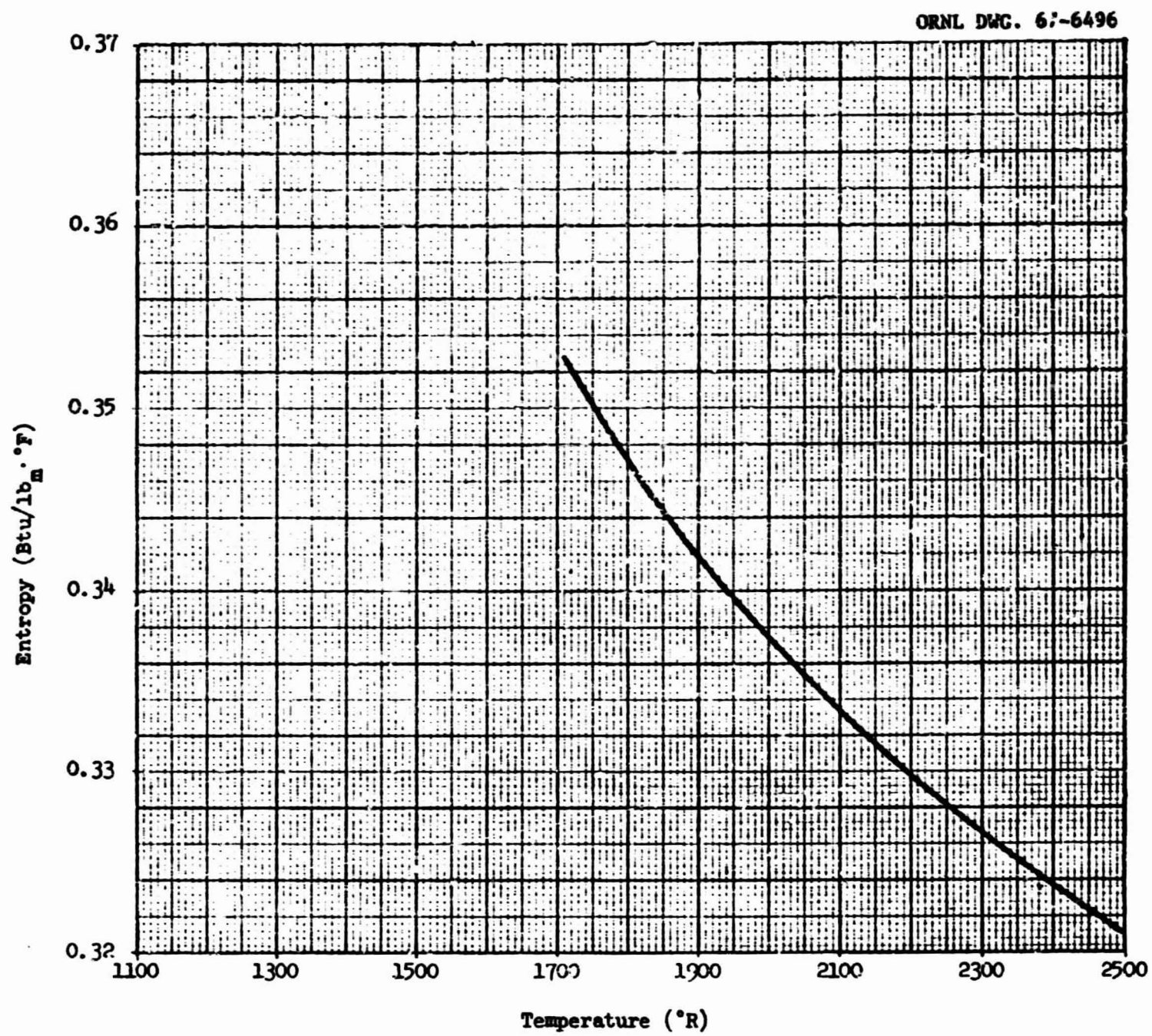


Fig. 11. Cesium: Entropy, Saturated Vapor.

Fig. 12. Cesium: Liquid Specific Heat

$$c_{p,liq} = 0.05683 \text{ Btu/lb}_m \cdot ^\circ\text{F} \quad [\text{Eq. (5)}]$$

For  $T > 1030^\circ\text{R}$

Table 8. Specific Heat (Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$c_p = 7.25 \text{ cal/}^\circ\text{K}\cdot\text{g}\cdot\text{atom}$	(1)	>600		Derivative of eq. for saturated-liquid enthalpy	No $V \frac{dP}{dT}$ correction	Tepper (1963)	12
$c_p = 0.08543 - 9.505 \times 10^{-5} T$ $+ 5.985 \times 10^{-8} T^2$ [ $c_p = \text{Btu/lb}_m$ ; $T = ^\circ\text{F}$ ]	(2)	152-1656		Derivative of eq. for saturated-liquid enthalpy	No $V \frac{dP}{dT}$ correction	Achener (1964)	2
$c_p = 33.6 - 0.019 T$ [ $c_p = \text{joule/g}\cdot\text{atom}\cdot^\circ\text{C}$ ; $T = ^\circ\text{C}$ ]	(3)	mp-212				Rengade (1913)	18
$c_p = 0.0554 \text{ cal/g}\cdot^\circ\text{C}$ $c_p = 0.060 \text{ cal/g}\cdot^\circ\text{C}$	(4)	86-212 572-2100			No $V \frac{dP}{dT}$ correction; was as much as 2% in places	Lemmon et al. (1964)	4
$c_p = 0.05683 \text{ Btu/lb}_m\cdot^\circ\text{F}$	(5)	>570			Gave greatest degree of internal consistency in 3rd-law calculations (trial and error)	Ewing et al. (1965)	1
$c_p = 7.455 \text{ cal/mole}\cdot^\circ\text{K}$	(6)	>600				Heimel (1965)	15

\* See Table of References.

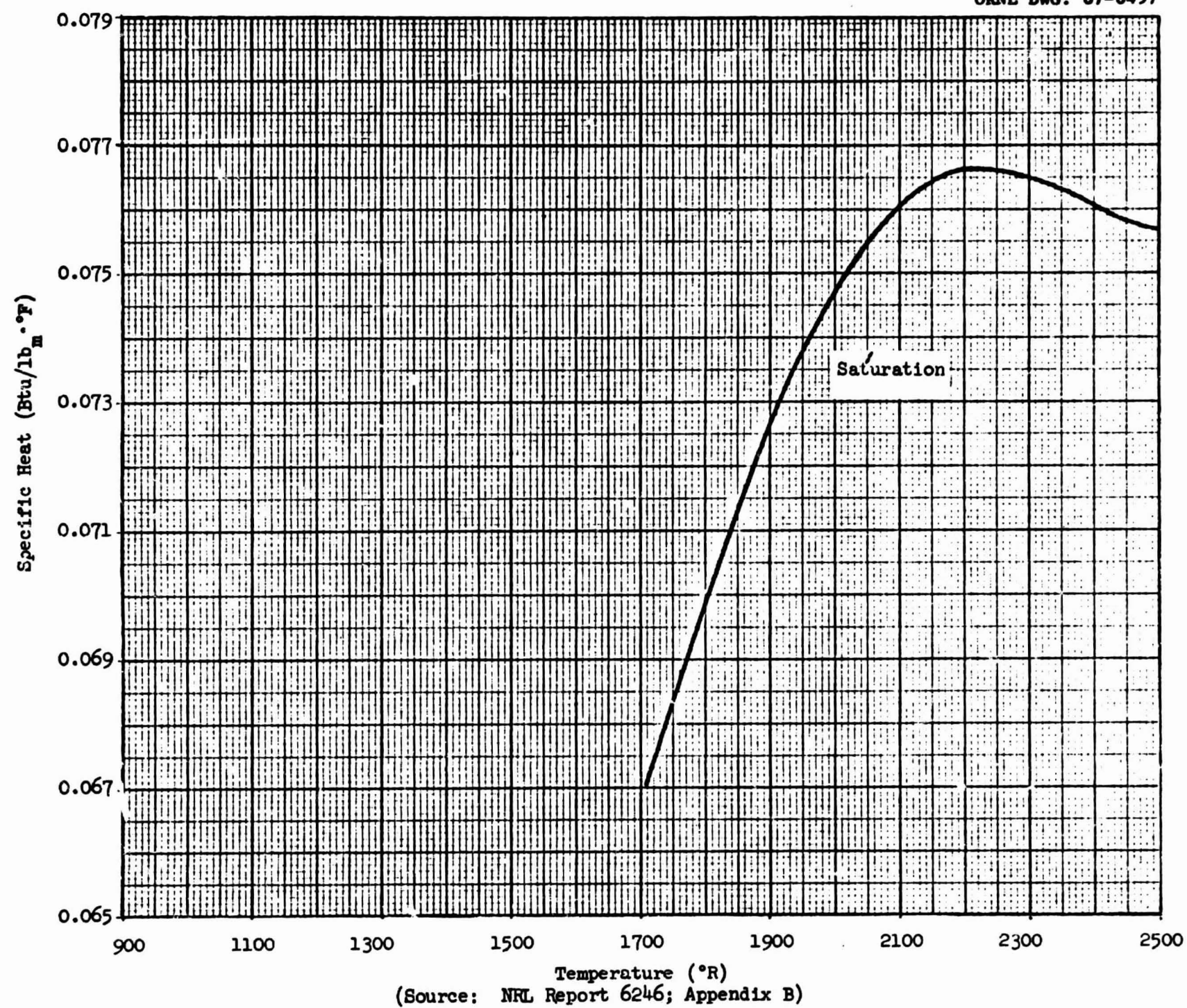


Fig. 13. Cesium: Vapor Specific Heat.

Table 9. Specific Heat (Vapor)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$(c_p)_s = \left[ \left( \frac{\Delta h}{\Delta T} \right)_p \right]_s$ <p> <math>[c_p = \text{Btu/lb}_m \cdot ^\circ\text{F}; \Delta h = \text{enthalpy change (Btu/lb}_m); \text{superscript } s = \text{saturation}]</math>  (Tabulated in Appendix B, Ref. 1) </p>		1250-2550		Calculation	Normal evaluation of the differential at 50°F increments	Ewing et al. (1965)	1
<u>Superheated Vapor</u>  Equation given in Ref. 1, p. 21; also tabulated in Appendix B.		1250-2550		Calculation	Computed along constant temperature lines with each saturation state as starting point.	Ewing et al. (1965)	1

\* See Table of References.

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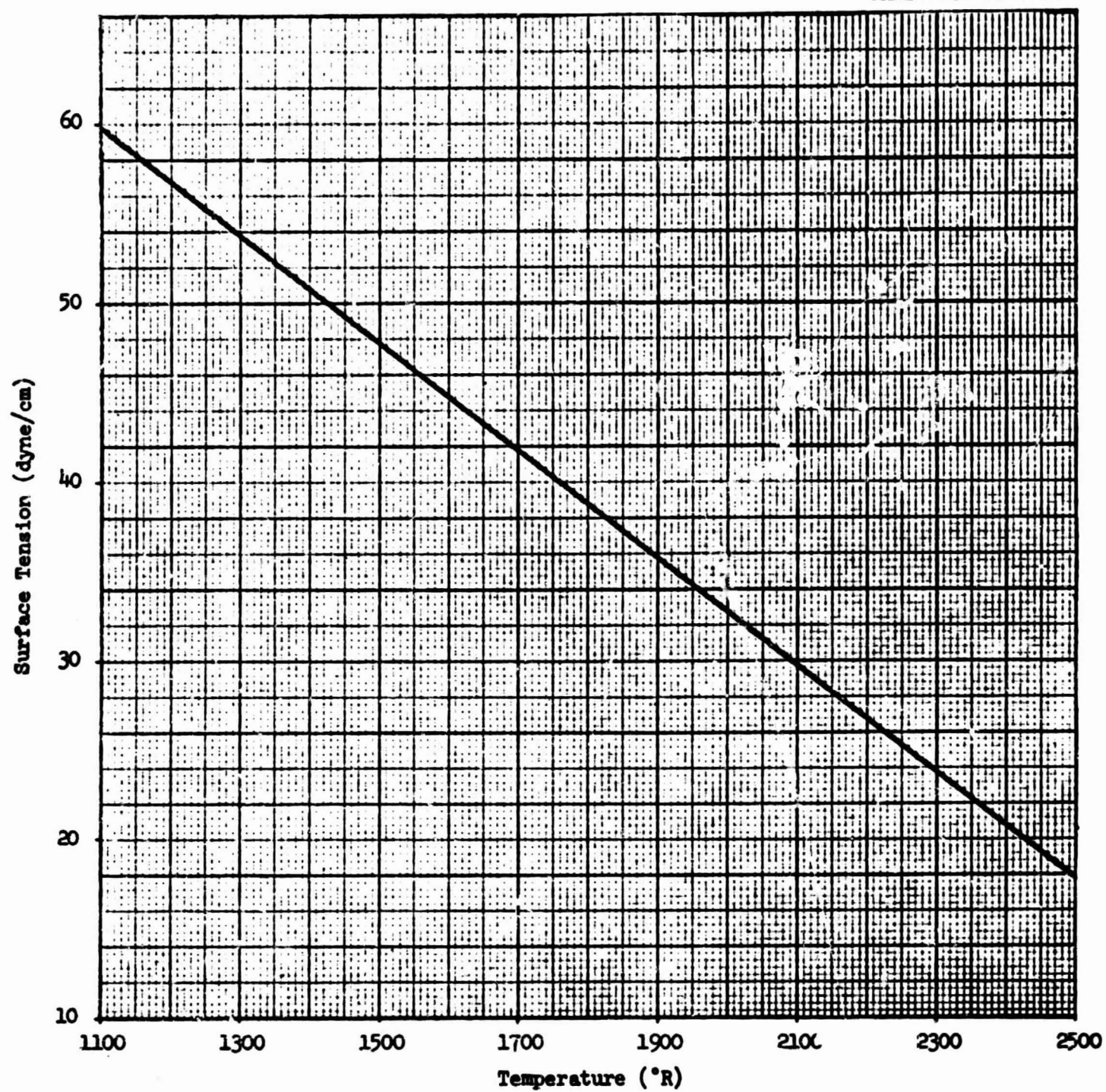


Fig. 14. Cesium: Liquid Surface Tension.

Table 10. Surface Tension

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs. *
$\sigma = 76.4 - 0.030 (T - 83)$ $[\sigma = \text{dyne/cm}; T = ^\circ\text{F}]$		150-1850	4%	Maximum bubble pressure		Tepper et al. (1964)	6,17

\* See Table of References.

## TRANSPORT PROPERTIES

### Introduction

The transport properties characterize a material with respect to the molecular processes of momentum, heat, and mass exchange. Viscosity, thermal conductivity, thermal diffusivity, thermal diffusion ratio, and mass diffusivity fall within this category. The electrical resistivity is also included in this section, since measurements of this property are often used, through the Wiedemann-Franz-Lorenz relationship, to calculate the thermal conductivity.

### Viscosity

The viscosity,  $\mu$ , characterizes the flow resistance of simple fluids and appears as the proportionality coefficient in Newton's law of viscosity:

$$\tau_{yx} = -\mu \frac{dv_x}{dy},$$

which states that the shear force per unit area is proportional to the negative of the local velocity gradient normal to the mean flow. The negative sign specifies that the viscous (molecular) momentum flux tends to go in the direction of decreasing velocity. This also enables a treatment which is consistent with that commonly employed for energy (heat) and mass transport.

Liquid Viscosity. The recommended equation [Fig. 15 and Table 11, Eq. (1)], obtained by Achener and Boyer,<sup>3</sup> is a reasonable fit to most of the available data. The results of Lemmon et al.<sup>4</sup> have been disregarded at this time, since the data obtained by these investigators differed

significantly from those reported in other sources. The equation of Tepper et al.<sup>17</sup> yields values about 10% higher than those predicted by the recommended equation.

Vapor Viscosity. Values along the saturation line are plotted in Fig. 16; the available data are summarized in Table 12. The upper curve gives the calculated results of Weatherford;<sup>29</sup> the lower curve is the polynomial fit [Eq. (2b)] to the data of Lee and Bonilla.<sup>23</sup> The data of the latter are recommended. Note, however, that the power [Eq. (2a)] and polynomial [Eq. (2b)] forms given by Lee and Bonilla give somewhat different results. Thus:

T (°R)	Power Fit (lb <sub>m</sub> /hr·ft)	Polynomial Fit
1710	0.0553	0.0533
1800	0.0568	0.0558
1900	0.0584	0.0597
2000	0.0600	0.0618
2100	0.0616	0.0628
2200	0.0631	0.0645

At this time, no preference is indicated between the two forms of the Lee and Bonilla correlation. Reasonable agreement exists between the Kitrilakis and Meeker<sup>19</sup> results, calculated using experimental thermal conductivity values and the kinetic theory relationship between  $\mu$  and  $k$ , and the Lee and Bonilla data. On the other hand, the experimental data of Weaver and Stratton<sup>22</sup> show significant deviation from that of Lee and Bonilla, possibly due to their use of the Taylor and Langmuir<sup>14</sup> relationship for the vapor pressure.

### Thermal Conductivity

The thermal conductivity,  $k$ , of a material is the proportionality coefficient appearing in Fourier's law of heat conduction:

$$q_y = -k \frac{dT}{dy} .$$

This is the one-dimensional form of the equation relating the heat flux to the temperature gradient. For an isotropic medium (in which  $k$  has the same value in all directions) and  $T = T(x, y, z)$ , the same equation applies, with the appropriate temperature gradient, in each of the three Cartesian directions. In a more general form, the law of heat conduction can be written:

$$\frac{\partial T}{\partial \tau} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) ,$$

neglecting heat sources, where  $\tau$  = time and  $\alpha$  = thermal diffusivity ( $k/\rho c_p$ ). This latter quantity is often of importance and can be calculated from the given values for  $k$ ,  $\rho$ , and  $c_p$ .

Liquid Conductivity. The data of Lemmon et al.<sup>4</sup> constitute the only thermal conductivity measurements for liquid cesium and are currently recommended [Fig. 17 and Table 13, Eq. (3)] as the best available values. The other tabulated equations (Lepper et al.,<sup>5</sup> Hochman and Bonilla,<sup>18</sup> and Hyman<sup>25</sup>) were obtained through calculation from electrical resistivity measurements; the agreement with the Lemmon et al. results is fair.

An expression suggested by Ewing and co-workers<sup>30</sup> for the calculation of thermal conductivity from electrical conductivity was applied to the resistivity data. However, this procedure yielded results which differed

more from the experimental data than the values calculated by the more normal Wiedemann-Franz-Lorenz relation.

Vapor Conductivity. The experimental results of Kitrilakis and Meeker<sup>19</sup> [Fig. 18, lower curve, and Table 14, Eq. (1)] are recommended on the basis that vapor viscosity values predicted from their data agree reasonably with the best available experimental data on vapor viscosity. The calculated values of Weatherford<sup>26</sup> [Fig. 18, upper curve, and Table 14, Eq. (3)] derive from his vapor viscosity prediction assuming a constant Prandtl modulus of 0.73 and a frozen specific heat as estimated by Shapiro and Meisl.<sup>31</sup> Note that Weatherford predicts conductivities which are about twice those measured by Kitrilakis and Meeker. In contrast, Gottlieb and Zollweg<sup>20</sup> reported conductivities measured by a heat-transfer technique which are about an order of magnitude smaller than the Weatherford prediction. Achener is currently also using a heat-transfer method to measure cesium-vapor conductivities; data have not yet been reported. Cooke (ORNL) has proposed a measurement utilizing a steady-state variable-gap conductivity apparatus (an improved version of the technique used by Kitrilakis and Meeker) which has been shown to give excellent data for argon and helium.

#### Electrical Resistivity

While the electrical resistivity of a liquid is needed in some applications (e.g., in the design of control and measurement instrumentation), major interest in this property derives from the relative ease in performing electrical resistivity measurements as opposed to thermal conductivity measurements. The Wiedemann-Franz-Lorenz (W-F-L) relationship,

$$k/\rho_e/T = L_0 ,$$

is then used to calculate  $k$  from the resistivity,  $\rho_e$ ;  $T$  is the absolute temperature and  $L_0$ , the so-called Lorenz number. Sommerfeld deduced through quantum mechanics that

$$L_0 = \pi^2 \kappa^2 / 3e^2 = 2.57 \times 10^{-8} \text{ Btu} \cdot \text{ohm} / \text{hr} \cdot (\text{°K})^2 ,$$

where  $\kappa$  = the Boltzmann constant and  $e$  = the elementary charge of an electron. For molten metals, the W-F-L relation should give thermal conductivities close to actual values. However, comparisons made with several liquid metals whose thermal conductivities and electrical resistivities are well-known give  $k$  predictions higher than the experimental values. It has not yet been resolved whether the discrepancies result from a breakdown in the theory or from inaccuracies in the experimental measurements.

Liquid Resistivity. No recommendation as to the best equation is made at this time; further evaluation of data in accord with the above discussion remains to be carried out.

The equations of Hochman and Bonilla<sup>18</sup> and of Kapelner and Bratton<sup>24</sup> agree closely at 1700°F (~198  $\mu\text{ohm} \cdot \text{cm}$  versus ~194  $\mu\text{ohm} \cdot \text{cm}$ ). The results of Tepper et al.<sup>5</sup> fall about 4% below these (~188  $\mu\text{ohm} \cdot \text{cm}$ ) and of Hyman<sup>25</sup> about 28% low (~142  $\mu\text{ohm} \cdot \text{cm}$ ). Either of the first two equations [Eqs. (2) and (3) in Table 15] appears adequate; the results of Hochman and Bonilla are shown in Fig. 19.

### Mass Diffusivity

While no data are included in this collection at the present time on the mass diffusivity,  $D$ , for the sake of completeness a few brief comments are merited. In a fashion analogous to that for viscous flow or heat conduction, the diffusivity is the proportionality coefficient in Fick's law of diffusion which, in one-dimensional form, can be written:

$$j_{Ay} = -D_{AB} \frac{dC_A}{dy},$$

where  $j_{Ay}$  is the molar diffusion flux of component A in the y-direction,  $C_A$  is the molar concentration of component A in the mixture, and  $D_{AB}$  ( $= D_{BA}$ ) is the diffusivity coefficient for component A through component B. Of the three transport processes, diffusion is the most complicated since it deals with mixtures. This property assumes importance in respect to the compatibility of cesium with its container materials, condensation of cesium vapor, etc.

### Thermal Diffusion Ratio

This describes the tendency for species to diffuse under the influence of a temperature gradient. Generally, this effect is quite small; but systems have been developed which produce temperature gradients sufficiently steep to effect separation of mixtures. The thermal diffusion ratio is defined as:

$$k_T = \frac{\rho}{c^2 M_A M_B} \cdot \frac{D_A^T}{D_{AB}},$$

where  $\rho$  is the fluid density;  $c$  is the total molar concentration;  $M_A$  and  $M_B$

are the molecular weights of species A and B, respectively;  $D_A^T$  is the thermal diffusion coefficient for species A in the mixture; and  $D_{AB}$  is the binary diffusivity in the mixture A-B. A discussion of this property and the interrelationships between the transport properties can be found in Section 18.4 of Ref. 32.

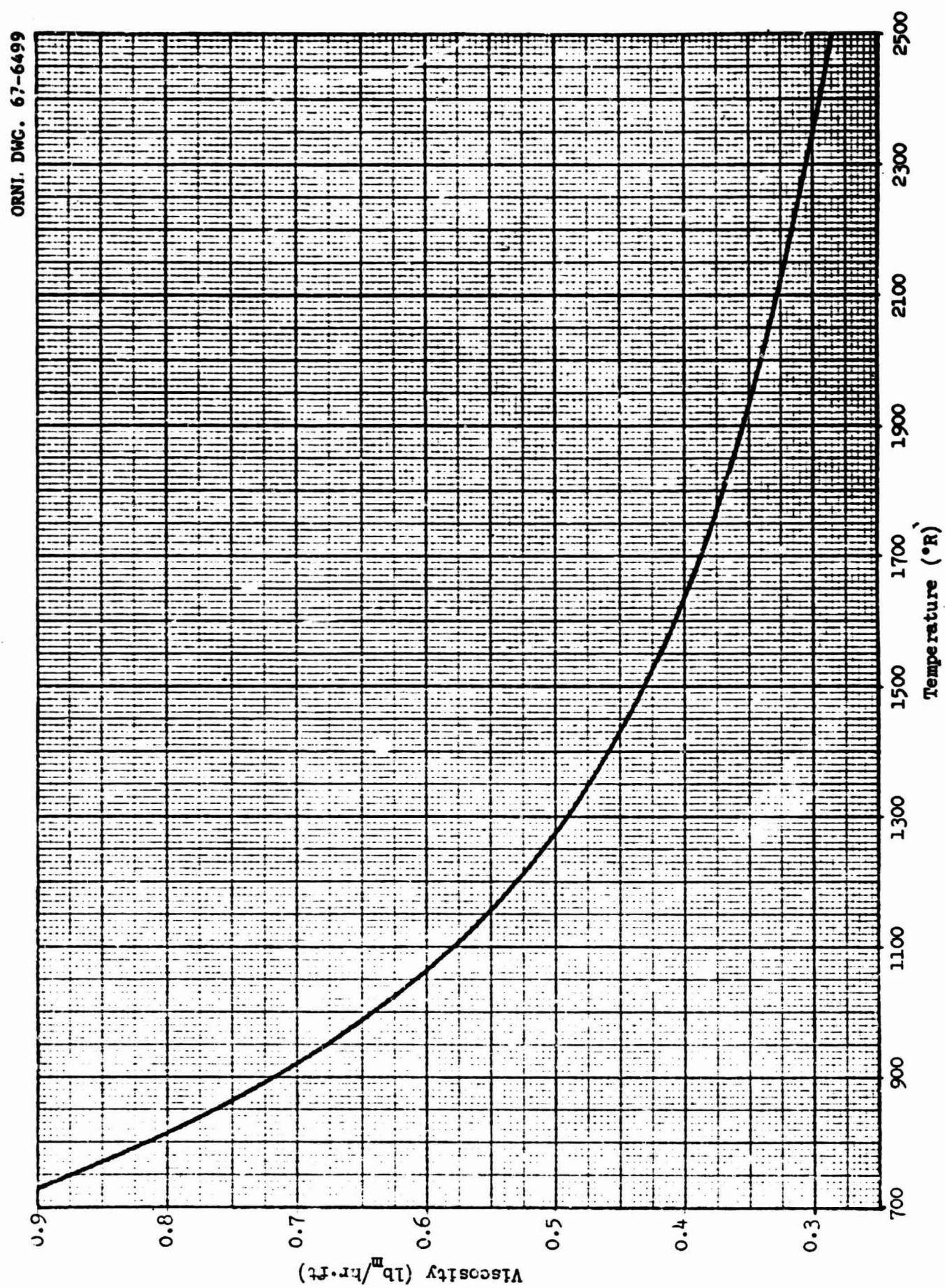


Fig. 15. Cesium: Liquid Viscosity.

Table 11. Viscosity (Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs. *
$\log_{10} \mu = \frac{187.223}{T} - 0.59911 \log_{10} T + 1.41467$ $[\mu = \text{lb}_m/\text{hr}\cdot\text{ft}; T = ^\circ\text{R}]$	(1.)	mp-1958	3.5%	Oscillating Cylinder	Used density of Ref. 2	Achener and Boyer (1966)	3
$\log_{10} \mu = \frac{454}{T} - 0.401$ $\log_{10} \mu = \frac{720}{T} - 0.645$ $[\mu = \text{lb}_m/\text{hr}\cdot\text{ft}; T = ^\circ\text{R}]$	(2)	85-620 620-2100		Oscillating Cylinder	Used density of Ref. 2	Lemmon et al. (1964)	4
$\mu = 10.14 e^{576/T}$ $[\mu = \text{millipoise}; T = ^\circ\text{C}]$	(3)	83-412		Oscillating Sphere		Andrade and Dobbs (1951)	21
$\log_{10} \mu = \frac{495.592}{T} - 0.64491$ $[\mu = \text{lb}_m/\text{hr}\cdot\text{ft}; T = ^\circ\text{R}]$	(4)	99-2000		Oscillating Cylinder		Tepper et al. (1965)	17

\* See Table of References.

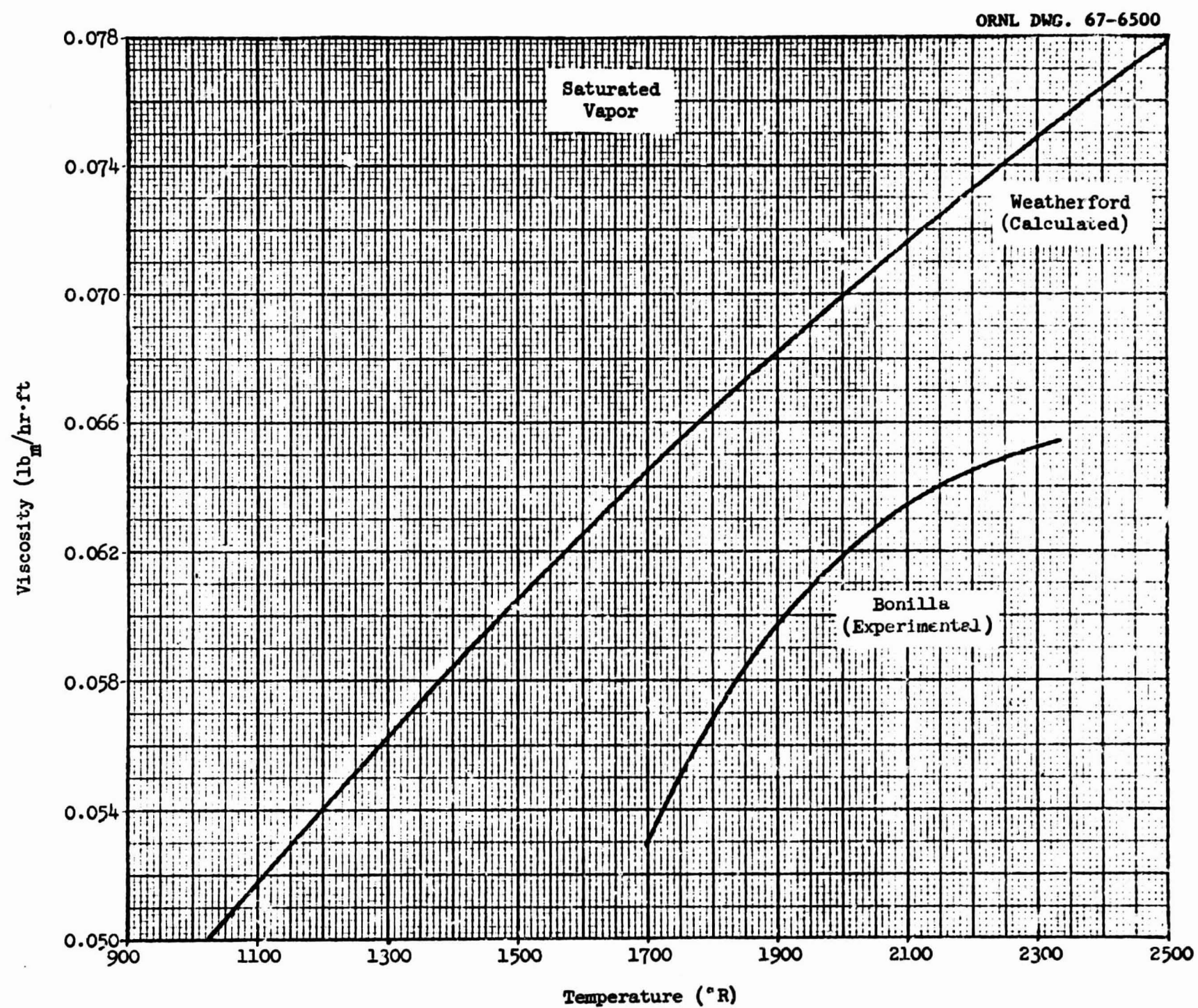


Fig. 16. Cesium: Vapor Viscosity.

Table 12. Viscosity (Vapor)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs. *
$\mu = 0.99 \times 10^{-9} T^{1.73}$ $[\mu = \text{gm/cm} \cdot \text{sec}; T = ^\circ\text{K}]$	(1)	980-3140		Transpiration		Weaver and Stratton (1965)	22
$\mu = 6.2887 T^{0.5241}$ or $\mu = -648.14 + 1511.52 \left( \frac{T}{1000} \right) - 628.65 \left( \frac{T}{1000} \right)^2$ $[\mu = \text{micropoise}; T = ^\circ\text{K}]$	(2a)  (2b)	1160-1810	$\pm 3.9\%$  $\pm 3.2\%$	Coiled Capillary, Steady Flow		Lee and Bonilla (1966)	23
$\mu = 7.05 T^{1/2}$ $[\mu = \text{micropoise}; T = ^\circ\text{K}]$	(3)			Derived	Based on kinetic theory relationship between $\mu$ and $k$ ; calculated from $k$ measurements	Kitrilakis and Meeker (1963)	19
Curve plotted in Ref. 26.	(4)	540-2240		Calculated	Computed for variable molecular weight saturated vapor using new equation for gas viscosity	Weatherford (1961)	29

\*See Table of References.

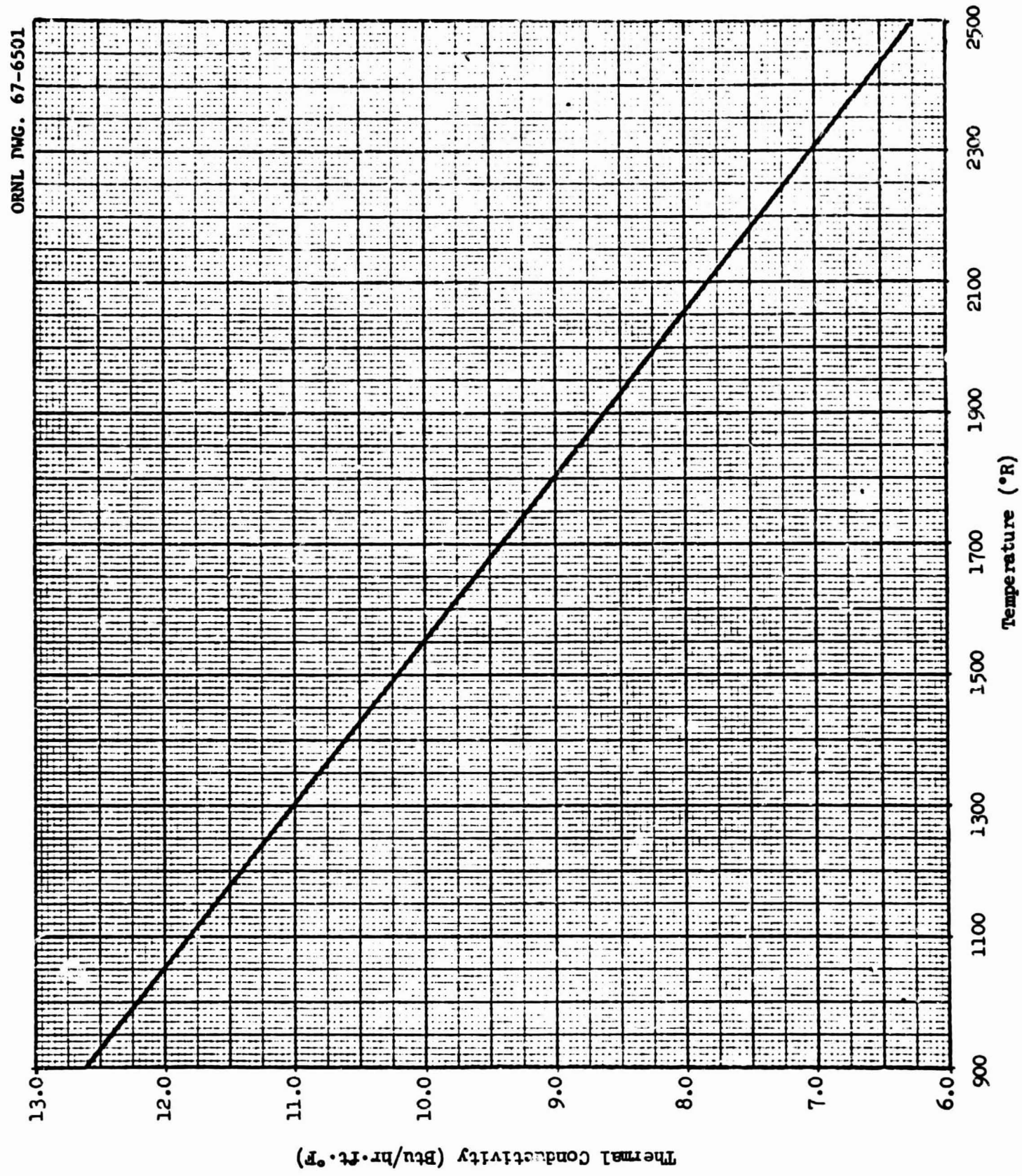


Fig. 17. Cesium: Liquid Thermal Conductivity.

Table 13. Thermal Conductivity (Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$k = 0.273508 + 7.340894 \times 10^{-5} T$ $- 7.422601 \times 10^{-8} T^2 + 7.491586$ $\times 10^{-12} T^3$ [k = w/in.°F; T = °F]	(1)	168-1946		Derived	Calculated from electrical resistivity measurements using Weidemann-Franz-Lorenz equation	Tepper et al. (1964)	5
$k = 0.124664 - 2.51402 \times 10^{-5} T$ $- 1.63806 \times 10^{-8} T^2$ [k = w/cm.°F; T = °F]	(2)	600-3000	2.4%	Derived	As above; W-F-L constant = $2.3 \times 10^8$ (volts/°K) <sup>2</sup>	Hochman and Bonilla (1965)	18
$k = 16.220 - 0.003995 T$ [k = Btu/hr.ft.°F; T = °R]	(3)	347-2160		Steady-state longitudinal heat flow apparatus	Least-square fit of data	Lemmon et al. (1964)	4
$k = 0.018 \text{ to } 0.050 \text{ cal/sec.°C.cm}$	(4)	mp-786		Derived	Calculated from electrical resistivity data through W-F-L relationship	Hyman (1961)	25

\*See Table of References.

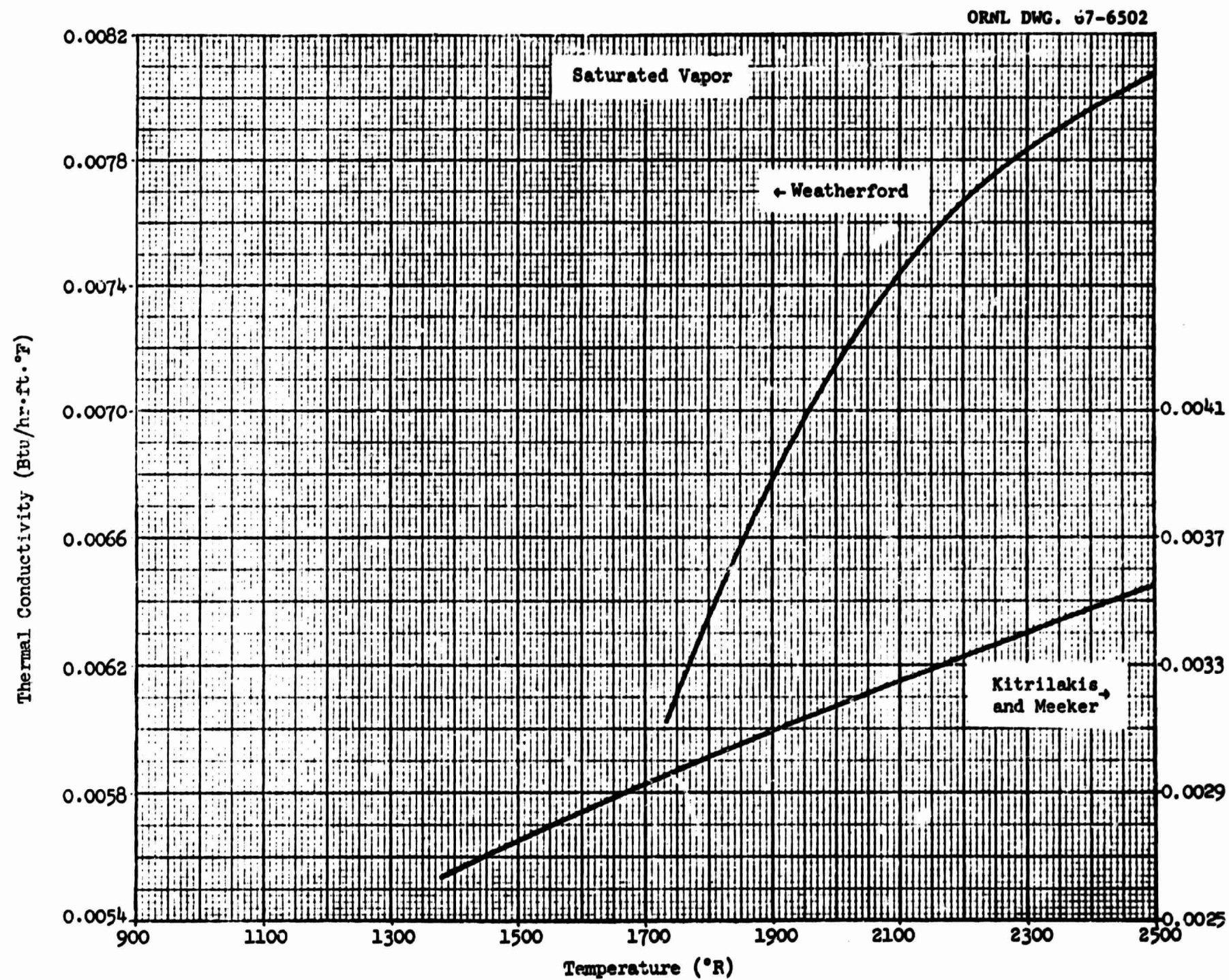


Fig. 18. Cesium: Vapor Thermal Conductivity.

Table 14. Thermal Conductivity (Vapor)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*												
$k = 1.65 \times 10^{-6} T_g^{1/2}$  [k = w/cm·°K; T = °K]	(1)	931-3184		Steady-state, parallel plates		Kitrilakis and Meeker (1963)	19												
<table><tr><th>T (°K)</th><th>k(w/cm·°K)</th></tr><tr><td>945</td><td><math>1.14 \times 10^{-5}</math></td></tr><tr><td>1000</td><td>1.49</td></tr><tr><td>1060</td><td>1.75</td></tr><tr><td>1123</td><td>2.0</td></tr><tr><td>1188</td><td>2.2</td></tr></table>	T (°K)	k(w/cm·°K)	945	$1.14 \times 10^{-5}$	1000	1.49	1060	1.75	1123	2.0	1188	2.2	(2)	1241-1679		Heat-loss	Method of calculation not clear	Gottlieb and Zollweg (1963)	20
T (°K)	k(w/cm·°K)																		
945	$1.14 \times 10^{-5}$																		
1000	1.49																		
1060	1.75																		
1123	2.0																		
1188	2.2																		
Curve shown in reference	(3)	540-2240		Calculated	Obtained using frozen specific heat and viscosity (Ref. 29) assuming a constant Prandtl modulus of 0.73	Weatherford et al.	26												

\* See Table of References.

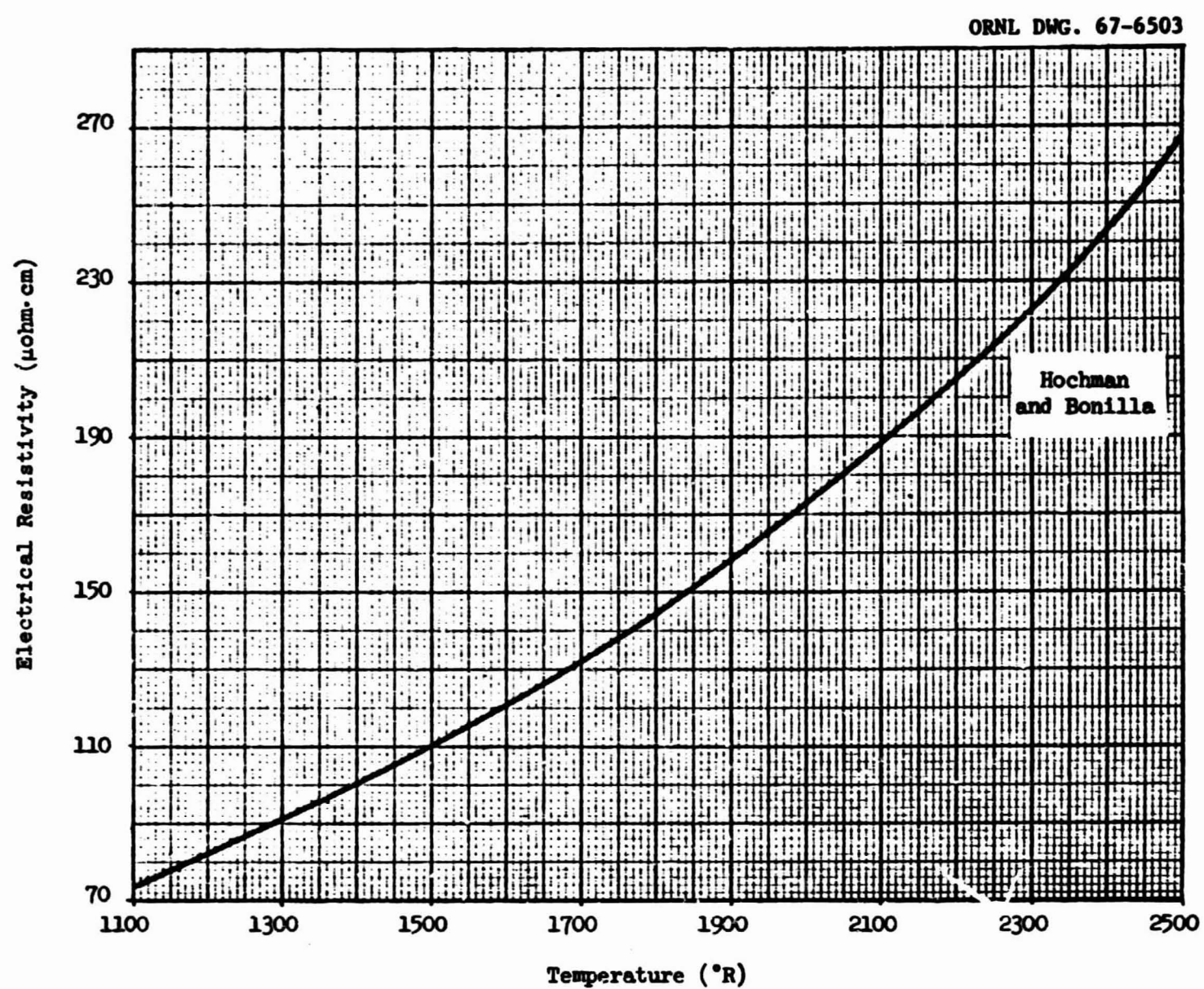


Fig. 19. Cesium: Electrical Resistivity.

Table 15. Electrical Resistivity (Liquid)

Equation	Eq. No.	Temperature Range (°F)	Standard Deviation	Method	Comments	Investigator (Date)	Refs.*
$\rho_e = 10.90857 + 3.39024 \times 10^{-2} T - 1.670142$ $\times 10^{-5} T^2 + 1.096439 \times 10^{-8} T^3$ [T = °F; $\rho_e$ = $\mu\text{ohm}\cdot\text{in.}$ ]	(1)	168-1946	1%		Measured resistance and calculated resistivity	Tepper et al. (1964)	5
$\ln \rho_e = 3.4630 + 1.4872 \times 10^{-3} T$ $- 3.62046 \times 10^{-7} T^2 + 6.99129$ $\times 10^{-11} T^3$ [T = °F; $\rho_e$ = $\mu\text{ohm}\cdot\text{cm}$ ]	(2)	600-3000	2.5%		Measured conductance and calculated resistivity	Hochman and Bonilla (1964)	18
$\rho_e = 34.383 + 1.124 \times 10^{-1} T - 2.869 \times 10^{-5} T^2$ $+ 1.007 \times 10^{-7} T^3$ [T = °C; $\rho_e$ = $\mu\text{ohm}\cdot\text{cm}$ ]	(3)	83-1610	±0.24%		Measured potential drop with known current	Kapelner and Bratton (1962)	24
$\rho_e = 38.5 [1 + 0.00308 (T - 50)]$ [T = °C; $\rho_e$ = $\mu\text{ohm}\cdot\text{cm}$ ]	(4)	mp-786	±1%			Hyman (1961)	25

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## NOMENCLATURE

A, B, C, D, E	Constants appearing in equations of state (Table 4); also designates species in a mixture
c	Total molar concentration; $C_A$ , molar concentration of species A in a mixture
$c_p$	Heat capacity; $c_{p,g}$ , of vapor; $c_{p,l}$ , of liquid; $(c_p)_s$ , at saturation conditions
D	Coefficient of mass diffusivity; $D_{AB}$ ( $= D_{BA}$ ), binary diffusivity in a mixture containing species A and B
$D_A^T$	Thermal diffusion coefficient for species A in a mixture
H	Enthalpy; $H_T$ , at temperature T; $H_0$ , at 0°R; $H_{298}$ , at 298°K; $H_g^T$ , of vapor at temperature T; $H_g^0$ , of vapor at 0°R
$h_{fg} = \Delta h$	Latent heat of vaporation
$j_{Ay}$	Molar diffusion flux of species A in y-direction
k	Thermal conductivity
$k_T$	Thermal diffusion ratio (p. 41)
$L_0$	Lorenz number ( $= k \rho_e / T$ )
M	Molecular weight; $M_1$ , of monomer; $M_A$ , $M_B$ , of species A and B, respectively, in a mixture
p, P	Pressure; $P_c$ , at critical condition
$q_y$	Heat flux in y-direction
R	Gas constant
S	Entropy; $S_g^T$ , of vapor at temperature T; $S_g^0$ , of vapor at 0°R
T	Temperature; $T_c$ , at critical condition; $\Delta T$ , temperature difference
v, V	Volume; $V_c$ , at critical condition; $v_g$ , of vapor; $v_l$ , of liquid; $\tilde{V}$ , molal volume
$v_x$	Velocity in x-direction

$x, y, z$	Cartesian coordinate directions
$z$	Compressibility factor ( $= p \tilde{V}/RT$ )
$\alpha$	Thermal diffusivity ( $= k/\rho c_p$ )
$e$	Elementary charge of an electron
$k$	Boltzmann constant
$\mu$	Viscosity
$\rho$	Density
$\rho_e$	Electrical resistivity
$\sigma$	Surface tension
$\tau$	Time
$\tau_{yx}$	Shear stress, or viscous flux of $x$ -momentum in $y$ -direction