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WADD TECHNICAL REPORT 60-56

A COMPENDIUM OF THE PROPERTIES OF MATERIALS AT LOW TEMPERATURE (PHASE II)

RICHARD B. STEWART
VICTOR J. JOHNSON

GENERAL EDITORS

NATIONAL BUREAU OF STANDARDS
CRYOGENIC ENGINEERING LABORATORY
BOULDER, COLORADO

DECEMBER 1961

AERONAUTICAL SYSTEMS DIVISION

SUPPLEMENTARY

INFORMATION

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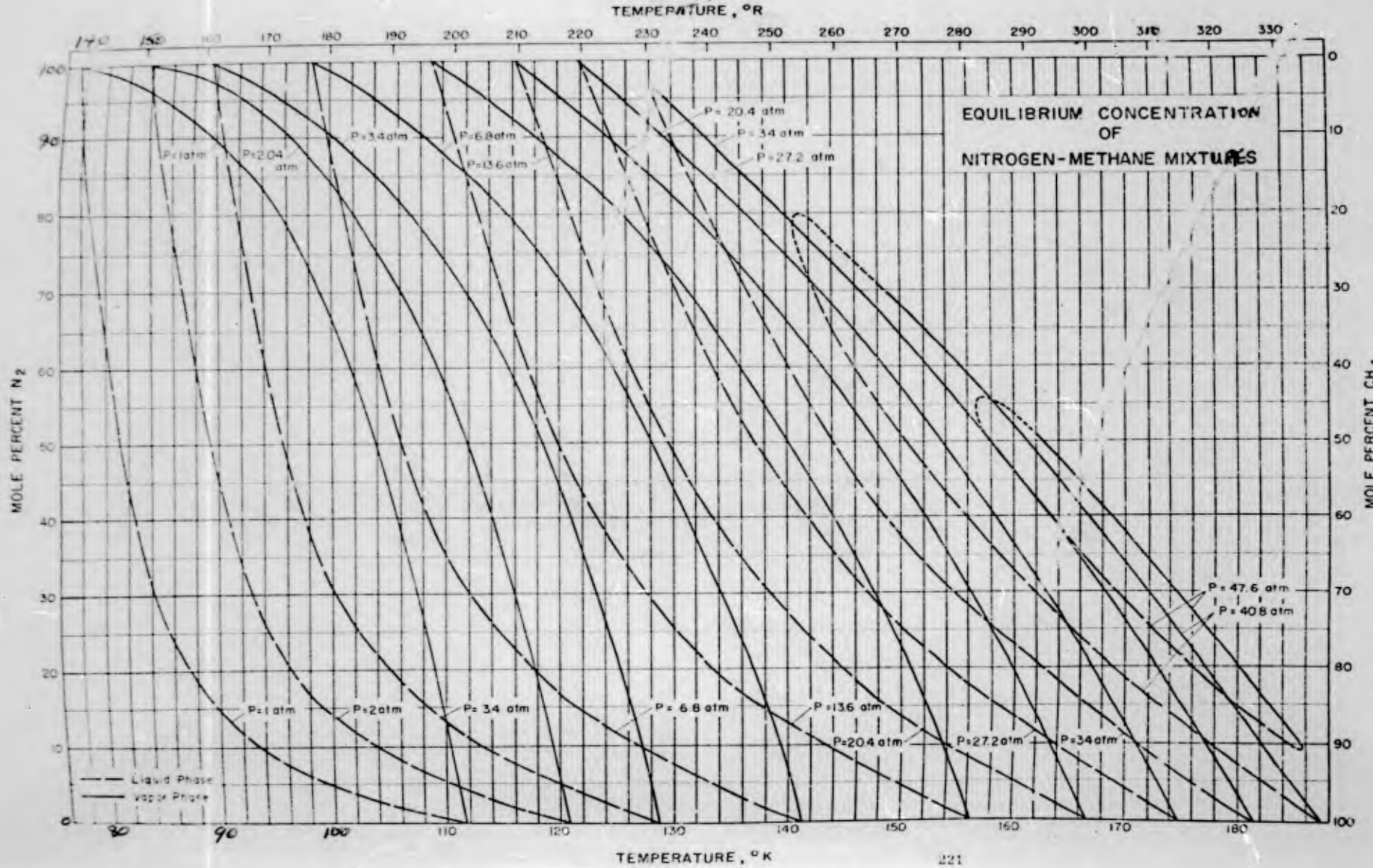

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WADD TECHNICAL REPORT 60-56
PART IV

A COMPENDIUM OF THE PROPERTIES OF MATERIALS AT LOW TEMPERATURE (PHASE II)

RICHARD B. STEWART
VICTOR J. JOHNSON

GENERAL EDITORS

NATIONAL BUREAU OF STANDARDS
CRYOGENIC ENGINEERING LABORATORY
BOULDER, COLORADO

DECEMBER 1961

DIRECTORATE OF MATERIALS AND PROCESSES
CONTRACT No. D O. 33(616);59-6
PROJECT No. 7360

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

800 - March 1962 - 23-946

FOREWORD

This report was prepared by the Evaluation and Compilation Unit of Cryogenic Technical Services Section in the National Bureau of Standards, Cryogenic Engineering Laboratory under U. S. Air Force Contract No. D. O. 33 (616)59-6. This contract was initiated under Project No. 7360, "Thermophysical Properties of Materials", Task No. 73603. The work was administered under the direction of the Physics Laboratory, Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Mr. Paul Dimiduk as project engineer. Work conducted from January 1959 to January 1961 is covered in this report.

In addition to the staff regularly assigned to the Evaluation and Compilation Unit, the following members of the Cryogenic Engineering Laboratory staff contributed to this phase of the Compendium in the literature search and preliminary phases of compiling data for the data sheets: Dr. P. L. Barrick (electrical resistivity); Dr. F. E. E. Germann (velocity of sound, equilibrium concentration of binary mixtures; D. E. Jordan (compressibility factor, solubility); Dr. K. D. Timmerhaus (equilibrium concentration of binary mixtures, entropy). In addition, the section on Thermal Conductivity Integrals was undertaken and completed by A. L. Bashford, J. R. Kluherz, and E. G. Payne, under the general supervision of R. L. Powell.

The professional staff assigned to the Evaluation and Compilation Unit for at least a part of the period represented by this report were: Richard B. Stewart, Project Leader; Robert D. McCarty, David R. Millhiser, James D. Cunningham, and M. Richard Eriksson. The data sheets completed by this staff are as follows: Robert McCarty (Compressibility Factor for Helium, Neon, Nitrogen; section on Velocity of Sound; section on Electrical Resistivity; Temperature-Entropy diagram for Neon); David Millhiser (Compressibility Factor for Methane; preliminary compilation for Electrical Resistivity); James Cunningham (Compressibility Factor for Hydrogen, Air); Richard Eriksson (preliminary compilation for Electrical Resistivity); Richard Stewart (Equilibrium Concentrations of Binary Mixtures). Mrs. Genevieve Michela was responsible for the organization of the bibliography and also supervised the preparation of all of the typed copy and tables of values. The graphs were drawn by Richard D. Weekley, Donald G. Harrison and Lewis J. Ericks. The final review of the data sheets was done by R. B. Scott, E. H. Brown and V. J. Johnson. These and many other staff members contributed to the Compendium in numerous ways and each contribution was valuable in the completion of this task.

ABSTRACT

Phase II of the Compendium includes data sheets on compressibility factor, velocity of sound and entropy of fluids, vapor-liquid equilibrium concentration of binary mixtures of fluids, and electrical resistivity and thermal conductivity integrals of metallic solids. Data sheets are included for each of these properties for the following materials: Compressibility Factor (Helium, Hydrogen, Neon, Nitrogen, Air, Methane); Entropy (a T-S diagram for Neon); Velocity of Sound (in liquids: Helium, Hydrogen, Nitrogen, Oxygen, Argon, Methane; in gases: Helium, Hydrogen, Neon, Nitrogen, Oxygen, Air, Carbon Monoxide, Argon, Methane); Liquid-Vapor Equilibrium Concentrations (Helium in Hydrogen, Nitrogen, Methane; Hydrogen in Nitrogen, Carbon Monoxide, Methane; Nitrogen in Oxygen, Carbon Monoxide, Argon, Methane); Electrical Resistivity (53 of the pure metallic elements); and Thermal Conductivity Integrals (44 pure metallic substances, 36 non-ferrous alloys, 9 ferrous alloys and 4 glasses and plastics). In general the data sheets present the data primarily in graphical form, and in addition include tables of selected values, references to the sources of the data and other references. Appropriate comments of interest to the user are also given.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

[redacted]

JULES I. WITTEBORT
Chief, Thermophysics Branch
Physics Laboratory
Directorate of Materials and Processes

NOTE TO USER

This volume is intended basically as a loose-leaf report for continuous expansion and revision as new and revised data sheets are produced. It has been bound as an economical means of assembly and distribution. It is also punched for standard three hole binders that are available from many commercial sources. A simple method of removing the bound cover and loosening the sheets is to shear off approximately 1/16" of the bound edge in an ordinary printers shear.

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* General Contents only; detailed contents given at the beginning of each chapter.

** Code designation sequence used in lieu of page numbers to permit internal expansion.

INTRODUCTION

This program for the compilation of thermophysical properties of fluids and solids at cryogenic temperatures is a continuing program to make available to the cryogenic industry, correlations and compilations of the data necessary for cryogenic systems design and analysis. These compilations are a result of an extensive search of the scientific and engineering literature and a careful analysis and comparison of the available data to select values for presentation on data sheets. The data sheets illustrate the information graphically, together with tables of "selected values", citations of references used in the compilation, and additional references. Suitable comments on the data and their arrangement or treatment are also given.

Phase I of this Compendium was issued October, 1960 in three parts which are: (1) Properties of Fluids, (2) Properties of Solids, and (3) Bibliography of Refernces, Cross-Indexed.

The following are the Properties and the Fluids included in Part I of the first phase of the work.

1.*- Density	Helium - - - - - .001*
2. - Expansivity	Hydrogen - - - - .002
3. - Thermal Conductivity	Neon - - - - - - .003
4. - Specific Heat and Enthalpy	Nitrogen - - - - .004
	Oxygen - - - - - .005
5. - Transition Heats	Air - - - - - - - .006
6. - Phase Equilibria	Carbon Monoxide - .007
7. - Dielectric Constants	Fluorine - - - - .008
8. - Adsorption	Argon - - - - - - .009
9. - Surface Tension	Methane - - - - - .010
10. - Viscosity	

The Properties of Solids included in Part II of the first phase of the Compendium are: Thermal Expansic. (2.000), Thermal Conductivity (3.000), and Specific Heat and Enthalpy (4.000). The solids covered and their code numbers grouped by classes are: .100 - Pure Metals; .200 - Non-Ferrous Alloys; .300 - Ferrous Alloys; .400 - Inorganic Compounds; and .500 - Organic Compounds.

*These are the code numbers assigned for sequence of presentation.

This second phase of the Compendium is issued as a supplement to the first phase and is arranged for uniform continuity. It covers additional properties of the same materials as follows:

11.* Compressibility Factor (Z = PV/RT) for: Helium, Hydrogen, Neon, Nitrogen, Air and Methane.

13. Thermal Conductivity Integrals. (The solids covered are listed in the "Table of Contents" preceding this section.)

14. Temperature-Entropy Chart for Neon.

15. Velocity of Sound (in liquids: Helium, Hydrogen, Nitrogen, Oxygen, Argon, Methane; in gases: Helium, Hydrogen, Neon, Nitrogen, Oxygen, Air, Carbon Monoxide, Argon, Methane).

16. Liquid-Vapor Equilibrium Concentrations of Binary Mixtures (Helium in Hydrogen, Nitrogen, Methane; Hydrogen in Nitrogen, Carbon Monoxide, Methane; Nitrogen in Oxygen, Carbon Monoxide, Argon, Methane).

17. Electrical Resistivity for 53 metallic elements. (The elements covered are listed in the "Table of Contents" preceding this section.)

The bibliography issued as a part of this second phase includes the following references:

1. All documents listed as "Sources of Data" and as "Other References" on the data sheets included in Phase II.

2. Additional references on compressibility factor, density, P-V-T, data, entropy, velocity of sound, and two-phase binary mixtures of the ten fluids listed in the following list on literature searches.

3. Electrical resistivity of the metallic elements.

The bibliography for the thermal conductivity integrals will be found in Part III of Phase I, and is not repeated here. The journal abreviations used in the bibliography are those used in Chemical Abstracts.

During the compilation of the data sheets for this second phase, several modifications in operating procedure and philosophy were effected. The addition of professional staff made this project no longer dependent on the part-time services of other laboratory staff members for the detailed

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* This number represents the coding sequence.

preparation of the material for the data sheets. Several members of the laboratory staff have continued to contribute to this Compendium as consultants in their field of specialization. The use of the Boulder Laboratories' computer facilities was also inaugurated at this time and these facilities have been used extensively in preparing this second phase. In several instances use of the computer has enabled us to (1) increase the number of data values considered in the compilation, (2) employ a more extensive and exacting comparison of alternate sources of data, and (3) to rigorously calculate the derived thermodynamic properties.

A literature search was conducted on each of the several subjects considered. The search was primarily of the various abstracting journals, but was supplemented by later reference to the bibliographies included in many of the documents. The pertinent articles were procured and the significant data compiled for evaluation and inclusion in the data sheets.

The extent of the literature searches for the various materials considered is as follows:

Properties of Helium

a. Chemical Abstracts: Volumes 46 thru 49 (1952 - 1955)
b. Industrial Arts Index: (1943 - 1957)
c. Engineering Index: (1950 - 1956)
d. ASME Seventy-Seven Year Index, Technical Papers: (1880 - 1956)
e. Bureau of Mines Information Circular 7344. A Comprehensive Bibliography from 1933 to 1945
f. Bureau of Mines Bulletin 484; Helium: Bibliography of Technical and Scientific Literature from its Discovery (1868) to January 1, 1947.
g. Helium by W. H. Keesom, covered an extensive search of the literature prior to 1942, as well as a thorough compilation of the data on helium.

Properties of Hydrogen

a. Chemical Abstracts (1948 thru 1955)
b. Physics Abstracts (1949 thru 1957)
c. Industrial Arts Index (1948 thru 1956; Feb., May, Aug., Nov. 1957; Jan.-Mar., May, Aug. 1958)
d. Engineering Index (1948 thru 1956)
e. Transactions of the American Society of Mechanical Engineers (1948 thru 1956)

f. National Bureau of Standards Research Paper 1932, Compilation of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications, covered an extensive search of the literature prior to 1948.

g. National Bureau of Standards Circular 564, Tables of Thermal Properties of Gases edited by J. Hilsenrath, et al., covers an extensive search of the literature prior to 1952.

Properties of Neon

a. Chemical Abstracts: Volumes 1 thru 52 (1907 thru 1958)
b. Physics Abstracts: (1892 thru 1912)
c. Engineering Index: (1945 thru 1957)

Properties of Nitrogen

a. Chemical Abstracts: Volumes 1 thru 52 (1907 thru 1959)
b. Reviews of American Chemical Research: (1900 thru 1906)
c. National Bureau of Standards Circular 564.

Properties of Oxygen

a. Chemical Abstracts: Volumes 19 thru 54 (1925 thru 1960)
b. Engineering Index: (1948 thru 1959)
c. Transactions ASME, individual indexes thru Volume 81 (1959)
d. Journal of the American Rocket Society, Volume 26 thru 30 (1956 thru 1960)

Properties of Air (including mixtures of oxygen and nitrogen)

a. Chemical Abstracts: Volumes 43 thru 52, No. 9 (1949 - Sept. 25, 1958)
b. Physics Abstracts: Volumes 46, 52 thru 61, No. 3 (1943, 1949 - August, 1958)
c. Industrial Arts Index: (1949 - 1957 and May - July, 1958)
d. The Engineering Index: (1949 - 1957)
e. Dissertation Abstracts: (1954 - Aug. 1958)

Properties of Carbon Monoxide

a. Chemical Abstracts: Volumes 44 thru 50 (1950 - 1956)

Properties of Fluorine

a. Chemical Abstracts: Volumes 1 thru 50 (1907 - 1956)
b. Industrial Arts Index: (1945 thru 1955)

Properties of Argon

a. Chemical Abstracts: Volumes 42 thru 44 (1948 - 1950)

Properties of Methane

a. Chemical Abstracts: Volumes 1 thru 50 (1907 - 1956)

Thermal Conductivity and Electrical Resistivity of Solids

a. Chemical Abstracts: Volumes 1 thru 50 (1907 - 1956)

b. Physics Abstracts: 1900 thru 1956

c. Landolt-Bornstein Physikalisch-chemische Tabellen, edited by W. A. Roth and K. Scheel (Julius Springer, Berlin) 5th ed., vol. 2, 1923; 5th ed., 1st supplement, vol. 1, 1927; 5th ed., 2nd supplement, vol. 2, 1931; 5th ed., 3rd supplement, vol. 3, 1936.

d. National Bureau of Standards Circular 556. Thermal Conductivity of Metal and Alloys at Low Temperatures; A Review of the Literature (195-)

In addition to the specific searches listed above, a considerable number of references were found from listings on file in the Cryogenic Data Center. Also, inasmuch as most of the searches were for all properties of a particular material, many of the articles covered several materials. These additional references were added to the bibliographies of the other materials covered and were used by task authors in their evaluation and selection of data. A third additional source of references was from the documents themselves. Selected documents frequently listed references of a broader coverage than the material presented in it, and thus provided a more extensive range of properties. As a result, the actual scope of the literature searching was much greater than indicated by the specific searches as listed.

11.000

COMPRESSIBILITY FACTOR of CRYOGENIC FLUIDS

CONTENTS

Compressibility Factor for Helium 11.001

Compressibility Factor for Normal-Hydrogen 11.002

Compressibility Factor for Neon 11.003

Compressibility for Nitrogen 11.004

Compressibility Factor for Air 11.006

Compressibility Factor for Methane 11.010

AN EXPLANATION OF THE AMAGAT UNIT

Values of pressure, volume, temperature are often reported in the literature with the specific volume or density reported with an Amagat unit. Several of the data sheets on compressibility factor contain such data and in reporting these values, the original Amagat unit is used. The Amagat unit is a dimensionless ratio of the density, specific volume, or of the PV product, divided by the corresponding property at a standard condition (usually 0°C and 1 atmosphere pressure). Three such Amagat units then are employed with the following definitions:

Amagat "density" -- $\text{Amagat} = \dfrac{\text{density}}{\text{standard density}}$

Amagat "volume" -- $\text{Amagat} = \dfrac{\text{volume}}{\text{standard volume}}$

Amagat "PV" -- $\text{Amagat} = \dfrac{PV}{\text{standard } PV}$

(Consistent dimensions are used in these definitions so that the Amagat is a dimensionless quantity.)

That these three Amagat units are consistent may be demonstrated as follows: (subscripts are used to designate the appropriate Amagat unit)

$$\text{Amagat}_\rho = \rho/\rho_{std} \text{ , } (\rho \text{ in gm/cc})$$

$$\text{but } \rho = 1/v \text{ , } (v \text{ in cc/gm})$$

$$\text{then, } \text{Amagat}_\rho = \rho/\rho_{std} = v_{std}/v = 1/\text{Amagat}_v$$

COMPRESSIBILITY FACTOR OF CRYOGENIC FLUIDS

likewise, $\text{Amagat}_{pv} = \text{Amagat}_{v} \times p$, (p in atm.)

or, $\text{Amagat}_{pv} = p/\text{Amagat}_{\rho}$

For example, at standard conditions of 0°C and 1 atm.,

by definition $\text{Amagat}_{\rho} = 1$

$\text{Amagat}_{v} = 1$

$\text{Amagat}_{pv} = 1$

thus, 1 Amagat_{v} = 1/1 Amagat_{ρ} = 1 Amagat_{pv}/1 atm. = 1

A further example, consider helium at 80°K, ρ = 0.0060 gm/cc, p = 10 atm.

($v = 1/\rho = 166.7$ cc/gm.)

[for helium at 0°C, 1 atm., v_{std} = 5601.9 cc/gm, (ρ_{std} = 0.0001785)]

The Amagat values are as follows:

$$\text{Amagat}_{v} = v/v_{std} = 166.7/5601.9 = 0.02975$$

$$\text{Amagat}_{\rho} = \rho/\rho_{std} = 0.0060/0.0001785 = 33.61$$

$$\text{Amagat}_{v} = 1/\text{Amagat}_{\rho} = 1/33.61 = 0.02975$$

$$\text{Amagat}_{pv} = pv/pv_{std} = \frac{10 \text{ atm.} \times 166.7 \text{ cc/gm.}}{1 \text{ atm.} \times 5601.9 \text{ cc/gm.}} = 0.2975$$

$$\text{Amagat}_{v} = \text{Amagat}_{pv}/p = 0.2975/10 \text{ atm.} = 0.02975$$

Thus, $\text{Amagat}_{v} = 1/\text{Amagat}_{\rho} = \text{Amagat}_{pv}/p = 0.02975$

11.001

COMPRESSIBILITY FACTOR for HELIUM

$Z = PV/RT$

Source of Data:

Keesom, W. H., Helium, Elsevier, Amsterdam (1942)

Other References:

Zelmenov, J. L., J. Phys. (U.S.S.R.) 8, 135-141 (1944)

Lounasmaa, O. V., Dissertation for Degree of Doctor of Philosophy, Oxford Univ. (1958)

Comments:

The compressibility factors and pressure-volume-temperature values listed in the accompanying table and graph were derived from the virial coefficients reported by Keesom. The range of the data presented here is from 20° to 300°K with pressures from 1 to 100 atmospheres. The P-V-T values reported here are for integral values of temperature and specific volume.

The virial coefficients by Keesom and the form of the expansion given below, represent an extensive correlation of the P-V-T values for helium, available in the scientific literature prior to 1942. The values at 20°K are in good agreement with the more recent data reported by Zelmenov and Lounasmaa. At lower temperatures, however, these virial coefficients from Keesom are not sufficient for the calculation of acceptable P-V-T values. The following comparisons of data calculated with Keesom's virial coefficients with data from Zelmenov and Lounasmaa illustrate the deviations at lower temperatures. The P-V-T values reported here represent the values as calculated with Keesom's virial coefficients with a maximum deviation of one percent for the entire range.

The constant density lines indicated on the graph by the shorter dashed lines are to be associated with the 20°, 25°, 30° and 40° isotherms only. The constant density lines indicated by the longer dashed lines are not to be associated with any of the above isotherms in the area to the left of the point where the isotherm in question crosses any other isotherm.

The dimensions of the P-V-T values are: pressures in atmospheres ($g = 980.665$), temperature in degrees Kelvin (0°C = 273.15°K) and density in gm/cc.

(Continued on following page)

COMPRESSIBILITY FACTOR for HELIUM (Cont.)

Comments: (Cont.)

The virial expansion adopted by Keesom is of the form:

$$PV = A[1 + (B/V) + (C/V^2)]$$

where:

A = RT

T is in °K

P is in atmospheres

V is in Amagats (1 Amagat = 5601.9 cc/gm at 273.15°K and 1 atm. pressure)

Ideal gas constant, $R = \frac{PV}{T} = \frac{1}{273.15} = 0.003661 \left(\frac{\text{Amagat atm.}}{^\circ K}\right)$

$\left[\text{Volume in cc/gm} = \text{Volume in Amagats} \times 5601.9 \frac{\text{cc/gm}}{\text{Amagat}}\right]$

The second and third virial coefficients B and C for the above expansion are given in the following table.

Table of Virial Coefficients for Helium by Keesom

Temp. °K	B Amagats	C Amagats	Temp. °K	B Amagats	C Amagats
8	-1.47×10^{-3}	1.02×10^{-6}	60	0.395×10^{-3}	0.65×10^{-6}
10	-1.04	1.03	70	0.435	0.61
12	-0.755	1.01	80	0.462	0.58
14	-0.549	0.99	90	0.480	0.55
16	-0.395	0.97	Temp. °C	B Amagats	C Amagats
18	-0.276	0.95			
20	-0.180	0.93			
22	-0.101	0.90	-150	0.509×10^{-3}	0.48×10^{-6}
30	0.108	0.83	-100	0.521	0.40
40	0.251	0.76	- 50	0.517	0.35
50	0.338	0.70	0	0.512	0.31

(Continued on following page)

COMPRESSIBILITY FACTOR for HELIUM (Cont.)

Percent Difference Between Values of Volumes Calculated by Keesom's Virial Expansion and Values Observed by Zelmenov

$\%\ \text{Diff.} = [(V_{\text{Keesom}} - V_{\text{Zel.}}) / V_{\text{Keesom}}] \times 100$

Pressure atm.	Temperature, °K						
	8°	10°	12°	14°	16°	18°	20°
5	- 0.30	0.04	- 0.16	- 0.13	-0.004	-0.06	-0.17
10	25.83	7.95	- 0.20	- 0.53	-0.01	0.13	0.47
20		10.94	1.61	- 0.91	-1.08	-0.62	0.40
30		19.83	8.63	3.06	-0.69	-0.79	-0.63
40			13.16	6.68	2.95	0.03	-0.73
50			15.97	9.05	4.12	0.80	-1.35
60				13.33	7.52	3.22	-1.34

All differences above the heavy line are less than 1.4%

Percent Difference Between Values of Volumes Calculated by Keesom's Virial Expansion and Values Observed by Lounasmaa

$\%\ \text{Diff.} = [(V_{\text{Keesom}} - V_{\text{Lou.}}) / V_{\text{Keesom}}] \times 100$

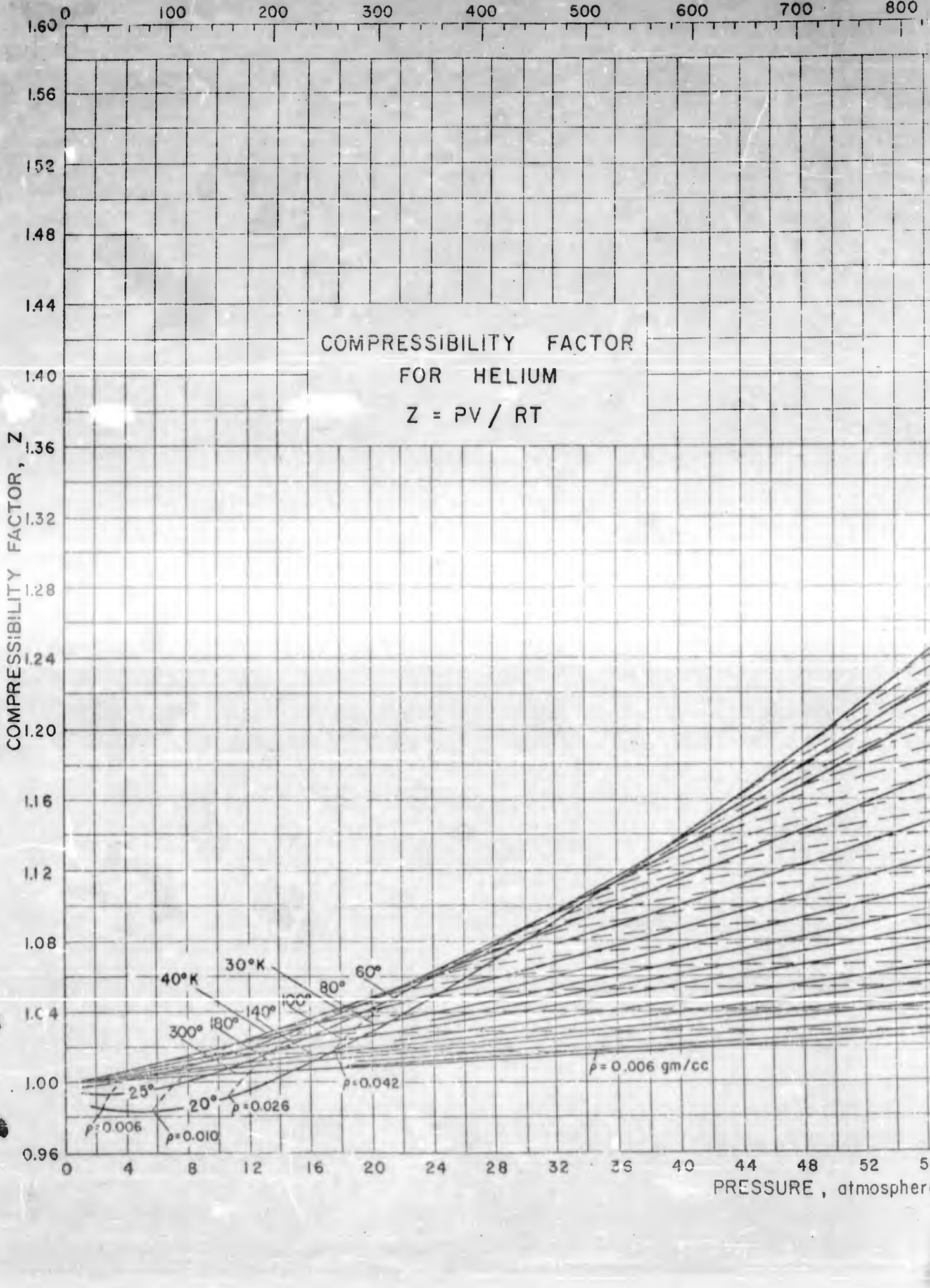
Pressure atm.	Percent Difference
18°K	
5	0.932
9.930	-0.41
14.95	-1.69
20.26	-2.39
26.20	-1.99
32.85	-1.25
49.7	1.53
60.85	3.35
74.8	5.29
92.65	7.13
103.05	7.67
19°K	
5.3	0.93
43.55	-0.10
53.45	1.38
98.8	6.18
20°K	
5.6	0.92
11.21	-0.16
16.950	-1.46
23.1	-1.03
29.95	-1.78
37.65	-1.18
46.6	-1.18
57.20	1.12
69.75	2.512
85.25	3.91

11.001

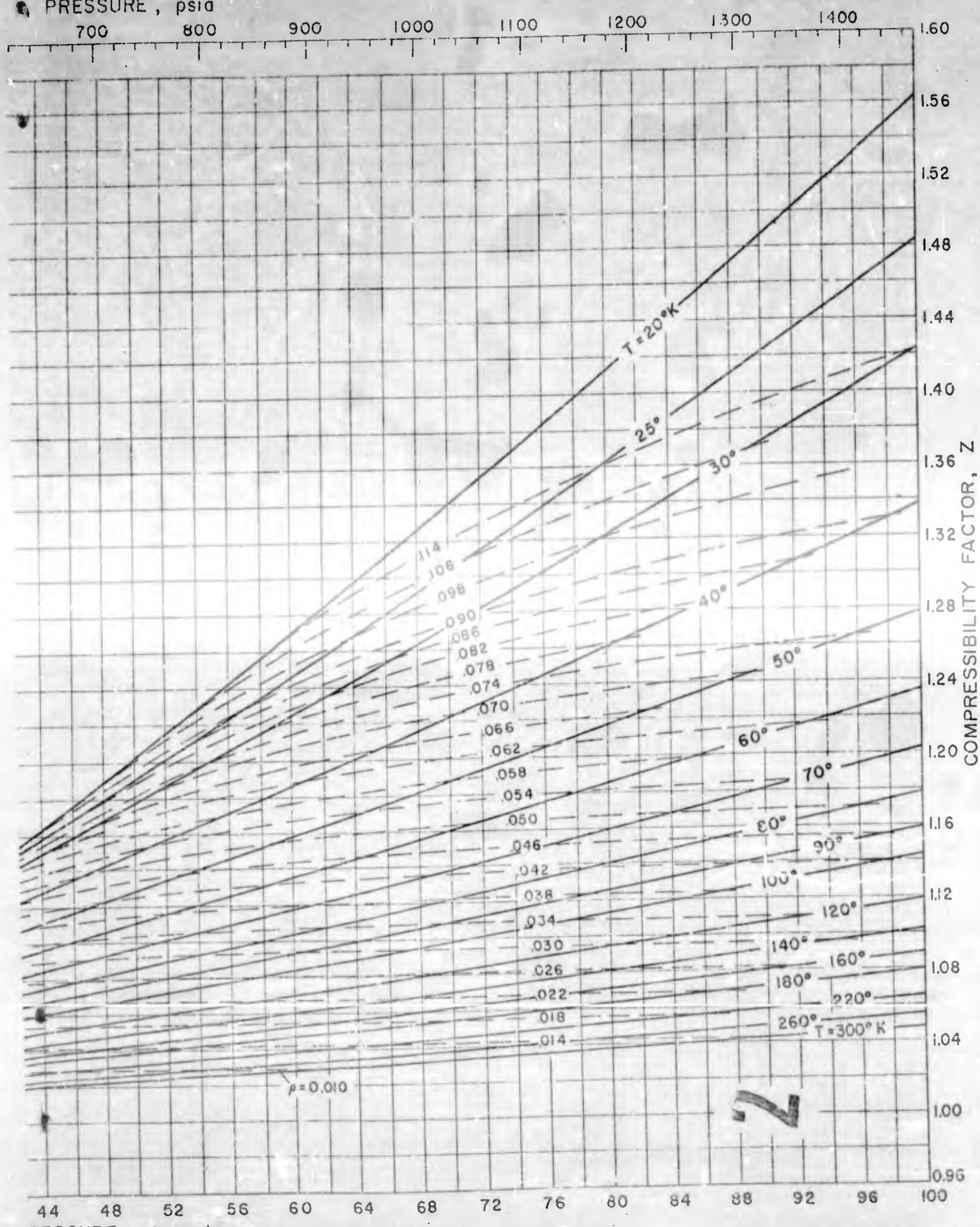
COMPRESSIBILITY FACTOR for HELIUM

[P = Pressure, (atm); Z = Compressibility Factor]

Density gm/cc		Temperature, °K																	Density gm/cc
		20	25	30	40	50	60	70	80	90	100	120	140	150	180	220	260	300	
.0002	P																1.067	1.231	.0002
	Z																1.001	1.001	
.0004	P												1.149	1.314	1.478	1.806	2.135	2.463	.0004
	Z												1.001	1.001	1.001	1.001	1.001	1.001	
.0010	P					1.026	1.232	1.438	1.644	1.850	2.056	2.467	2.879	3.290	3.701	4.523	5.346	6.168	.0010
	Z					1.001	1.002	1.003	1.002	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	
.0012	P					1.232	1.480	1.727	1.974	2.221	2.468	2.962	3.456	3.950	4.444	5.431	6.419	7.406	.0012
	Z					1.001	1.002	1.003	1.003	1.003	1.002	1.003	1.003	1.003	1.003	1.003	1.003	1.003	
.0014	P				1.149	1.438	1.727	2.016	2.304	2.593	2.881	3.458	4.034	4.611	5.187	6.340	7.493	8.645	.0014
	Z				1.000	1.003	1.003	1.003	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	
.0016	P				1.313	1.644	1.974	2.305	2.635	2.965	3.295	3.954	4.613	5.273	5.932	7.250	8.568	9.886	.0016
	Z				1.001	1.002	1.003	1.004	1.004	1.004	1.004	1.005	1.005	1.005	1.005	1.005	1.005	1.005	
.0018	P			1.104	1.477	1.850	2.222	2.594	2.966	3.337	3.709	4.451	5.193	5.935	6.677	8.161	9.644	11.13	.0018
	Z			.9975	1.001	1.003	1.004	1.004	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	
.0020	P		1.020	1.227	1.642	2.056	2.470	2.884	3.297	3.710	4.123	4.948	5.773	6.598	7.423	9.073	10.72	12.37	.0020
	Z		.9948	.9975	1.001	1.003	1.004	1.005	1.005	1.005	1.006	1.006	1.005	1.006	1.006	1.006	1.006	1.006	
.0040	P	1.619	2.037	2.455	3.292	4.129	4.964	5.798	6.630	7.461	8.290	9.953	11.61	13.27	14.93	18.25	21.57	24.89	.0040
	Z	.9872	.9933	.9978	1.004	1.007	1.009	1.010	1.011	1.011	1.011	1.011	1.011	1.011	1.011	1.012	1.012	1.012	
.0060	P	2.423	3.055	3.688	4.956	6.221	7.484	8.743	10.00	11.26	12.51	15.02	17.52	20.02	22.53	27.53	32.54	37.55	.0060
	Z	.9848	.9932	.9993	1.007	1.011	1.014	1.015	1.016	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.018	
.0080	P	3.226	4.075	4.928	6.633	8.335	10.03	11.72	13.41	15.09	16.78	20.14	23.50	26.86	30.21	36.93	43.65	50.37	.0080
	Z	.9835	.9939	1.001	1.011	1.016	1.019	1.021	1.022	1.023	1.023	1.023	1.023	1.023	1.023	1.023	1.024	1.024	
.0100	P	4.031	5.101	6.175	8.326	10.47	12.61	14.74	16.86	18.98	21.09	25.32	29.55	33.77	37.99	46.44	54.89	63.34	.0100
	Z	.9829	.9952	1.004	1.015	1.021	1.025	1.027	1.028	1.028	1.029	1.029	1.029	1.029	1.029	1.030	1.030	1.030	
.0120	P	4.837	6.132	7.432	10.04	12.63	15.21	17.78	20.35	22.91	25.46	30.57	35.67	40.77	45.87	56.07	66.27	76.48	.0120
	Z	.9829	.9969	1.007	1.020	1.027	1.031	1.033	1.034	1.035	1.035	1.035	1.036	1.036	1.036	1.036	1.036	1.036	
.0140	P	5.645	7.169	8.700	11.76	14.81	17.85	20.87	23.88	26.89	29.89	35.88	41.86	47.85	53.84	65.82	77.80	89.79	.0140
	Z	.9834	.9991	1.010	1.025	1.032	1.036	1.039	1.040	1.041	1.041	1.042	1.042	1.042	1.042	1.042	1.043	1.043	
.0160	P	6.458	8.214	9.979	13.51	17.02	20.52	23.99	27.46	30.91	34.36	41.25	48.14	55.03	61.91	75.70	89.49		.0160
	Z	.9843	1.002	1.014	1.030	1.038	1.042	1.044	1.046	1.047	1.048	1.048	1.048	1.048	1.049	1.049	1.049		
.0180	P	7.274	9.266	11.27	15.27	19.26	23.22	27.19	31.08	34.99	38.89	46.70	54.49	62.29	70.09	85.70			.0180
	Z	.9855	1.004	1.019	1.035	1.044	1.049	1.051	1.053	1.053	1.054	1.054	1.055	1.055	1.055	1.056			
.0200	P	8.095	10.33	12.57	17.06	21.52	25.95	30.36	34.74	39.12	43.48	52.21	60.93	69.65	78.36	95.84			.0200
	Z	.9870	1.007	1.022	1.040	1.050	1.056	1.059	1.059	1.060	1.060	1.061	1.061	1.062	1.062	1.062			
.0240	P	9.731	12.48	15.22	20.69	26.13	31.52	36.80	42.21	47.53	52.84	63.45	74.06	84.67	95.29				.0240
	Z	.9909	1.014	1.031	1.051	1.062	1.068	1.071	1.072	1.073	1.074	1.075	1.075	1.075	1.076				
.0280	P	11.43	14.67	17.92	24.41	30.85	37.24	43.57	49.88	56.17	62.45	74.99	87.54						.0280
	Z	.9957	1.022	1.040	1.063	1.075	1.081	1.084	1.086	1.087	1.088	1.089	1.089						
.0320	P	13.14	16.90	20.68	28.23	35.70	43.10	50.45	57.75	65.04	72.31	86.85							.0320
	Z	1.001	1.030	1.051	1.076	1.088	1.095	1.099	1.100	1.102	1.102	1.103							
.0360	P	14.88	19.18	23.51	32.14	40.68	49.13	57.51	65.84	74.15	82.45	99.05							.0360
	Z	1.000	1.039	1.062	1.089	1.102	1.109	1.113	1.115	1.116	1.117	1.118							
.0400	P	16.64	21.51	26.41	36.16	45.80	55.32	64.76	74.15	83.52	92.88								.0400
	Z	1.015	1.049	1.073	1.102	1.117	1.124	1.128	1.130	1.132	1.133								
.0440	P	18.45	23.90	29.38	40.29	51.06	61.69	72.22	82.70	93.16									.0440
	Z	1.023	1.060	1.086	1.117	1.132	1.140	1.144	1.146	1.148									
.0480	P	20.29	26.34	32.43	44.54	56.47	68.26	79.93	91.54										.0480
	Z	1.031	1.071	1.099	1.132	1.148	1.156	1.160	1.163										
.0520	P	22.17	28.85	35.57	48.91	62.06	75.02	87.85											.0520
	Z	1.040	1.082	1.112	1.147	1.164	1.173	1.177											
.0600	P	26.07	34.07	42.10	58.07	73.73	89.16												.0600
	Z	1.060	1.108	1.141	1.180	1.199	1.208												
.0700	P	31.22	41.01	50.86	70.34	89.40													.0700
	Z	1.088	1.143	1.181	1.225	1.246													
.0800	P	36.73	48.51	60.34	83.66														.0800
	Z	1.120	1.183	1.226	1.275														
.0900	P	42.66	56.65	70.66	98.21														.0900
	Z	1.156	1.226	1.276	1.331														
.1000	P	49.10	65.52	81.96															.1000
	Z	1.198	1.273	1.333															
.1100	P	56.12	75.28	94.42															.1100
	Z	1.244	1.325	1.396															
.1200	P	63.84	86.08																.1200
	Z	1.297	1.400																
.1300	P	72.38	98.13																.1300
	Z	1.358	1.475																
.1400	P	81.93																	.1400
	Z	1.427																	
.1500	P	92.78																	.1500
	Z	1.508																	


PRESSURE , psia
0
100
200
300
400
500
600
700
800
COMPRESSIBILITY FACTOR
FOR HELIUM
Z = PV / RT
COMPRESSIBILITY FACTOR, Z
1.60
1.56
1.52
1.48
1.44
1.40
1.36
1.32
1.28
1.24
1.20
1.16
1.12
1.08
1.04
1.00
0.96
40°K
30°K
60°
80°
100°
140°
180°
300°
25°
20°
ρ=0.042
ρ=0.026
ρ=0.006
ρ=0.010
ρ=0.006 gm/cc
0
4
8
12
16
20
24
28
32
36
40
44
48
52
PRESSURE , atmospher

11.001


PRESSURE , psia
700
800
900
1000
1100
1200
1300
1400
1.60
1.56
1.52
1.48
1.44
1.40
1.36
1.32
1.28
1.24
1.20
1.16
1.12
1.08
1.04
1.00
0.96
COMPRESSIBILITY FACTOR, Z
T=20°K
25°
30°
40°
50°
60°
70°
80°
90°
100°
120°
140°
160°
180°
220°
260°
T=300° K
.114
.106
.098
.090
.086
.082
.078
.074
.070
.066
.062
.058
.054
.050
.046
.042
.038
.034
.030
.026
.022
.018
.014
ρ=0.010
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
RESSURE , atmospheres

COMPRESSIBILITY FACTOR for NORMAL HYDROGEN
Z = PV/RT

Sources of Data:

Woolley, H. W., Scott, R. B., Brickwedde, F. G.; J. Research Natl. Bur. Standards 41, (Nov. 1948) RP 1932

Stewart, R. B. and Johnson, V. J.; Advances in Cryogenic Engineering, 5, Plenum Press, Inc., New York (1960) pp 557-565

Other References:

Friedman, A. S.; Dissertation for Degree of Doctor of Philosophy, Ohio State Univ. (1950)

Johnston, H. L., Keller, W. E. and Friedman, A. S.; J. Am. Chem. Soc. 76, 1482-6 (1954)

Johnston, H. L., White, D., Wirth, H., Swanson, C.; Ohio State Univ. Cryogenic Lab. Tech. Rept. TR 264-25 (1953)

Comments:

The values of compressibility factor, pressure, density and temperature are from the correlation by Woolley, Scott and Brickwedde, and in the region of high density at low temperatures (V = 26 to 29 cc/mole, T = 18° to 70° K) from the correlation by Stewart and Johnson. These values illustrated on the compressibility factor graph, are also listed in the following tables.

The reliability of the values used for this data sheet may be best considered by reference to the data sources. The N.B.S. report specifies a possible variation in compressibility factor (PV/RT) of 0.2 percent for densities as high as 100 Amagat near 33°K. In addition a graphical comparison was made of Friedman's P-V-T data and the values reported by Woolley, Scott and Brickwedde, for the vapor region below 33°K. A maximum deviation of one percent was noted for this range. The values used for the saturation envelope are also from the N.B.S. report. The properties of saturated vapor were determined by Woolley, Scott and Brickwedde by extrapolation of the vapor data along isotherms to the vapor pressure for each isotherm. The values of the properties for saturated liquid, however, were correlated from experimental values and are probably more reliable than the saturated vapor volumes.

The correlation by Stewart and Johnson includes values from the two publications listed above by Johnston, et al. as well as those from the N.B.S. report. Stewart and Johnson indicated the variation between the data of Johnston et al. from 33° to 80° and that of Woolley, Scott and Brickwedde to be very small with a few exceptions where pressure variation with their smoothed values was as much as two percent. The P-V-T data for liquid (below 33°K) are perhaps more questionable since Stewart and Johnson report a lack of consistency between data for liquid and the values at higher temperatures as well as at saturation, with pressure variations of as much as seven percent between the pressures reported by Johnston and the smoothed values. They report further, however, an excellent agreement with their smoothed values and the saturated liquid properties from Woolley, Scott and Brickwedde. The P-V-T values for the liquid region (below 33°K) included in the report by Stewart and Johnson were

COMPRESSIBILITY FACTOR for NORMAL HYDROGEN (Cont.)

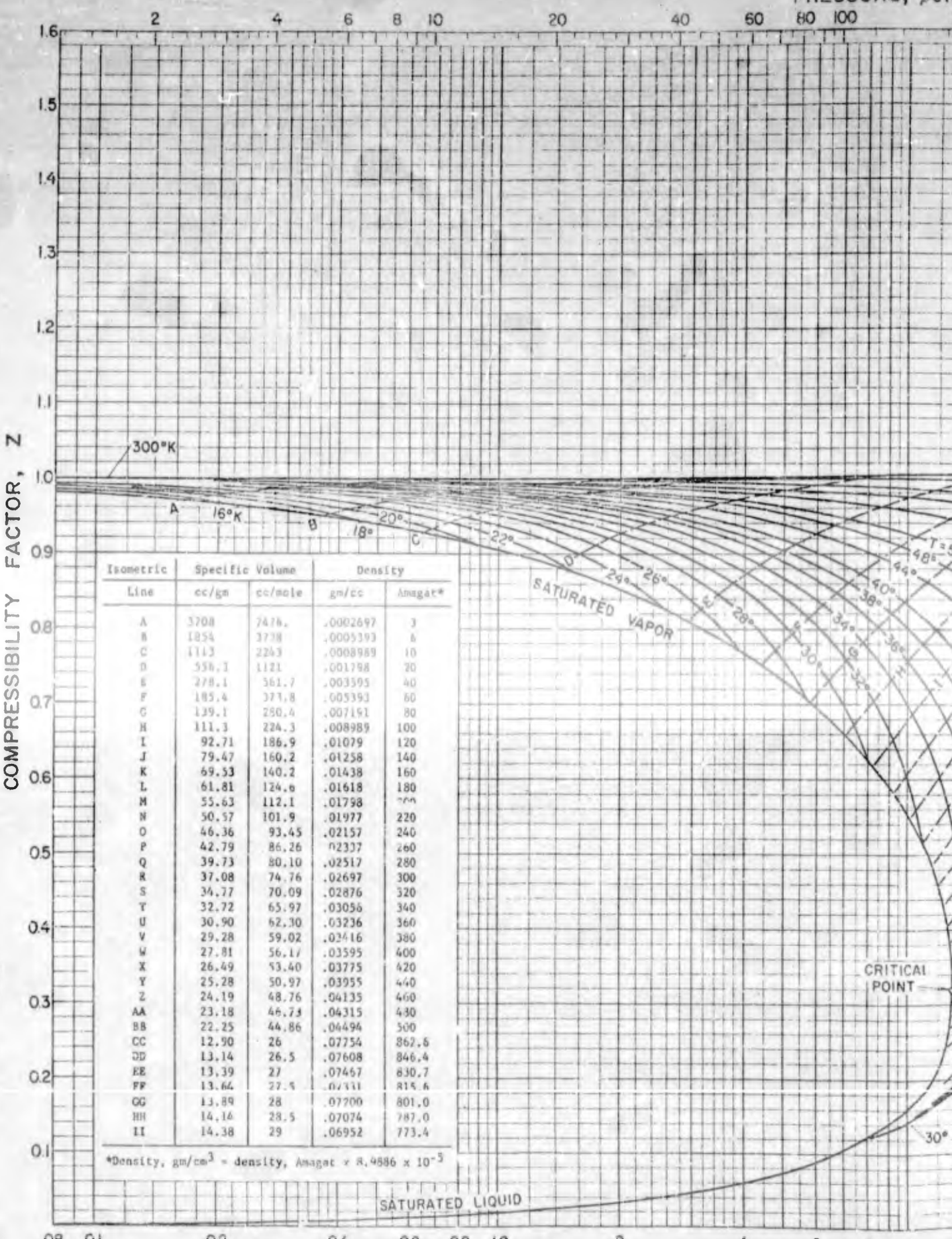
$Z = PV/RT$

Comments: (cont.)

not included on this graph. These isotherms are close to the saturated liquid line and are better illustrated on other coordinates such as the P-T coordinates used on data sheet 1.002. A graphical comparison of the values from Woolley, Scott and Brickwedde and those reported by Stewart and Johnson indicated excellent agreement, except near the critical point where the methods of correlation used by Stewart and Johnson were not sufficiently accurate.

JDC/RS Issued: 3-18-61

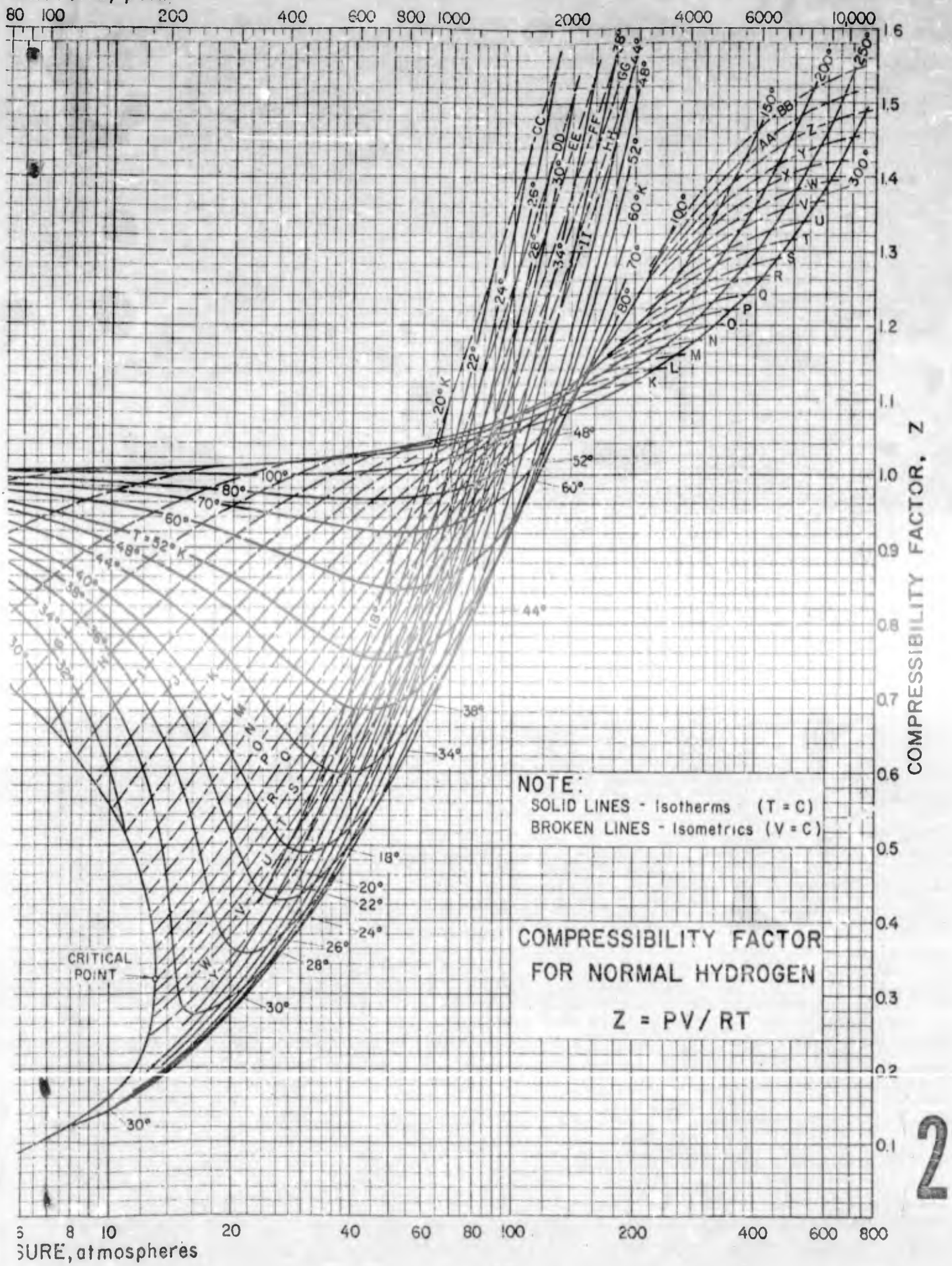
11.002



Isometric Line	Specific Volume cc/gm	Specific Volume cc/mole	Density gm/cc	Density Amagat*
A	3708	7476.	.0002697	3
B	1854	3738	.0005393	6
C	1113	2243	.0008989	10
D	556.1	1121	.001798	20
E	278.1	561.7	.003595	40
F	185.4	374.8	.005393	60
G	139.1	280.4	.007191	80
H	111.3	224.3	.008989	100
I	92.71	186.9	.01079	120
J	79.47	160.2	.01258	140
K	69.53	140.2	.01438	160
L	61.81	124.6	.01618	180
M	55.63	112.1	.01798	200
N	50.57	101.9	.01977	220
O	46.36	93.45	.02157	240
P	42.79	86.26	.02337	260
Q	39.73	80.10	.02517	280
R	37.08	74.76	.02697	300
S	34.77	70.09	.02876	320
T	32.72	65.97	.03056	340
U	30.90	62.30	.03236	360
V	29.28	59.02	.03416	380
W	27.81	56.17	.03595	400
X	26.49	53.40	.03775	420
Y	25.28	50.97	.03955	440
Z	24.19	48.76	.04135	460
AA	23.18	46.73	.04315	480
BB	22.25	44.86	.04494	500
CC	12.90	26	.07754	862.6
DD	13.14	26.5	.07608	846.4
EE	13.39	27	.07467	830.7
FF	13.64	27.5	.07331	815.6
GG	13.89	28	.07200	801.0
HH	14.16	28.5	.07074	787.0
II	14.38	29	.06952	773.4

*Density, gm/cm^3 = density, Amagat x 8.4886 x 10^{-5}

11.002


PRESSURE, psia
80 100 200 400 600 800 1000 2000 4000 6000 10,000
COMPRESSIBILITY FACTOR, Z
1.6 1.5 1.4 1.3 1.2 1.1 1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1
NOTE:
SOLID LINES - Isotherms (T = C)
BROKEN LINES - Isometrics (V = C)
COMPRESSIBILITY FACTOR
FOR NORMAL HYDROGEN
Z = PV/RT
CRITICAL POINT
6 8 10 20 40 60 80 100 200 400 600 800
SURE, atmospheres

2

11.002

COMPRESSIBILITY FACTOR for NORMAL HYDROGEN

[P=Pressure, (atm); Z=Compressibility Factor]

(The following values are from [illegible] by Woolley, Scott and Brickwedde)

Density amagat	Volume cc/mole		Temperature, °K	Density amagat	Volume cc/mole
[illegible]	[illegible]	P / Z	[illegible]	[illegible]	[illegible]

The following values are given the paper by Stewart and Johnson

Pressure	Temperature, °F													
psia	50	60	70	80	90	100	110	120	130	140	150	160	170	180
20	22.30	66.0 1.0010	82.10 1.0017	108.0 1.0030	132.0 1.0047									
40	13.44	49.40 1.0158	64.30 1.0200	88.70 1.0265	105.6 1.0351	129.0 1.0457	148.2 1.0580							
60	8.81	33.20 1.0304	47.70 1.0348	62.20 1.0408	84.50 1.0481	103.1 1.0572	121.4 1.0680	139.7 1.0804						
80	6.49	16.90 1.0450	31.10 1.0494	45.40 1.0554	64.70 1.0627	82.50 1.0717	100.5 1.0824	118.8 1.0947	136.9 1.1087					
100	5.14		14.50 1.0640	29.00 1.0700	46.70 1.0773	64.70 1.0863	82.80 1.0969	100.9 1.1093	119.0 1.1233					
120	4.19		0.10 1.0785	27.40 1.0847	41.80 1.0919	60.20 1.1009	78.10 1.1115	96.20 1.1240	114.40 1.1380	132.60 1.1540				
140	3.53			25.30 1.0993	37.10 1.1065	55.10 1.1155	73.10 1.1261	91.10 1.1386	109.10 1.1526	127.00 1.1686				
160	3.05			14.10 1.1139	21.60 1.1211	40.00 1.1301	60.20 1.1407	80.40 1.1532	100.60 1.1672	120.80 1.1832	141.00 1.2012			
180	2.69			7.00 1.1285	15.40 1.1357	33.40 1.1447	53.30 1.1553	73.30 1.1678	93.20 1.1818	113.20 1.1978	133.00 1.2158	152.80 1.2358		
200	2.39				12.50 1.1671	25.10 1.1741	38.30 1.1831	57.50 1.1937	76.50 1.2060	95.50 1.2200	114.60 1.2360	133.60 1.2540	152.70 1.2740	171.80 1.2960
220	2.17				3.900 1.2058	17.00 1.2130	30.20 1.2220		51.70 1.2447	70.80 1.2703	89.90 1.2980	109.00 1.3280	128.10 1.3600	147.20 1.3940
240	1.99					10.10 1.2618	23.40 1.2708		37.40 1.2933	56.50 1.3190	75.60 1.3470	94.70 1.3770	113.80 1.4090	132.90 1.4430
260	1.84						17.50 1.3197		24.00 1.3417	44.00 1.3683	63.00 1.3983	82.00 1.4303	101.00 1.4643	120.00 1.5003
280	1.71						13.10 1.3663		27.10 1.3903	46.00 1.4183	65.00 1.4503	84.00 1.4843	103.00 1.5203	122.00 1.5583
300	1.60						10.10 1.4177		31.30 1.4397	50.30 1.4677	69.30 1.4997	88.30 1.5337	107.30 1.5697	126.30 1.6077
320	1.50						8.170 1.4698		47.00 1.4901	66.73 1.5160	86.63 1.5503	106.6 1.5883	126.4 1.6283	
340	1.42									72.60 1.5630	92.30 1.5976	112.0 1.6356	131.6 1.6756	151.2 1.7176
360	1.35									67.35 1.6109	87.40 1.6455	107.5 1.6835	127.5 1.7235	147.5 1.7655
380	1.28									63.40 1.6624	83.10 1.6955	97.30 1.7335	118.5 1.7735	139.9 1.8154
400	1.22									57.30 1.7100	73.90 1.7404	90.50 1.7800	107.1 1.8200	123.6 1.8600
420	1.17									52.80 1.7635	67.03 1.7901	81.10 1.8301	109.4 1.8777	104.8 1.9169

Volume and Compressibility Factors for Saturated Liquid and Vapor

Pressure	Temp.	Saturated Liquid		Saturated Vapor	
psia	°F	V ft³/lb	Z	V ft³/lb	Z
.2563	16	14.73	.00+127	1.83+	1.0+72
.4551	19	15.60	.00+481	2.00+	.9940
.0891	20	3+.00	.0152+	330.9	.9161
1.161	22	14.50	.02588	900.4	.9742
2.2493	24	15.15	.0598	117.7	.9576
3.1036	26	15.67	.08547	309.0	.9330
4.604	28	16.0+	.0854+	241.6	.9017
5.730	30	16.42	.1200	4.9.6+	.8673
10+.+11	32	31.47	.1779	61.49	.7917
10.36	33.13	35.82	.3109	33.72	.5178

11.003

COMPRESSIBILITY FACTOR for NEON

$Z = PV/RT$

Sources of Data:

Yendall, E. F.; Private communication to Dr. K. D. Timmerhaus, University of Colorado (June 1, 1960)

Other References:

Crommelin, C. A., Martinez, J. P. and Onnes, H. K.; Koninkl. Akad. Wetenschap. Amsterdam 27, 1316-26 (1919)

Onnes, H. K. and Crommelin, C. A.; Communs. Phys. Lab. Univ. Leiden No. 147d (1915)

Comments:

The compressibility factors were calculated from a modified Benedict-Webb-Rubin equation of state as determined by Yendall. The coefficients for this equation of state are primarily based on experimental data by Crommelin, et al.

A comparison of calculated pressures by Yendall's equation with the pressures at the 103 experimental points of Crommelin et al., was made by Yendall. On the basis of this comparison, Yendall reports a mean percentage deviation of 0.5%.

A graphical study was made of the experimental pressure, volume, temperature data reported by Crommelin et al. This study employed the method of graphical residuals, i.e., a correction term expressing, in this case, the departure of experimentally determined volumes from the ideal volume. The order of magnitude of these residuals was sufficiently small to provide a graphical comparison to five significant figures over the entire range of values. This study indicated a random scatter of the fourth significant figure of this data, indicating the experimental accuracy of the original data is limited to three significant figures.

A comparison was also made between the experimental P-V-T data reported by Crommelin et al., and the P-V-T values calculated from Yendall's equation of state. The results of this study (see graphs) indicate good agreement between the experimental data and the calculated values, except at 55.57°K. This comparison and the study of the data as discussed above, both indicate a departure from the general pattern as compared to values at higher temperatures. In conclusion, there appears to be some doubt in the relative accuracy of the values at 55.57°K as reported by Crommelin et al.

The P-V-T values at 55°K included on the graph were also calculated from Yendall's equation of state, but because of the uncertainty of both the experimental data and the calculated values, these values were limited to 55 atmospheres at which point the deviation between the experimental data and the calculated values exceeded four percent.

The P-V-T graphical and tabular values are presented here with dimensions of pressure in atmospheres (g = 980.665), temperatures in degrees Kelvin (0°C = 273.16°K), and density in gm/cc.

COMPRESSIBILITY FACTOR for NEON (Cont.)

$$Z = PV/RT$$

The modified Benedict-Webb-Rubin equation of state as determined by Yendall for neon is:

$$P/\rho RT - 1 = \sum (a_{pq}\, \rho^q/T^p)$$

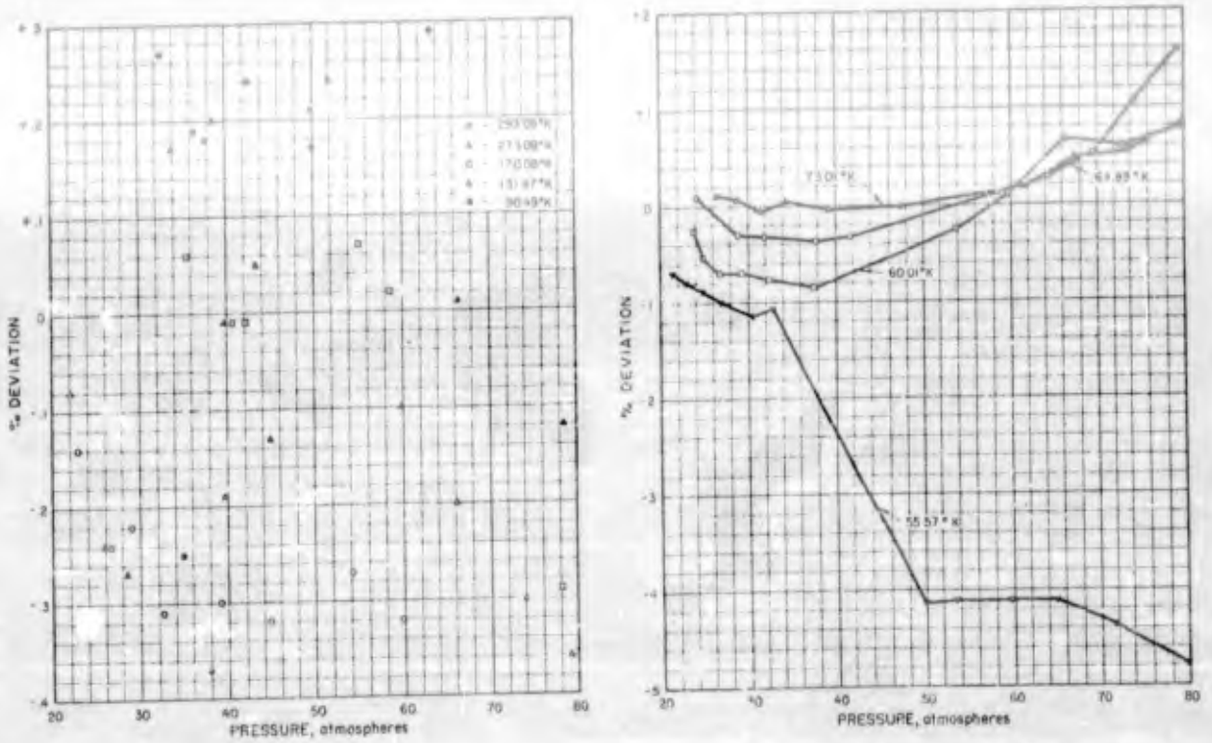
Note: The 12 terms of this summation have coefficients a_{pq} listed below. In each term the subscripts of a_{pq} are the exponents of T and ρ respectively.

where T is in °K (0°C = 273.16°K)
mol. wt. Ne = 20.183

ρ is in gm-mole/liter
P is in atm.
R = 0.0820544 atm. liters/gm-mole°K

The coefficients a_{pq} determined by Yendall are as follows:

$a_{01} = 0.014208884$	$a_{12} = -0.050955574$	$a_{52} = 120477.74$
$a_{11} = -1.7734560$	$a_{32} = 103.28801$	$a_{53} = -7305.4880$
$a_{31} = -2773.7632$	$a_{33} = 0.66305973$	$a_{73} = 204222.81$
$a_{02} = 0.00088955035$	$a_{51} = 499549.48$	$a_{54} = 68.509204$



COMPARISON of PRESSURES from YENDALL'S EQUATION WITH DATA by CROMMELIN, ET AL.

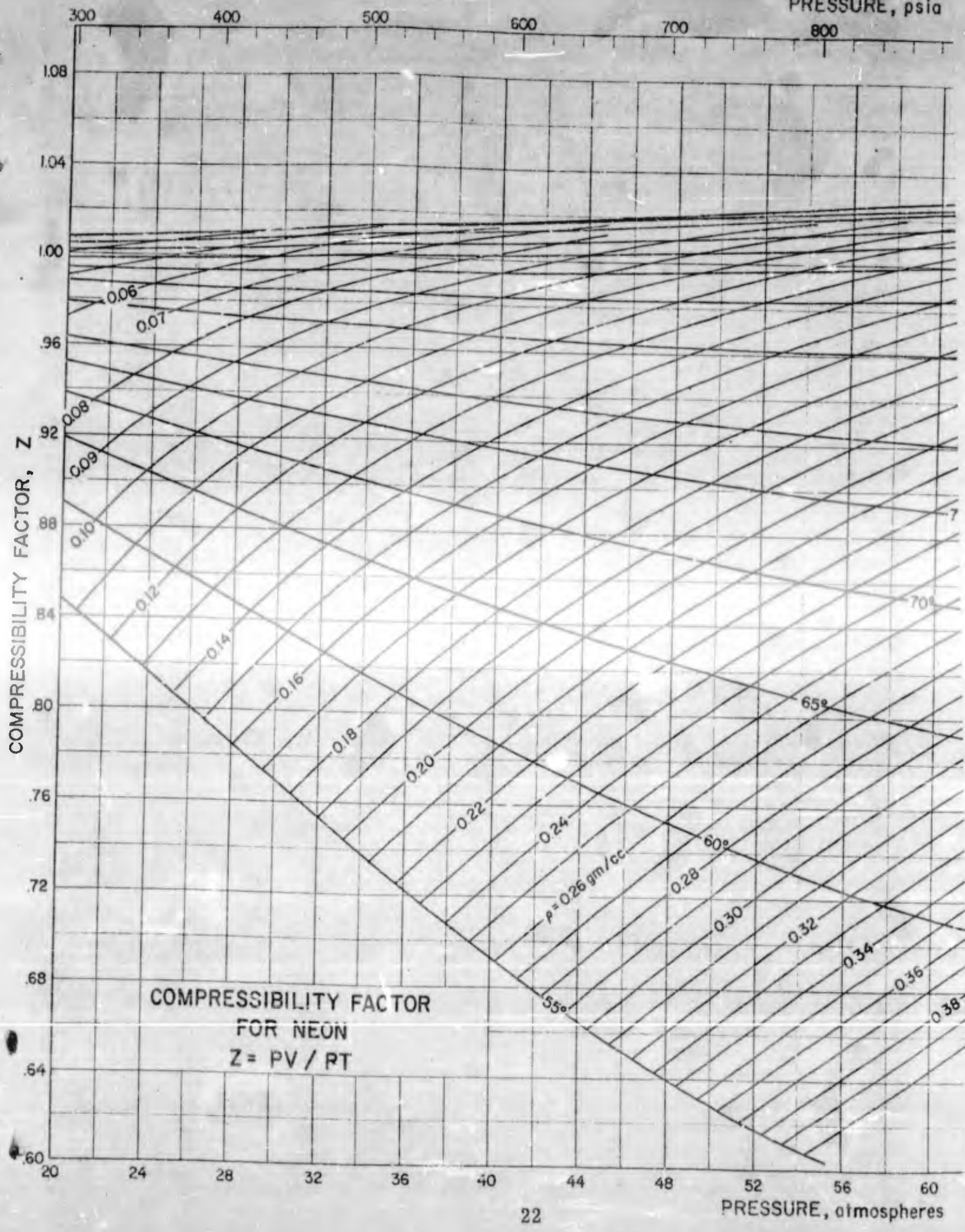
$$\% \text{ Deviation} = \frac{P_{Yend.} - P_{Crom.}}{P_{Crom.}}$$

COMPRESSIBILITY FACTOR for NEON

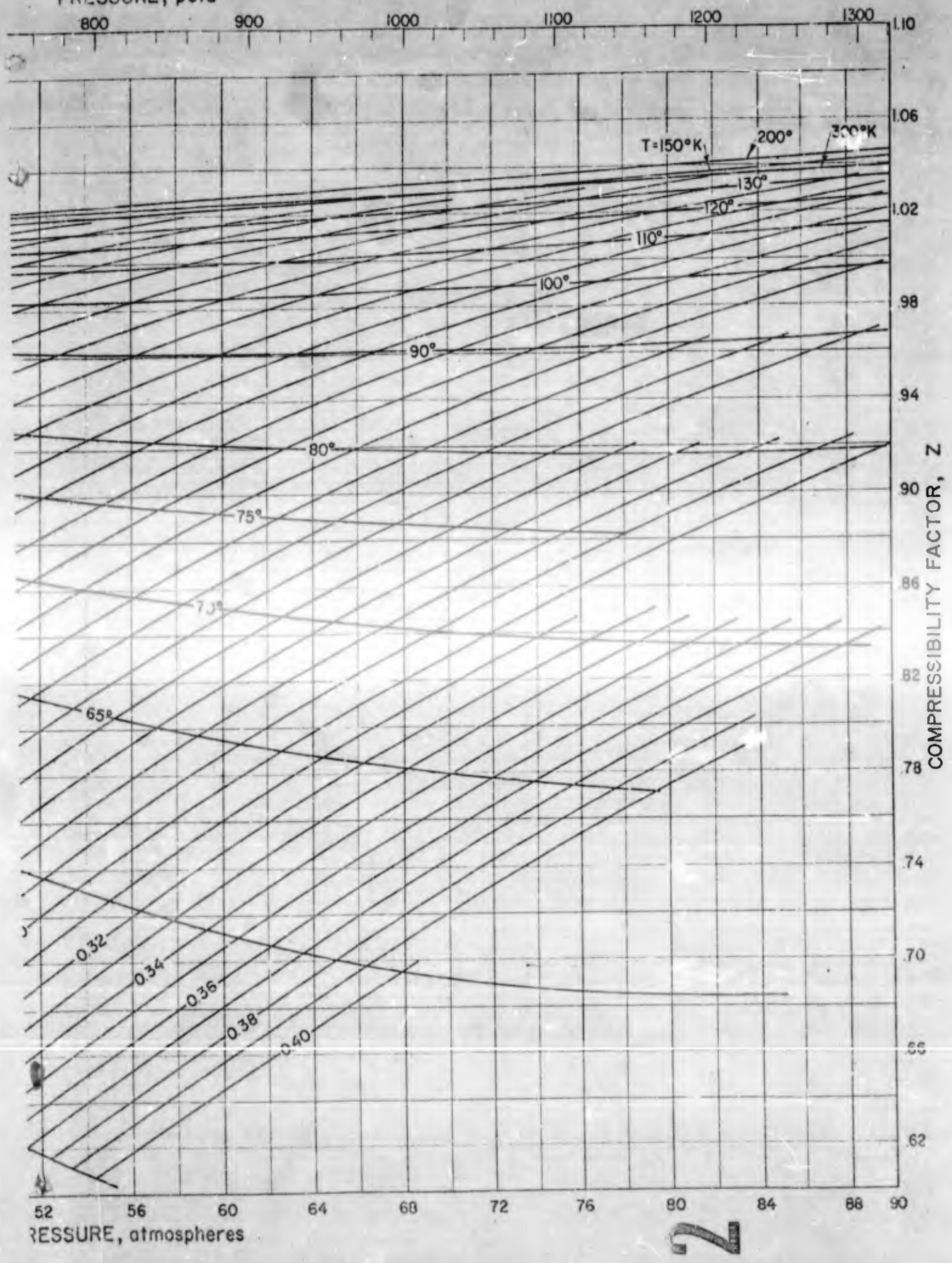
[P=Pressure, (atm); Z = Compressibility Factor]

Density gm/cc		Temperature, °K 55	60	65	70	75	80	90	100	110	120	130	150	200	300		Density gm/cc
.01	P	2.200	2.407	2.614	2.821	3.027	3.233	3.644	4.055	4.465	4.876	5.286	6.106	8.155	12.25	P	.01
	Z	.9838	.9868	.9892	.9911	.9926	.9939	.9959	.9973	.9985	.9994	1.000	1.001	1.003	1.005	Z	
.02	P	4.329	4.752	5.172	5.592	6.010	6.427	7.259	8.090	8.919	9.748	10.58	12.23	16.36	24.62	P	.02
	Z	.9680	.9740	.9786	.9824	.9854	.9880	.9919	.9949	.9972	.9990	1.001	1.003	1.006	1.009	Z	
.03	P	6.390	7.036	7.677	8.315	8.951	9.585	10.85	12.11	13.37	14.62	15.87	18.38	24.63	37.13	P	.03
	Z	.9526	.9614	.9684	.9740	.9785	.9823	.9883	.9927	.9961	.9989	1.001	1.005	1.010	1.015	Z	
.04	P	8.336	9.262	10.13	10.99	11.85	12.71	14.41	16.11	17.81	19.50	21.18	24.56	32.97	49.78	P	.04
	Z	.9375	.9492	.9584	.9656	.9719	.9769	.9846	.9908	.9953	.9990	1.002	1.007	1.014	1.020	Z	
.05	P	10.32	11.43	12.54	13.63	14.72	15.80	17.96	20.11	22.25	24.38	26.51	30.77	41.36	62.58	P	.05
	Z	.9229	.9373	.9487	.9579	.9654	.9717	.9816	.9890	.9948	.9994	1.003	1.009	1.018	1.026	Z	
.06	P	12.19	13.55	14.89	16.23	17.55	18.87	21.49	24.09	26.69	29.27	31.86	37.02	49.88	75.56	P	.06
	Z	.9086	.9257	.9393	.9502	.9592	.9668	.9787	.9876	.9943	1.000	1.005	1.012	1.022	1.033	Z	
.07	P	14.00	15.61	17.21	18.78	20.35	21.90	25.00	28.07	31.13	34.19	37.23	43.31	58.47	88.73	P	.07
	Z	.8946	.9144	.9301	.9428	.9533	.9621	.9759	.9864	.9945	1.001	1.006	1.015	1.027	1.039	Z	
.08	P	15.76	17.63	19.48	21.30	23.12	24.92	28.49	32.05	35.59	39.12	42.63	49.65	67.16		P	.08
	Z	.8811	.9034	.9212	.9357	.9476	.9576	.9735	.9854	.9947	1.002	1.008	1.018	1.032		Z	
.09	P	17.47	19.60	21.71	23.79	25.86	27.91	31.98	36.03	40.06	44.07	48.07	56.05	75.95		P	.09
	Z	.8678	.8927	.9126	.9288	.9422	.9534	.9712	.9847	.9952	1.004	1.011	1.021	1.038		Z	
.10	P	19.12	21.52	23.90	26.24	28.57	30.88	35.48	40.01	44.54	49.05	53.54	62.51	84.86		P	.10
	Z	.8550	.8823	.9042	.9221	.9369	.9494	.9692	.9842	.9959	1.005	1.013	1.025	1.044		Z	
.11	P	20.72	23.40	26.05	28.67	31.26	33.83	38.94	44.00	49.04	54.06	59.06	69.04	93.90		P	.11
	Z	.8424	.8722	.8966	.9157	.9320	.9457	.9674	.9839	.9969	1.007	1.016	1.029	1.050		Z	
.12	P	22.28	25.24	28.17	31.06	33.93	36.77	42.41	48.00	53.56	59.10	64.62	75.63			P	.12
	Z	.8302	.8624	.8883	.9095	.9272	.9421	.9659	.9839	.9981	1.010	1.019	1.034			Z	
.13	P	23.79	27.05	30.26	33.43	36.56	39.70	45.88	52.02	58.11	64.18	70.24	82.31			P	.13
	Z	.8183	.8528	.8807	.9036	.9227	.9389	.9646	.9842	.9996	1.012	1.022	1.038			Z	
.14	P	25.26	28.81	32.31	35.78	39.22	42.61	49.36	56.05	62.69	69.31	75.91	89.06			P	.14
	Z	.8068	.8436	.8734	.8980	.9189	.9358	.9635	.9846	1.001	1.015	1.026	1.043			Z	
.15	P	26.68	30.54	34.34	38.10	41.83	45.52	52.84	60.09	67.30	74.48	81.64	95.90			P	.15
	Z	.7955	.8346	.8664	.8925	.9144	.9330	.9627	.9854	1.003	1.018	1.030	1.048			Z	
.16	P	28.07	32.24	36.35	40.41	44.43	48.42	56.33	64.16	71.95	79.70	87.43				P	.16
	Z	.7846	.8259	.8596	.8874	.9106	.9304	.9602	.9863	1.006	1.021	1.034				Z	
.17	P	29.42	33.90	38.32	42.69	47.02	51.32	59.88	68.26	76.63	84.97	93.29				P	.17
	Z	.7740	.8175	.8530	.8824	.9071	.9281	.9617	.9876	1.008	1.025	1.038				Z	
.18	P	30.74	35.54	40.26	44.96	49.61	54.21	63.34	72.38	81.36	90.31	99.22				P	.18
	Z	.7636	.8094	.8467	.8777	.9038	.9260	.9615	.9890	1.011	1.028	1.043				Z	
.19	P	32.02	37.15	42.21	47.22	52.18	57.12	66.86	76.53	86.14	95.70					P	.19
	Z	.7536	.8015	.8407	.8733	.9007	.9241	.9617	.9907	1.014	1.032					Z	
.20	P	33.27	38.73	44.13	49.47	54.76	60.00	70.41	80.72	90.96						P	.20
	Z	.7439	.7939	.8349	.8691	.8979	.9224	.9603	.9927	1.017						Z	
.21	P	34.49	40.29	46.03	51.71	57.33	62.91	73.97	84.94	95.84						P	.21
	Z	.7345	.7865	.8293	.8660	.8952	.9213	.9687	.9949	1.020						Z	
.22	P	35.68	41.83	47.91	53.93	59.90	65.82	77.56	89.20							P	.22
	Z	.7253	.7794	.8241	.8613	.8929	.9196	.9635	.9973							Z	
.23	P	36.85	43.35	49.78	56.16	62.47	68.74	81.11								P	.23

													.17
.18	P	30.74	35.54	40.28	44.96	49.61	54.21	63.34	72.38	81.36	90.31	99.22	.18
	Z	.7635	.8094	.8467	.8777	.9038	.9260	.9616	.9890	1.011	1.028	1.043	
.19	P	32.02	37.15	42.21	47.22	52.18	57.11	66.86	76.53	86.14	95.70		.19
	Z	.7536	.8015	.8407	.8733	.9007	.9241	.9617	.9907	1.014	1.032		
.20	P	33.27	38.73	44.13	49.47	54.76	60.00	70.41	80.72	90.96			.20
	Z	.7439	.7939	.8349	.8691	.8979	.9224	.9621	.9927	1.017			
.21	P	34.49	40.29	46.03	51.71	57.33	62.91	73.97	84.94	95.84			.21
	Z	.7345	.7865	.8293	.8650	.8952	.9210	.9627	.9949	1.020			
.22	P	35.68	41.83	47.91	53.93	59.90	65.82	77.56	89.20				.22
	Z	.7253	.7794	.8241	.8613	.8929	.9198	.9635	.9973				
.23	P	36.85	43.35	49.78	56.15	62.47	68.74	81.18	93.51				.23
	Z	.7165	.7726	.8190	.8578	.8907	.9189	.9646	1.000				
.24	P	37.99	44.85	51.64	58.37	65.05	71.67	84.82	97.86				.24
	Z	.7079	.7660	.8142	.8546	.8888	.9182	.9659	1.003				
.25	P	39.11	46.33	53.49	60.59	67.63	74.62	88.50					.25
	Z	.6996	.7597	.8096	.8515	.8871	.9177	.9674					
.26	P	40.21	47.80	55.33	62.80	70.22	77.59	92.21					.26
	Z	.6916	.7537	.8053	.8488	.8857	.9175	.9692					
.27	P	41.28	49.26	57.17	65.02	72.82	80.57	95.95					.27
	Z	.6838	.7479	.8012	.8462	.8845	.9175	.9722					
.28	P	42.35	50.70	59.00	67.25	75.43	83.57	99.74					.28
	Z	.6763	.7423	.7974	.8439	.8835	.9177	.9765					
.29	P	43.39	52.14	60.84	69.48	78.06	86.60						.29
	Z	.6691	.7370	.7938	.8418	.8828	.9182						
.30	P	44.42	53.57	62.67	71.72	80.71	89.66						.30
	Z	.6622	.7320	.7905	.8400	.8823	.9188						
.31	P	45.44	54.99	64.50	73.97	83.38	92.74						.31
	Z	.6555	.7272	.7874	.8384	.8820	.9198						
.32	P	46.45	56.41	66.34	76.23	86.06	95.85						.32
	Z	.6491	.7227	.7845	.8370	.8820	.9209						
.33	P	47.44	57.83	68.19	78.50	88.77	99.00						.33
	Z	.6429	.7184	.7819	.8359	.8822	.9223						
.34	P	48.43	59.25	70.04	80.79	91.51							.34
	Z	.6370	.7144	.7795	.8350	.8826							
.35	P	49.42	60.67	71.90	83.11	94.27							.35
	Z	.6314	.7106	.7774	.8343	.8833							
.36	P	50.40	62.09	73.78	85.44	97.06							.36
	Z	.6260	.7070	.7755	.8339	.8842							
.37	P	51.37	63.52	75.67	87.79	99.89							.37
	Z	.6209	.7037	.7738	.8337	.8854							
.38	P	52.35	64.95	77.57	90.17								.38
	Z	.6161	.7007	.7724	.8338								
.39	P	53.33	66.40	79.49	92.58								.39
	Z	.6115	.6979	.7713	.8341								
.40	P	54.31	67.85	81.43	95.01								.40
	Z	.6071	.6954	.7703	.8346								


11.003
PRESSURE, psia
300
400
500
600
700
800
1.08
1.04
1.00
.96
.92
.88
.84
.80
.76
.72
.68
.64
.60
COMPRESSIBILITY FACTOR, Z
0.06
0.07
0.08
0.09
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
ρ = 0.26 gm/cc
0.28
0.30
0.32
0.34
0.36
0.38
7
70°
65°
60°
55°
COMPRESSIBILITY FACTOR
FOR NEON
Z = PV / RT
20
24
28
32
36
40
44
48
52
56
60
PRESSURE, atmospheres

11.003


PRESSURE, psia
800
900
1000
1100
1200
1300
T=150°K
200°
300°K
130°
120°
110°
100°
90°
80°
75°
70°
65°
0.32
0.34
0.36
0.38
0.40
1.10
1.06
1.02
.98
.94
.90
.86
.82
.78
.74
.70
.66
.62
COMPRESSIBILITY FACTOR, Z
52
56
60
64
68
72
76
80
84
88
90
RESSURE, atmospheres

COMPRESSIBILITY FACTOR for NITROGEN

$Z = PV/RT$

Sources of Data:

Benedict, M.; J. Am. Chem. Soc. 59, 2224-33 (1937)

Bloomer, O. T., Rao, K. N.; Inst. Gas Tech. Res. Bull. 18, 1-28 (1953)

Other References:

Hilsenrath, J., et al.; Natl. Bur. Standards Cir. 564, 297-368 (1955)

Comments:

The compressibility factors are illustrated on two graph sheets, one for the pressure range 1 to 500 atm., and the other, 300 to 3000 atm. These graphs illustrate the data with both constant temperature and constant density lines on pressure-compressibility factor coordinates. The compressibility factors for densities of 0.20 gm/cc and greater were calculated from an equation of state developed by Benedict. The coefficients for this equation of state were based on density data reported by Benedict as well as values from other researchers. These values are illustrated as the high pressure range on the graph covering the pressure range 1 - 500 atmospheres and in addition all of the values on the graph covering the pressure range 300 - 3000 atmospheres. The compressibility factors for the low pressure range, i.e., for densities less than 0.20 gm/cc were calculated with a modified Benedict-Webb-Rubin equation of state presented by Bloomer and Rao. The coefficients for this equation were based on experimental values from several sources, including those from Benedict for the high density range.

An estimate of the reliability of these equations of state is indicated by the authors' estimate of deviation between their calculated and experimental values. The deviations of calculated pressures from observed pressures reported by Bloomer and Rao have an overall average deviation of 0.36% and a maximum deviation of 2.98% for the range of values suggested by Bloomer and Rao. The maximum deviation in the range where this equation was used for this data sheet, however, is 0.24% except for the value at 120° and 24 atm. where the deviation is 1.3%. Comparisons made by Benedict indicate an average percentage deviation of 0.55% between his calculated P-V-T values and the observed P-V-T data, from both his own measurements and values reported by other researchers.

The pressure-volume-temperature values calculated by each equation of state were compared over a range which, according to the respective authors, is common to the two equations of state. This comparison is given in Figure 1. The calculated values are in excellent agreement for this "common range", except at temperatures from 130° to 150°K.

(Continued on following page.)

COMPRESSIBILITY FACTOR for NITROGEN (cont.)

$Z = PV/RT$

Comments: (cont.)

Although Bloomer and Rao used P-V-T data calculated by Benedict's equation for the values at high densities, it is in this range that the larger deviations occur between the calculated and the observed values of pressure according to the estimated errors reported by Bloomer and Rao. Where a significant difference was observed in this "common range", the values determined from Benedict's equation of state were therefore used. A comparison was also made of the deviations between the P-V-T values listed by Hilsenrath, et al., from those calculated by these equations of state. This check indicated these values to be in excellent agreement, i.e., the maximum percentage difference in densities in the range from 0.1 to 100 atmospheres pressure and 100° to 300°K with three exceptions, was 0.035%. This comparison is illustrated in Figure 2.

The equations of state used in the preparation of this data sheet together with their coefficients as determined by Bloomer and Rao and by Benedict, are given on the following page.

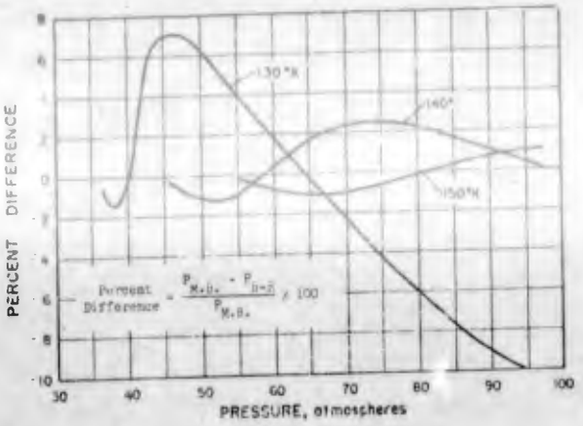


FIGURE 1a. COMPARISON OF COMPRESSIBILITY FACTOR FROM BLOOMER AND RAO, AND M. BENEDICT

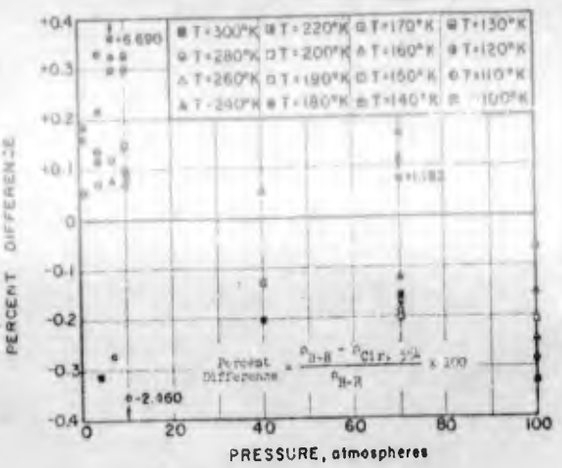


FIGURE 2. COMPARISON OF DENSITY FROM BLOOMER-RAO EQUATION AND NBS CIRCULAR 564
(Variations of less than ± 0.05% are not illustrated.)

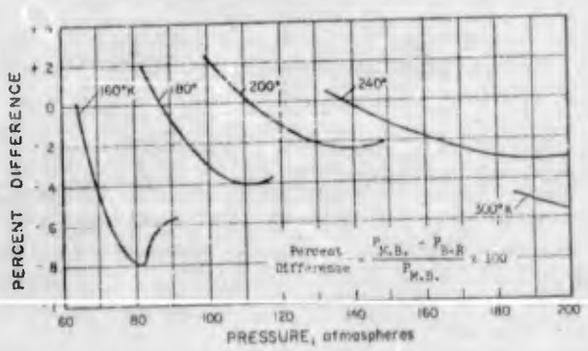
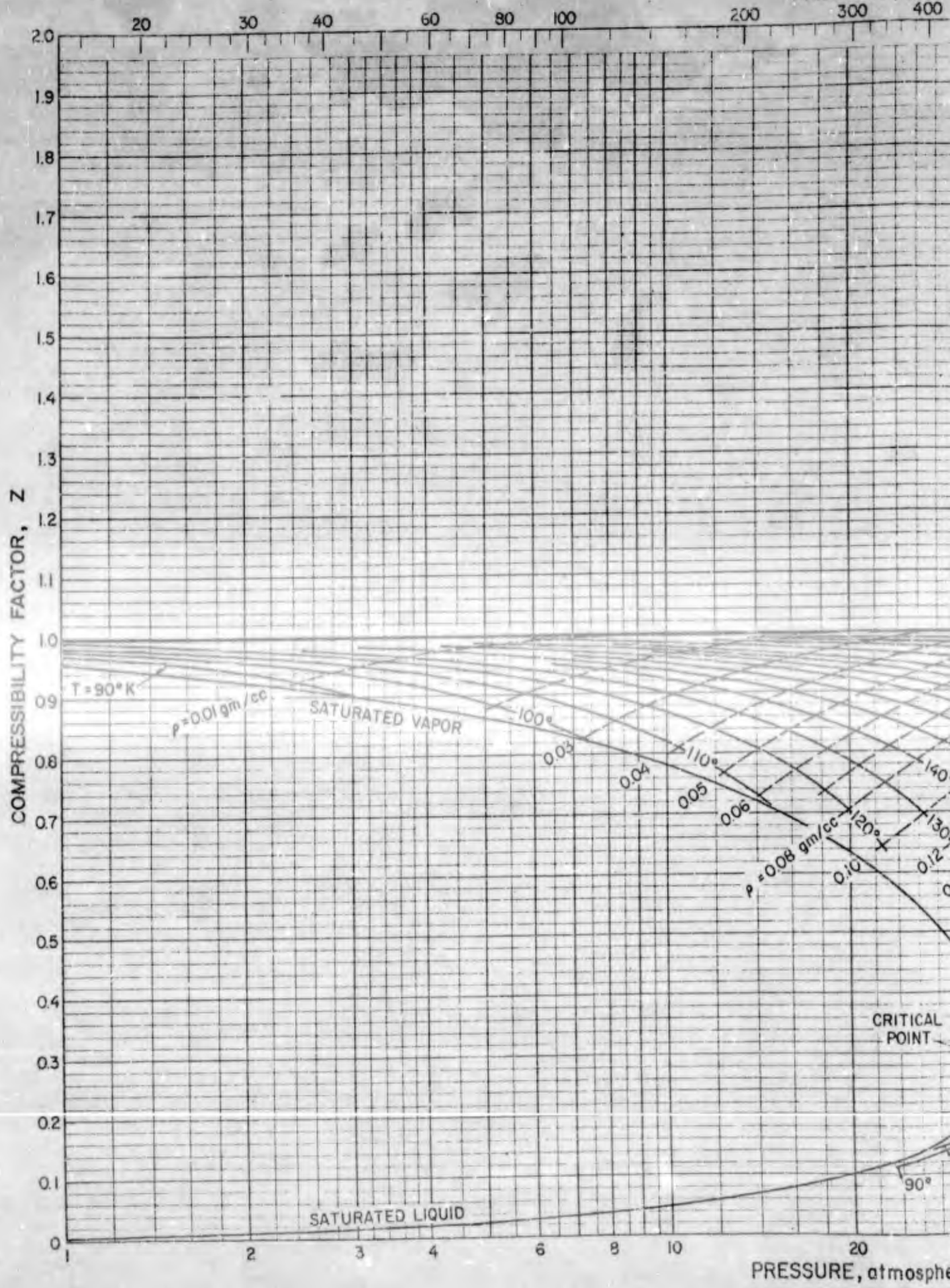
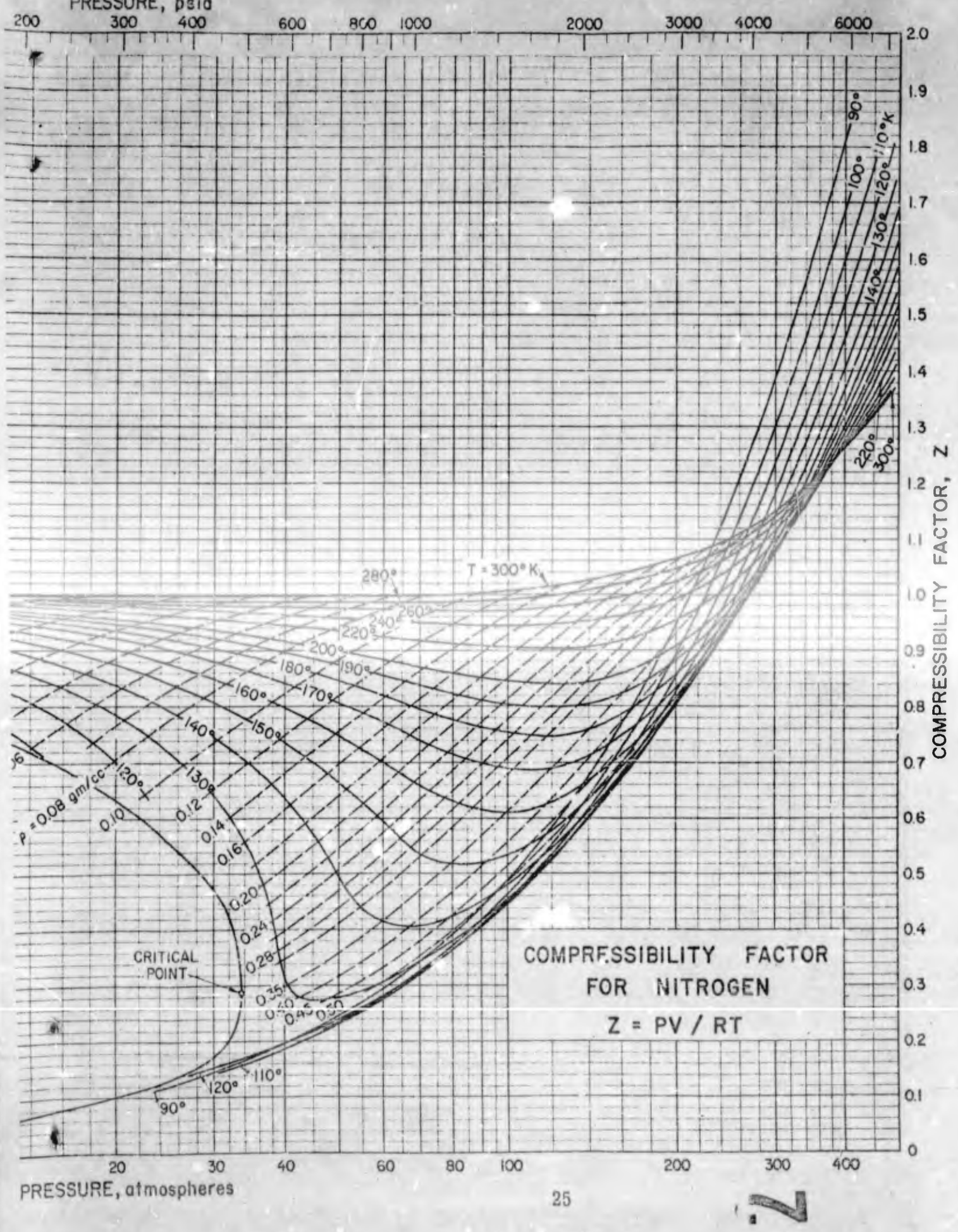


FIGURE 1b. COMPARISON OF COMPRESSIBILITY FACTOR FROM BLOOMER AND RAO, AND M. BENEDICT


PRESSURE, psia
20
30
40
60
80
100
200
300
400
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
COMPRESSIBILITY FACTOR, Z
T=90°K
ρ=0.01 gm/cc
SATURATED VAPOR
100°
110°
120°
130°
140°
0.03
0.04
0.05
0.06
ρ=0.08 gm/cc
0.10
0.12
CRITICAL POINT
90°
SATURATED LIQUID
1
2
3
4
6
8
10
20
PRESSURE, atmosphe

11.004


PRESSURE, psia
200
300
400
600
800
1000
2000
3000
4000
6000
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
COMPRESSIBILITY FACTOR, Z
90°
100°
110°
120°
130°
140°
220°
300°
T = 300° K
280°
260°
240°
220°
200°
190°
180°
170°
160°
150°
140°
130°
120°
ρ = 0.08 gm/cc
0.10
0.12
0.14
0.16
0.20
0.24
0.28
0.35
0.40
0.50
CRITICAL POINT
COMPRESSIBILITY FACTOR
FOR NITROGEN
Z = PV / RT
90°
110°
120°
20
30
40
60
80
100
200
300
400
PRESSURE, atmospheres

COMPRESSIBILITY FACTOR for NITROGEN (Cont.)

$Z = PV/RT$

The Benedict-Webb-Rubin equation of state as modified by Bloomer and Rao for nitrogen is:

$$P = RT\rho + \left[B_oRT - A_o - \frac{C_o}{T^2} - \frac{D_o}{T^4}\right]\rho^2 + \rho^3\left[bRT - a + \left(\frac{c}{T^2} + \frac{\delta}{T^4}\right)\left(1 + \gamma\rho^2\right)e^{-\gamma\rho^2}\right] + a\alpha\rho^6$$

where T is in °K (0°C = 273.16°K)
mole wt. N_2 = 28.014

ρ is in gm-mole/liter
P is in atm.
R = 0.08206 atm. liters/gm-moles°K

The coefficients determined by Bloomer and Rao are as follows:

$B_o = 0.0484824$
$A_o = 1.27389$
$C_o = 4273.00$
$D_o = 7.61781 \times 10^6$

$b = 0.00232373$
$a = 0.0178444$
$c = 475.000$
$\delta = 0.832 \times 10^6$
$\gamma = 0.0065$
$\alpha = 0.00015300$

The equation of state determined by Benedict is:

$PV = A + \beta\rho$

$A = 1.00046\ T/T_o$

$\beta = p + q\rho + \gamma\rho^4 + (T/100)(s + t\rho + \mu\rho^2) + (100/T)v + (100/T)^3\rho^3 W\ 10^{-x\rho^2}$

where T is in °K (0°C = 273.20°K)

P is in atmospheres
ρ is in Amagat units (1 Amagat = density of normal gas at 1 atm., 0°C)
(density gas at 1 atm. 0°C = 1.2506 gm/cc)

The coefficients determined by Benedict are as follows:

$T_o = 273.20$°K
$p = -1.66453$
$q = -1.35938$
$\gamma = 11.3200$
$s = 0.67617$

$t = 0.91512$
$\mu = 2.06932$
$v = -1.21342$
$W = 107.03$
$x = 6.975$

Rao

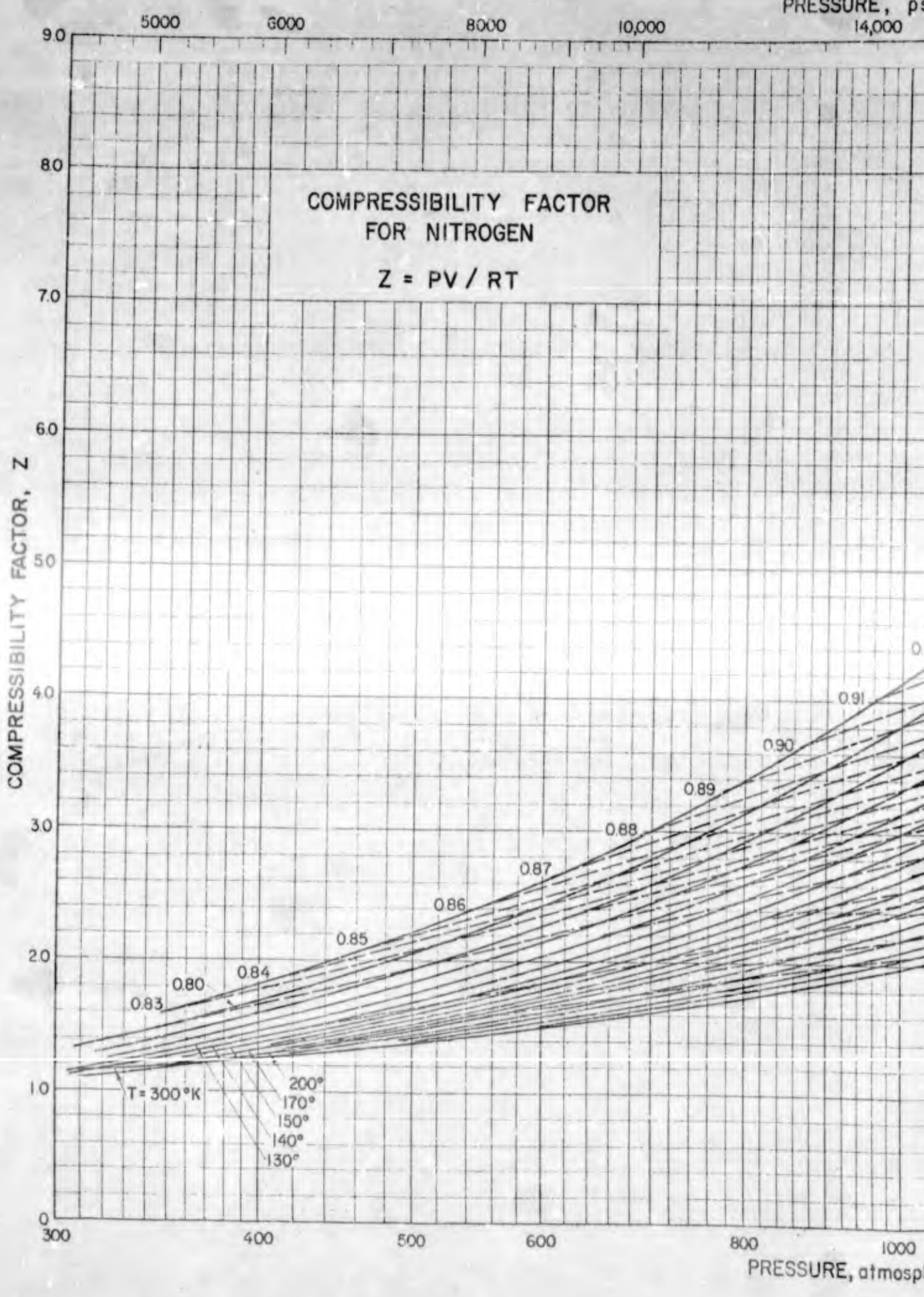
$\gamma\rho^2 \Big] + a\alpha\rho^6$

Volume and Compressibility Factors for Saturated Liquid and Vapor

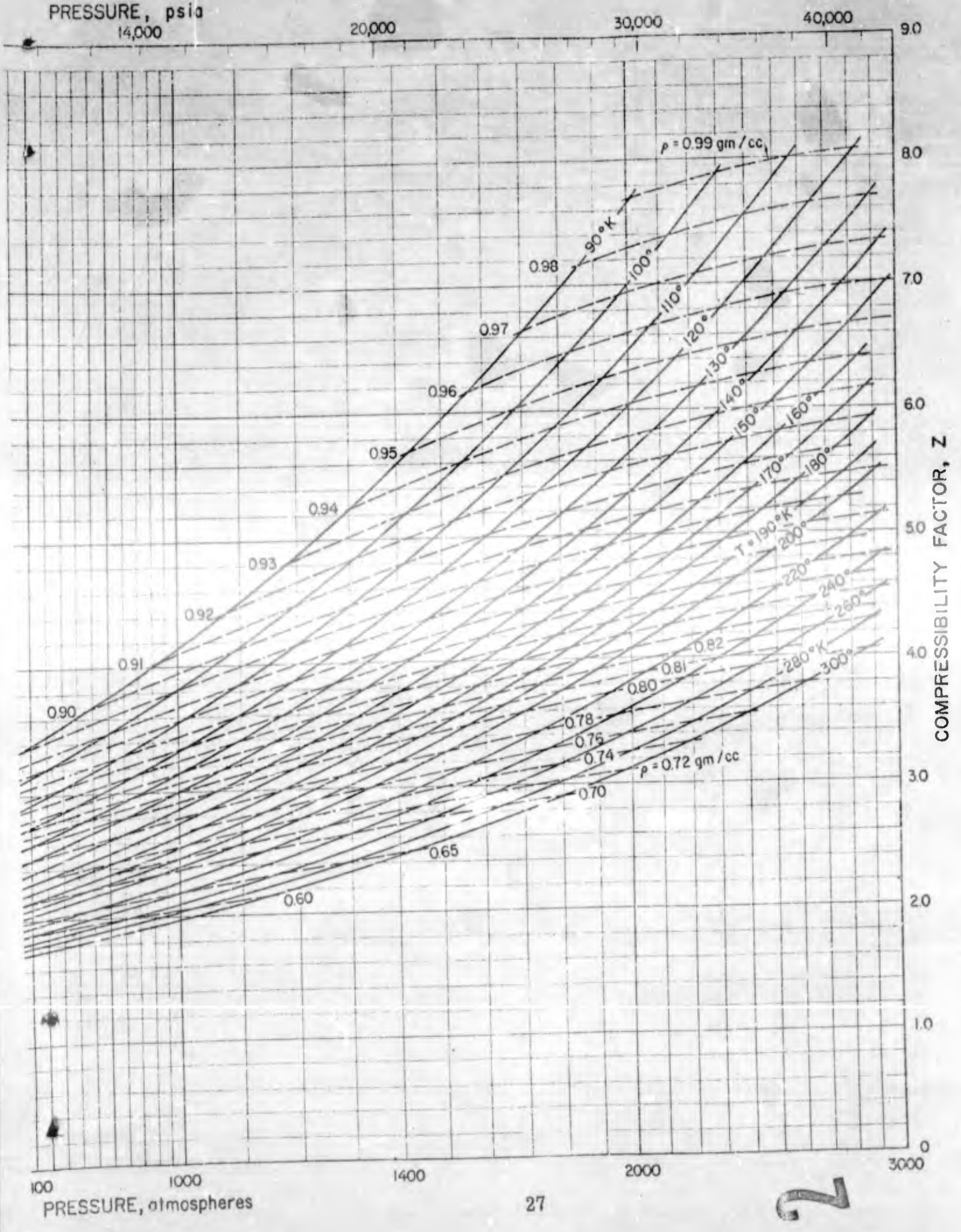
Pressure atm.	Temp. °K	Saturated Liquid		Saturated Vapor	
		V cc/gm	Z	V cc/gm	Z
1.000	77.38	1.239	.005468	216.8	.9567
1.414	80.38	1.260	.007565	157.0	.9424
1.874	83.16	1.282	.009861	120.6	.9275
2.451	85.94	1.305	.01271	93.77	.9133
3.166	88.72	1.329	.01620	74.17	.9038
4.016	91.49	1.355	.02031	58.80	.8812
5.025	94.27	1.383	.02517	47.20	.8590
6.204	97.05	1.413	.03084	38.60	.8425
7.571	99.83	1.446	.03744	31.70	.8208
9.141	102.61	1.483	.04512	26.09	.7936
10.93	105.38	1.526	.05404	21.66	.7673
12.96	108.16	1.573	.06436	18.03	.7376
15.25	110.94	1.626	.07631	14.97	.7027
17.82	113.72	1.686	.09019	12.49	.6681
20.68	116.49	1.761	.1067	10.31	.6252
23.88	119.27	1.871	.1279	8.416	.5752
27.41	122.05	2.021	.1550	6.742	.5170
31.33	124.83	2.262	.1938	5.207	.4462
33.54	126.26	3.179	.2883	3.179	.2883

$\times 10^{-x\rho^2}$

, 0°C)


PRESSURE, ps
5000
6000
8000
10,000
14,000
COMPRESSIBILITY FACTOR
FOR NITROGEN
Z = PV / RT
COMPRESSIBILITY FACTOR, Z
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
0.91
0.90
0.89
0.88
0.87
0.86
0.85
0.84
0.83
0.80
T = 300°K
200°
170°
150°
140°
130°
300
400
500
600
800
1000
PRESSURE, atmosp

11.004

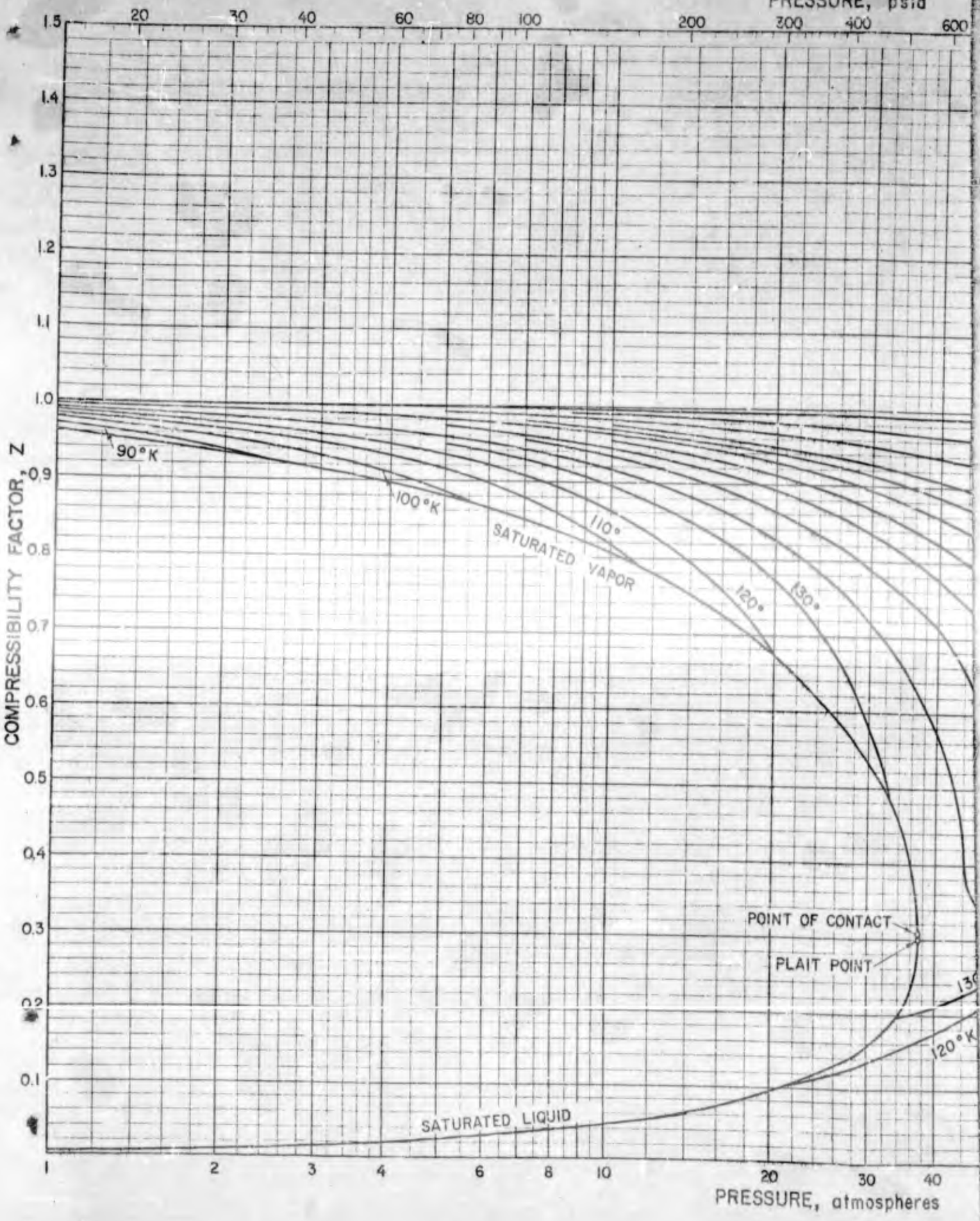

PRESSURE, psia
14,000
20,000
30,000
40,000
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
COMPRESSIBILITY FACTOR, Z
ρ = 0.99 gm / cc
ρ = 0.72 gm / cc
T = 190°K
90°K
100°
110°
120°
130°
140°
150°
160°
170°
180°
200°
220°
240°
260°
280°K
300°
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
0.82
0.81
0.80
0.78
0.75
0.74
0.70
0.65
0.60
100
1000
1400
2000
3000
PRESSURE, atmospheres

COMPRESSIBILITY FACTOR for NITROGEN*

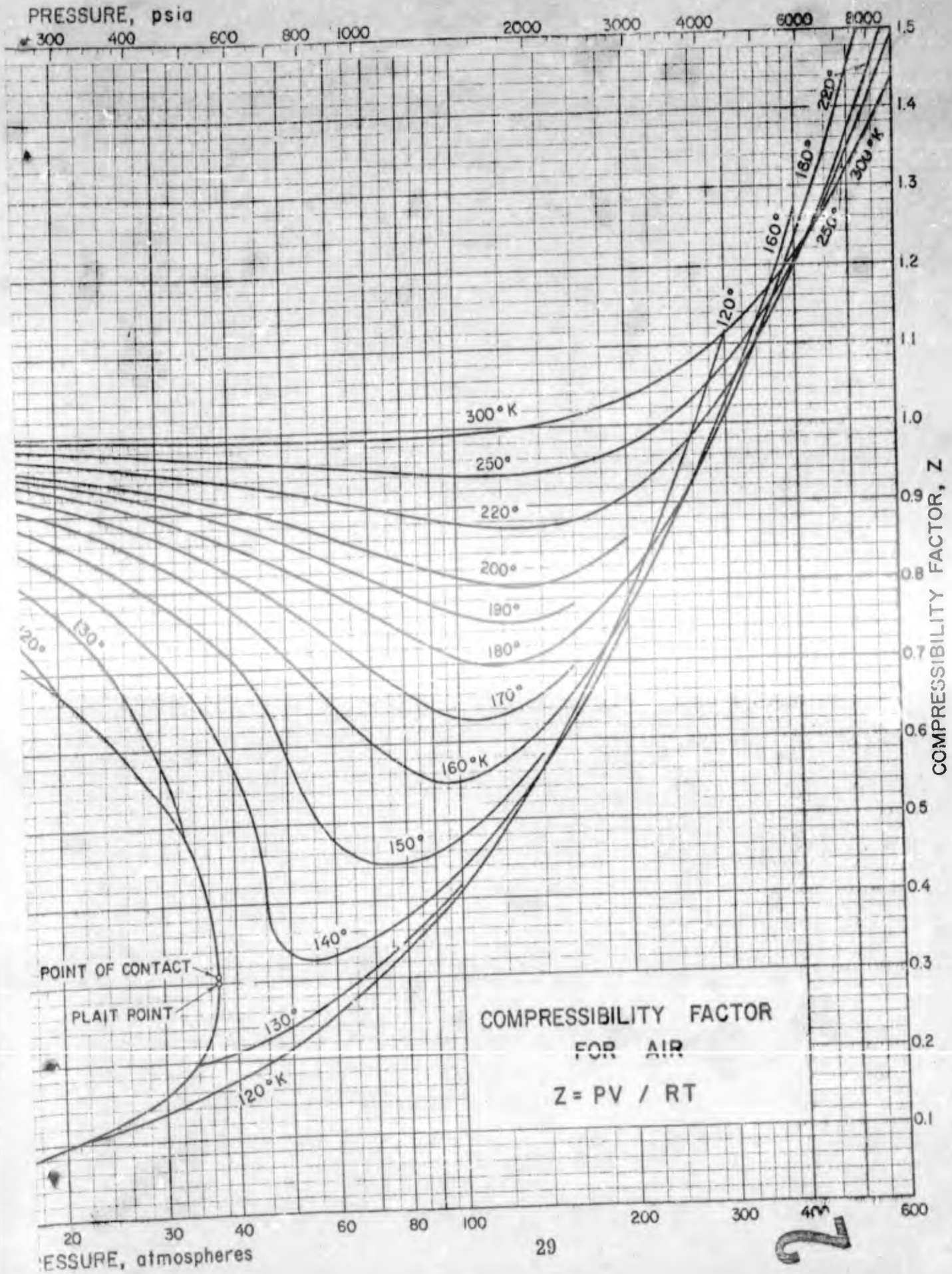
[P=Pressure, (atm); Z = Compressibiliy Factor]

Density gm/cc		Temperature, °K																	Density gm/cc
		90	100	110	120	130	140	150	160	170	180	190	200	220	240	260	280	300	
.01	P	2.441	2.756	3.066	3.373	3.678	3.981	4.283	4.584	4.885	5.185	5.485	5.785	6.384	6.982	7.579	8.177	8.774	.01
	Z	.9858	.9409	.9516	.9596	.9658	.9707	.9748	.9781	.9810	.9834	.9856	.9874	.9905	.9931	.9951	.9969	.9964	
.02	P		5.176	5.829	6.470	7.102	7.728	8.351	8.970	9.587	10.20	10.82	11.43	12.65	13.87	15.09	16.31	17.53	.02
	Z		.8835	.9045	.9203	.9325	.9423	.9503	.9568	.9626	.9674	.9716	.9754	.9816	.9866	.9907	.9942	.9972	
.03	P		7.276	8.302	9.301	10.28	11.25	12.21	13.16	14.11	15.06	16.00	16.94	18.81	20.68	22.55	24.41	26.27	.03
	Z		.8279	.8588	.8820	.9001	.9145	.9264	.9363	.9447	.9520	.9583	.9638	.9731	.9806	.9868	.9920	.9965	
.04	P			10.50	11.88	13.23	14.56	15.88	17.19	18.47	19.76	21.05	22.33	24.88	27.42	29.96	32.49	35.02	.04
	Z			.8145	.8449	.8656	.8876	.9032	.9163	.9274	.9370	.9454	.9527	.9651	.9751	.9834	.9903	.9962	
.06	P			14.11	16.32	18.47	20.57	22.66	24.70	26.73	28.75	30.76	32.77	36.76	40.73	44.68	48.63	52.56	.06
	Z			.7299	.7738	.8083	.8361	.8590	.8783	.8947	.9089	.9213	.9322	.9506	.9655	.9776	.9882	.9971	
.08	P				19.89	22.90	25.84	28.74	31.60	34.43	37.24	40.04	42.82	48.36	53.87	59.36	64.83	70.30	.08
	Z				.7071	.7516	.7877	.8176	.8429	.8643	.8829	.8992	.9136	.9380	.9577	.9742	.9880	.9999	
.10	P				22.67	26.60	30.45	34.23	37.98	41.64	45.30	48.94	52.56	59.76	66.92	74.06	81.18	88.28	.10
	Z				.6448	.6965	.7425	.7839	.8206	.8532	.8592	.8793	.8972	.9273	.9519	.9724	.9897	1.005	
.12	P					29.67	34.47	39.18	43.83	48.44	53.00	57.54	62.06	71.05	79.98	88.88	97.76	106.6	.12
	Z					.6492	.7004	.7431	.7793	.8105	.8377	.8616	.8828	.9187	.9480	.9725	.9933	1.011	
.14	P					32.17	37.97	43.66	49.31	54.88	60.42	65.92	71.40	82.29	93.12	103.9	114.7	125.4	.14
	Z					.6034	.6614	.7100	.7515	.7872	.8185	.8460	.8704	.9120	.9461	.9746	.9988	1.022	
.16	P					34.18	41.04	47.78	54.45	61.06	67.62	74.14	80.64	93.57	106.4	119.3	132.0	144.8	.16
	Z					.5610	.6254	.6797	.7261	.7663	.8015	.8326	.8603	.9074	.9462	.9786	1.006	1.030	
.18	P					35.78	43.73	51.57	59.31	67.03	74.68	82.29	89.87	105.0	120.0	135.0	150.0	164.9	.18
	Z					.5220	.5924	.6521	.7033	.7476	.7868	.8214	.8522	.9049	.9483	.9847	1.016	1.042	
.20	P					36.83	45.96	55.03	64.03	72.97	81.84	90.66	99.41	116.8	134.0	151.1	168.0	184.9	.20
	Z					.4837	.5605	.6264	.6833	.7323	.7763	.8147	.8487	.9064	.9533	.9921	1.025	1.052	
.22	P					37.56	47.86	58.13	68.32	78.53	88.63	98.68	108.7	128.5	148.2	167.7	187.0	206.3	.22
	Z					.4485	.5306	.6018	.6632	.7170	.7644	.8062	.8435	.9067	.9583	1.001	1.037	1.067	
.24	P					38.12	49.62	61.15	72.65	84.12	95.53	106.9	118.2	140.6	162.9	185.0	206.9	228.8	.24
	Z					.4172	.5043	.5800	.6461	.7040	.7552	.8005	.8409	.9096	.9658	1.012	1.052	1.085	
.26	P					38.57	51.32	64.15	77.00	89.83	102.6	115.4	128.1	153.3	178.3	203.2	227.9	252.5	.26
	Z					.3897	.4815	.5617	.6321	.6941	.7489	.7976	.8411	.9153	.9760	1.028	1.069	1.105	
.28	P					38.99	53.03	67.03	81.00	95.73	110.0	124.3	138.4	166.7	194.7	222.5	250.1	277.6	.28
	Z					.3658	.4620	.5460	.6212	.6871	.7456	.7977	.8443	.9239	.9892	1.044	1.089	1.129	
.30	P					39.40	54.81	70.46	85.94	102.1	117.9	133.7	149.5	180.8	212.0	243.0	273.8	304.4	.30
	Z					.3450	.4456	.5347	.6139	.6834	.7455	.8010	.8506	.9357	1.006	1.064	1.113	1.155	
.35	P					40.64	59.95	79.14	98.00	120.0	140.3	160.5	180.8	221.1	261.2	301.1	340.8	380.3	.35
	Z					.3050	.4178	.5157	.5986	.6888	.7603	.8243	.8819	.9806	1.062	1.130	1.188	1.237	
.40	P					42.73	67.07	92.05	117.4	143.0	168.6	194.2	219.9	270.9	321.7	372.2	422.5	472.4	.40
	Z					.2806	.4090	.5239	.6283	.7179	.7996	.8728	.9383	1.051	1.144	1.222	1.288	1.344	
.45	P					47.31	78.29	109.9	142.0	174.1	206.3	238.5	270.7	334.6	398.2	461.3	524.1	586.5	.45
	Z					.2762	.4244	.5563	.6733	.7773	.8700	.9523	1.027	1.164	1.268	1.357	1.435	1.504	

11.006


PRESSURE, psia
20
30
40
60
80
100
200
300
400
600
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
COMPRESSIBILITY FACTOR, Z
90°K
100°K
110°
120°
130°
SATURATED VAPOR
POINT OF CONTACT
PLAIT POINT
120°K
SATURATED LIQUID
1
2
3
4
6
8
10
20
30
40
PRESSURE, atmospheres

11.006


PRESSURE, psia
300
400
600
800
1000
2000
3000
4000
6000
8000
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
COMPRESSIBILITY FACTOR, Z
220°
180°
300°K
160°
250°
120°
300°K
250°
220°
200°
190°
180°
170°
160°K
150°
140°
130°
120°K
120°
130°
POINT OF CONTACT
PLAIT POINT
COMPRESSIBILITY FACTOR
FOR AIR
Z = PV / RT
20
30
40
60
80
100
200
300
400
600
ESSURE, atmospheres

11.006

COMPRESSIBILITY FACTOR for AIR

$Z = PV/RT$

Source of Data:

Din, F.; Thermodynamic Functions of Gases, Vol. 2, Butterworths Scientific Publications, London (1956)

Other References:

Hilsenrath, J., et al.; Natl. Bur. Standards Cir. 564, 14-74 (1955)

Michels, A., Wassenaar, T., and Wolkers, G. J.; Appl. Sci. Res. A5, 121-136 (1954)

Michels, A., Wassenaar, T., Levelt, J. M., and De Graaff, W.; Appl. Sci. Res. A4, No. 5-6, 381-392 (1954)

Comments:

The compressibility factors were calculated from the values of pressure, volume and temperature reported in the correlation of thermodynamic properties by F. Din. The data used in the correlation by Din were taken primarily from the data by Michels and his co-workers. These more recent data by Michels, et al., according to Din, "... have a quite different order of accuracy and precision..." than the older data used in the correlation by Hilsenrath, et al., done prior to the availability of Michels' data.

A graphical comparison of the values from Din and from Hilsenrath is given in Figure 1. In addition, a comparison of Michels' values with the correlation by Din indicated that Din's smoothed values are an excellent representation of Michels' data. (Din has also used these P-V-T values to calculate thermodynamic properties, reported in another part of the Compendium.)

The P-V-T values are given in the diagrams as functions of the pressure in atmospheres ($g = 980.665$) and temperature in degrees Kelvin ($0°C = 273.15°K$). The properties of air were measured by the experimenters for a composition of air, excluding water vapor and carbon dioxide, but including argon and other inert gases.

The molecular weight for this mixture is considered as 28.96 and the ideal gas constant, $R = 2.8334$ cc atm/gm°K, (53.36 ft.-lb_f/lb_m°R).

These values are not the same as used by Hilsenrath, et al., in their correlation of the properties of air in the range of properties considered. The composition of air for the values reported in NBS Circular 564 included .03% carbon dioxide and a molecular weight of 28.966.

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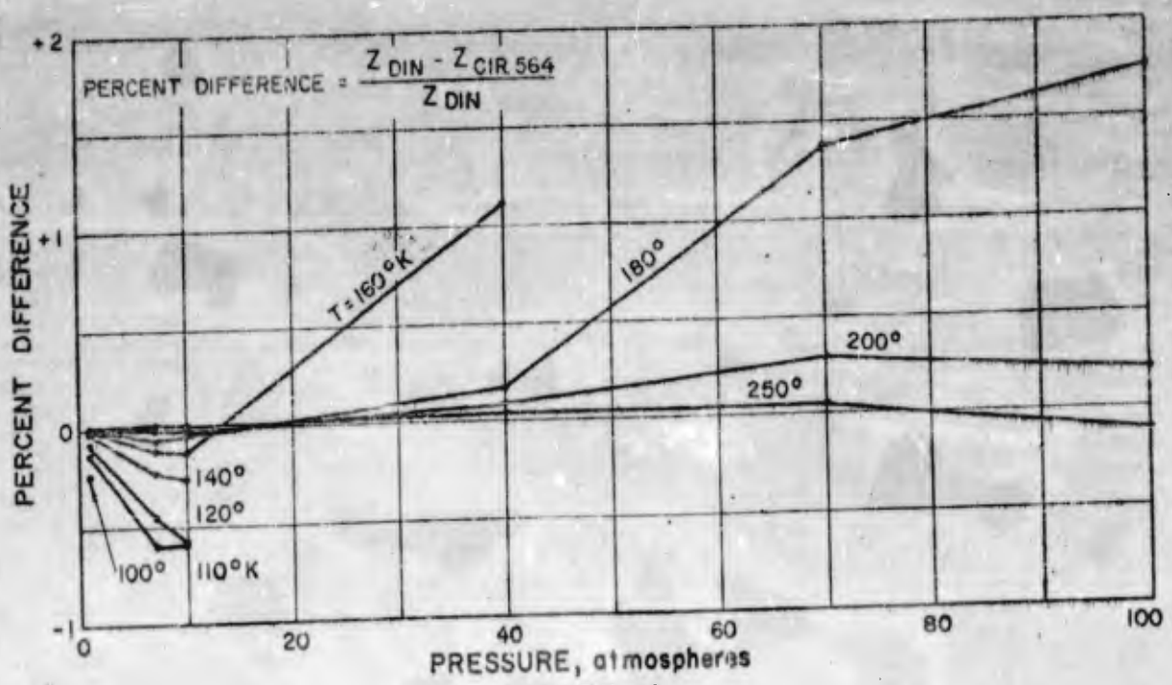

FIGURE 1

DIFFERENCE BETWEEN VALUES OF COMPRESSIBILITY FACTOR, Z FROM F. DIN AND NBS CIR 564.

Comments: (cont.)

It should be noted that the composition of air for these diagrams is constant and thus the points of intersections of the isobars or isotherms with the lines of saturated vapor and of saturated liquid, are not equilibrium states. In addition, a distinction must be made between two different critical points. These are the "plait point" (which may be determined by a plot of rectilinear diameters bisecting the isobars between the points of saturated vapor and liquid) and the "critical point of contact" (determined by rectilinear diameters bisecting the isotherms). The coordinates for these points are as follows:

Plait Point:

Temperature	132.42°K
Pressure (max.)	37.25 atm.
Compressibility Factor	0.3026

Point of Contact:

Temperature (max.)	132.52°K
Pressure	37.17 atm.
Compressibility Factor	0.3094

The possible errors in Din's determination of the smoothed P-V-T values are considered by Din to be negligible in the low pressure range, i.e., and accuracy of 1 part in 10,000 is claimed for Michel's work and the techniques employed by Din in interpolation should maintain this accuracy at low pressures. In the region of high pressures and densities, and also in the critical region at lower pressures, the possible error of interpolation is greater and Din estimates an accuracy to only three significant figures.

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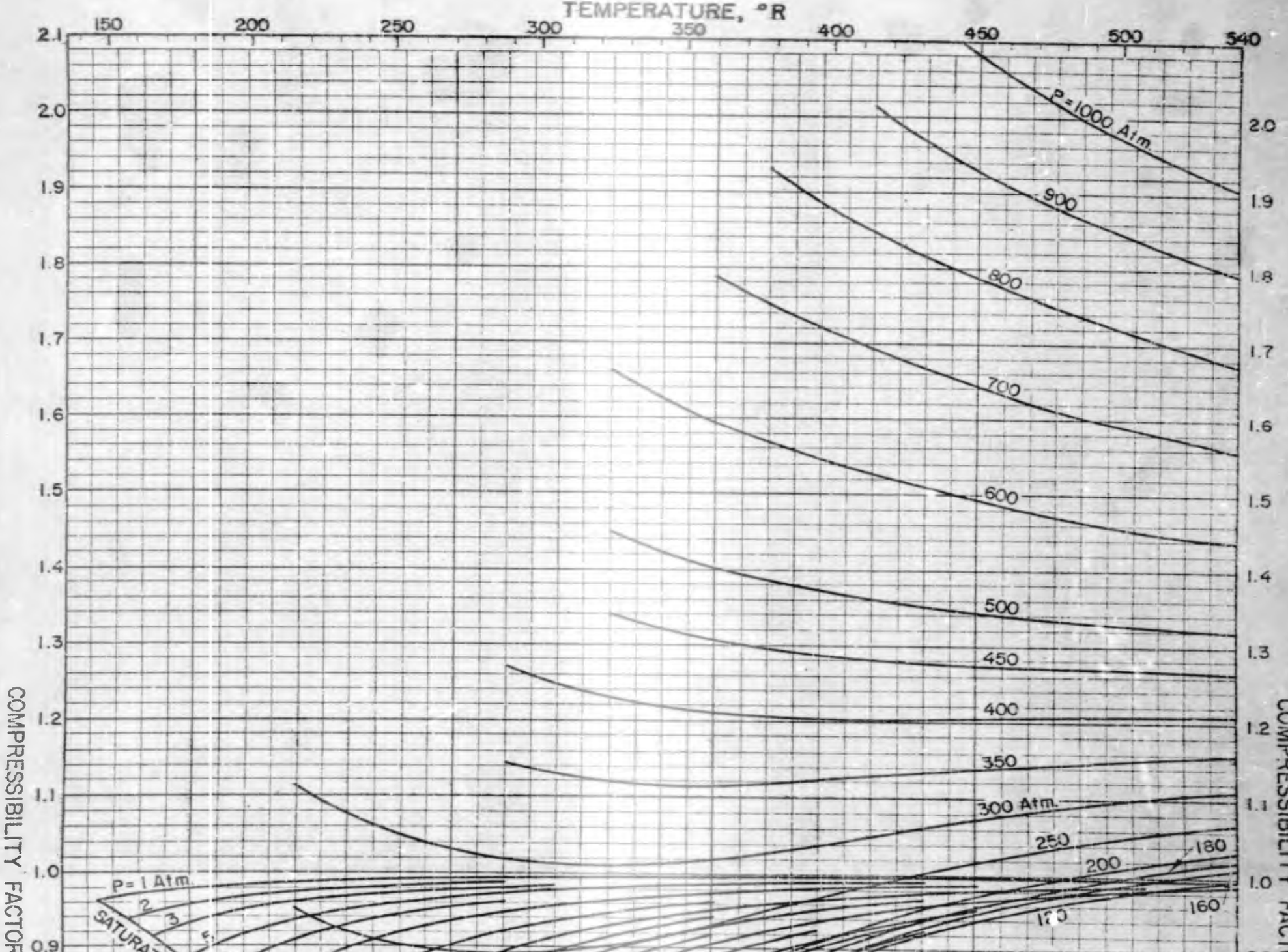
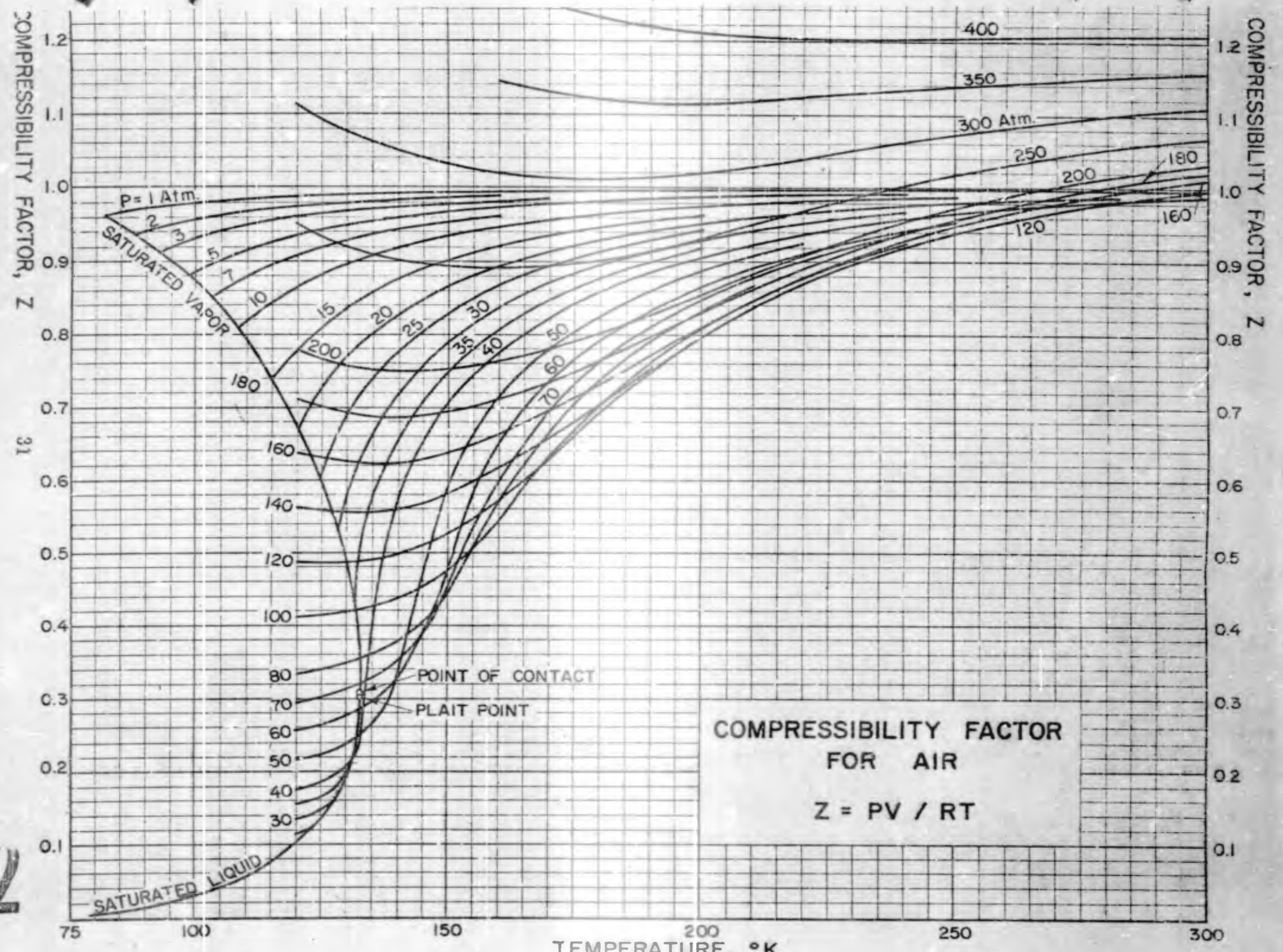

TEMPERATURE, °R
150
200
250
300
350
400
450
500
540
COMPRESSIBILITY FACTOR
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
P = 1000 Atm.
900
800
700
600
500
450
400
350
300 Atm.
250
200
180
160
140
P = 1 Atm.
2
3
SATURA


COMPRESSIBILITY FACTOR, Z
COMPRESSIBILITY FACTOR, Z
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
P = 1 Atm.
2
3
5
7
10
15
20
25
30
35
40
50
60
70
200
180
160
140
120
100
80
70
60
50
40
30
400
350
300 Atm.
250
200
180
160
120
SATURATED VAPOR
SATURATED LIQUID
POINT OF CONTACT
PLAIT POINT
COMPRESSIBILITY FACTOR
FOR AIR
Z = PV / RT
75
100
150
200
250
300
TEMPERATURE, °K

COMPRESSIBILITY FACTOR FOR AIR

Z = PV/RT (Cont.)

Comments: (cont.) The following tables were determined from Din's estimate of the probable errors.

* Percent Estimated Maximum Errors in Z of Gaseous Air

Pressure	Temperature °K				
atm.	120	130	140	160	200
1	± .02	± .01	0.0	0.0	0.0
20		± .07	± .04	0.0	0.0
30	±0.9	±0.25	±0.1	0.0	0.0
50	±1.0	±1.0	± .65	0.0	0.0
100	±1.0	±0.9	±0.6	±0.15	0.0
200	±1.0	±0.75	±0.5	±0.4	±0.15
500					±0.5

* Percent Estimated Maximum Errors in Z at the Saturation Boundary

	Pressure, Atmospheres				
	1	5	10	20	30
Liquid	0.6	0.55	0.5	0.65	0.7
Vapor	0.2	0.2	0.3	0.3	0.55

* Determined from Din's estimate of the probable errors.

The compressibility factors are illustrated by graphical presentation of Z vs P and Z vs T diagrams and by the following tabular values.

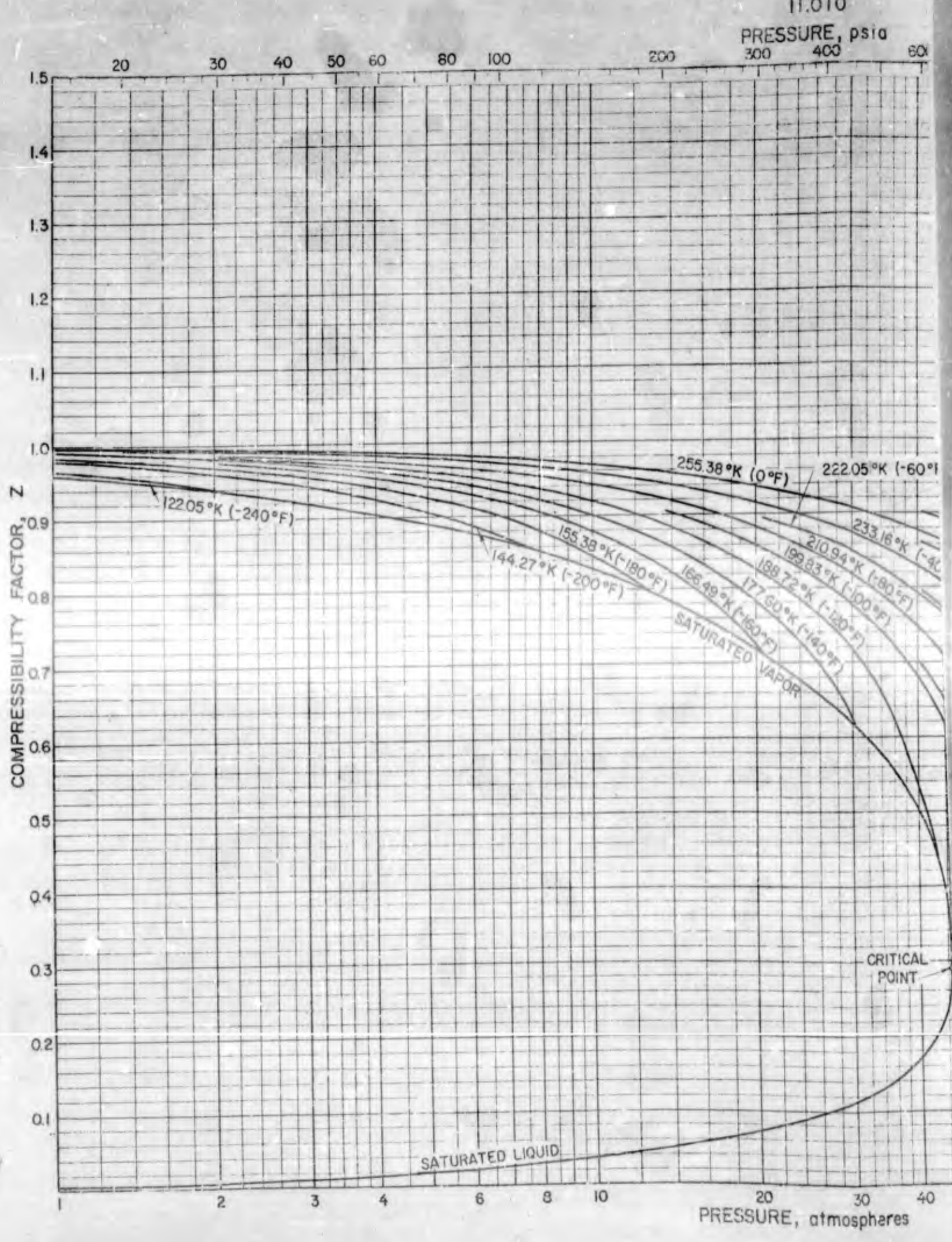
Volume and Compressibility Factors for Saturated Liquid and Vapor

Pressure	Saturated Liquid			Saturated Vapor		
	Temp.	V	Z	Temp.	V	Z
atm.	°K	cc/gm		°K	cc/gm	
1	78.80	1.144	.005 125	81.80	223.0	.9619
2	85.55	1.188	.009 798	88.31	117.0	.9354
3	90.94	1.222	.014 23	92.63	80.08	.9153
5	96.38	1.276	.023 35	98.71	49.30	.8813
7	101.04	1.319	.032 26	103.16	35.54	.8510
10	106.47	1.381	.045 78	108.35	24.81	.8080
15	113.35	1.492	.069 69	114.91	16.05	.7394
20	118.77	1.610	.095 69	120.07	11.41	.6707
25	123.30	1.739	.124 5	124.41	8.515	.6039
30	127.26	1.923	.160 0	128.12	6.443	.5325
35	130.91	2.241	.211 5	131.42	4.634	.4356
37.17	132.52	3.126	.309 4	132.52	3.126	.3094
37.25	132.42	3.048	.302 6	132.42	3.048	.3026

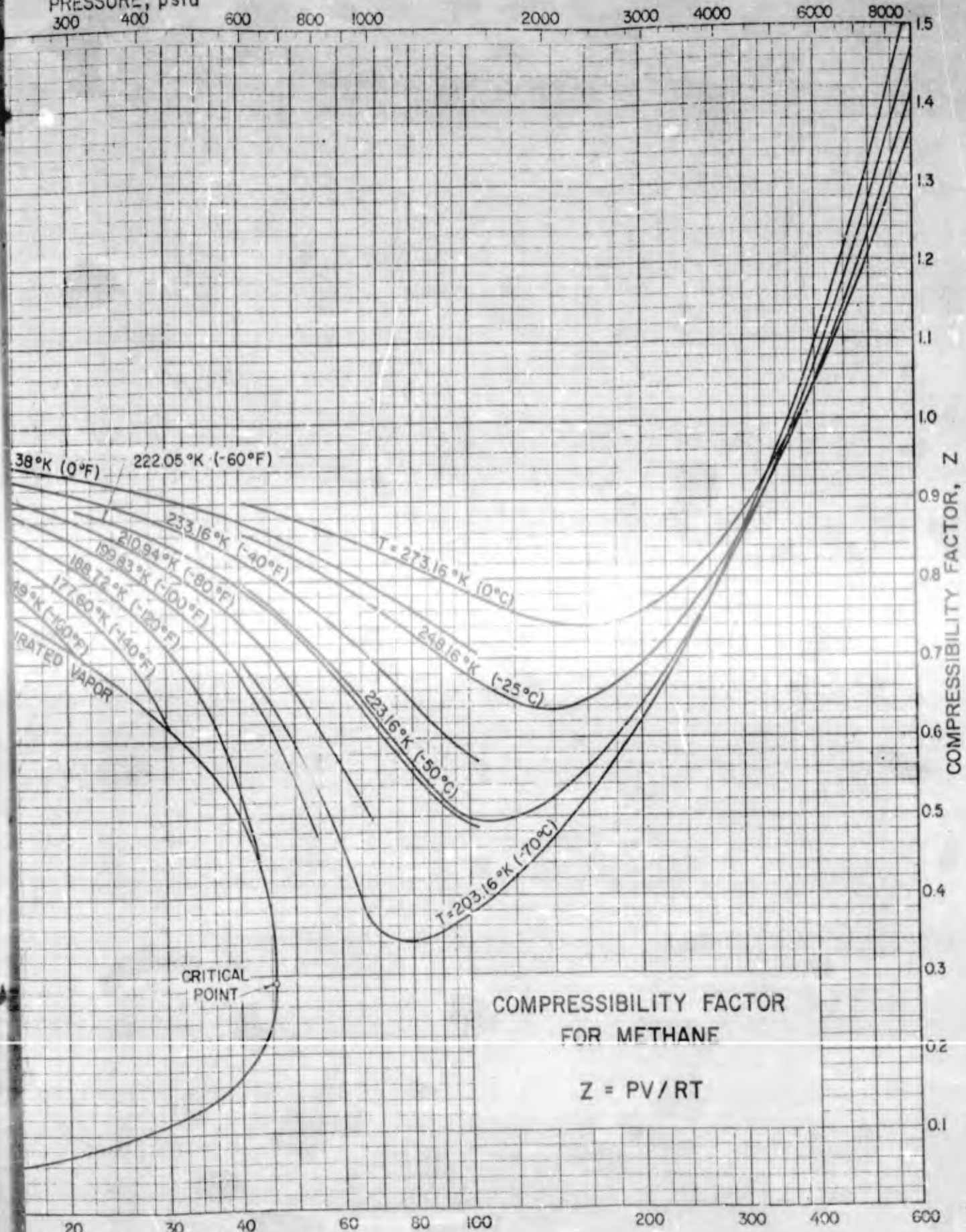
COMPRESSIBILITY FACTOR for GASEOUS AIR

[V Volume, (cc/gm); Z = Compressibility Factor]

Pressure atm.		Temperature °K										
		100	120	140	160	180	200	220	240	260	280	300
1	V	277.3	335.8	393.6	451.1	508.3	565.4	622.3	679.3	736.2	793.0	849,8
	Z	.9787	.9877	.9923	.9950	.9966	.9977	.9984	.9989	.9993	.9995	.9997
5	V	50.28	63.67	67.34	88.36	100.3	112.0	123.7	135.3	146.8	158.3	169.8
	Z	.8872	.9363	.8740	.9746	.9831	.9883	.9918	.9945	.9963	.9976	.9985
10	V		29.42	36.48	43.00	49.25	55.34	61.33	67.24	73.12	78.95	84.77
	Z		.8652	.9197	.9484	.9657	.9765	.9838	.9808	.9925	.9952	.9972
20	V			16.43	20.27	23.73	27.01	30.17	33.26	36.29	39.30	42.28
	Z			.8285	.8942	.9304	.9531	.9681	.9782	.9853	.9907	.9948
30	V		1.56	9.513	12.65	15.22	17.58	19.80	21.95	24.04	26.10	28.14
	Z		.138	.7195	.8372	.8951	.9305	.9531	.9682	.9790	.9869	.9930
40	V		1.51	5.691	8.812	10.97	12.87	14.63	16.31	17.93	19.52	21.08
	Z		.178	.5738	.7775	.8604	.9086	.9390	.9593	.9736	.9840	.9918
60	V		1.46	2.196	4.952	6.754	8.201	9.492	10.70	11.84	12.96	14,04
	Z		.257	.3322	.6554	.7946	.8683	.9137	94.39	.9646	.9798	,9908
80	V		1.43	1.88	3.23	4.724	5.915	7.276	7.925	8.929	9.696	1.053
	Z		.336	.380	.570	.7410	.8350	.9337	.9323	.9588	.9777	.9912
100	V		1.41	1.74	2.49	3.608	4.603	5.480	6.285	7.037	7.759	8,450
	Z		.413	.439	.549	.7075	.8122	.8791	.9242	.9552	.9780	,9940
120	V		1.39	1.65	2.18	2.97	3.778	4.530	5.221	5.870	6.485	7,072
	Z		.490	.500	.576	.699	.7999	.8721	.9213	.9562	.9809	,9983
140	V		1.37	1.59	2.00	2.59	3.24	3.885	4.482	5.048	5.587	6.102
	Z		.564	.562	.617	.710	.801	.8725	.9227	.9594	.9859	,1005
160	V		1.36	1.55	1.88	2.34	2.88	3.43	3.950	4.451	4.927	5.387
	Z		.639	.625	.664	.734	.812	.880	.9294	.9667	.9937	,1014
180	V		1.34	1.52	1.80	2.18	2.60	3.09	3.553	3.999	4.423	4.834
	Z		.711	.689	.713	.768	.832	.893	.9405	.9770	.1004	,1024
200	V		1.33	1.49	1.73	2.05	2.43	2.84	3.25	3.650	4.033	4.403
	Z		.782	752	.765	.804	.858	.911	.956	.9909	1.017	1.036
250	V		1.29	1.43	1.62	1.85	2.12	2.42	2.73	3.05	3.35	3.643
	Z		.952	.903	.893	.906	.934	.969	1.01	1.03	1.06	1,071
300	V		1.26	1.39	1.54	1.72	1.93	2.17	2.41	2.67	2.91	3.16
	Z		1.12	1.05	1.02	1.01	1.02	1.04	1.06	1.09	1.10	1.11
400	V				1.44	1.57	1.72	1.88	2.05	2.22	2.40	2.58
	Z				1.27	1.23	1.21	1.21	1.20	1.21	1.21	1.21
500	V					1.48	1.59	1.71	1.84	1.98	2.11	2.25
	Z					1.45	1.40	1.37	1.36	1.34	1.33	1.32
600	V					1.42	1.51	1.61	1.71	1.82	1.93	2.04
	Z					1.67	1.60	1.55	1.51	1.48	1.46	1,44
700	V						1.45	1.53	1.62	1.71	1.80	1,89
	Z						1.79	1.72	1.67	1.62	1.59	1.56
800	V							1.47	1.55	1.62	1.70	1,78
	Z							1.89	1.82	1.76	1.72	1.68
900	V								1.49	1.56	1.62	1,70
	Z								1.97	1.90	1.84	1.80
1000	V								1.45	1.50	1.56	1.62
	Z								2.13	2.04	1.97	1.91
1200	V									1.42	1.47	1.52
	Z									2.31	2.22	2.14


11.010
PRESSURE, psia
20
30
40
50
60
80
100
200
300
400
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
COMPRESSIBILITY FACTOR, Z
255.38°K (0°F)
222.05°K (-60°F)
233.16°K (-40
210.94°K (-80°F)
199.83°K (-100°F)
188.72°K (-120°F)
177.60°K (-140°F)
166.49°K (-160°F)
155.38°K (-180°F)
144.27°K (-200°F)
122.05°K (-240°F)
SATURATED VAPOR
CRITICAL POINT
SATURATED LIQUID
1
2
3
4
6
8
10
20
30
40
PRESSURE, atmospheres

11.010


PRESSURE, psia
300
400
600
800
1000
2000
3000
4000
6000
8000
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
COMPRESSIBILITY FACTOR, Z
38°K (0°F)
222.05°K (-60°F)
233.16°K (-40°F)
210.94°K (-80°F)
199.83°K (-100°F)
188.72°K (-120°F)
177.60°K (-140°F)
49°K (-160°F)
RATED VAPOR
T = 273.16°K (0°C)
248.16°K (-25°C)
223.16°K (-50°C)
T=203.16°K (-70°C)
CRITICAL POINT
COMPRESSIBILITY FACTOR
FOR METHANE
Z = PV/RT
20
30
40
60
80
100
200
300
400
600
ESSURE, atmospheres

35

2

11.010

COMPRESSIBILITY FACTOR for METHANE

$Z = PV/RT$

Sources of Data:

Matthews, C. S. and Hurd, C. O.; Trans. Am. Inst. Chem. Engrs. 42, 55-78 (1946)

Kvalnes, H. M. and Gaddy, V. L.; J. Am. Chem. Soc. 53, 394-399 (1931)

Rossini, F. D., et al.; Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds, Published for the American Petroleum Institute by Carnegie Press, Pittsburgh, Penn. (1953)

Comments:

The compressibility factors were calculated from the values of pressure, volume and temperature reported in the correlation of thermodynamic properties by Matthews and Hurd, for saturated liquid and vapor and for gaseous methane from saturation temperatures to 0°F and for pressures to 1500 psia. The second source of data by Kvalnes and Gaddy provided experimental values of the product PV which were used for determining compressibility factors for temperatures from -70° to 0°C and for pressures to 600 atmospheres. The values from these two references are presented on the graph of compressibility factor (Z), vs. pressures as isothermal lines (T = C), however, since the data are reported with temperatures in °F in one reference and °C in the other, there are no common isotherms. A graphical comparison was made, however, by cross-plotting the values in a range common to both references. This comparison indicated a satisfactory consistency for graphical presentation, i.e., an average difference of about 0.6% was observed, with a maximum difference of approximately 1.6%. In addition to these values, the P-V-T values at the critical point were taken from the more recent work reported by Rossini, et al.

The molecular weight for methane is 16.042 and the gas constants (R), used in the calculation of Z are:

$R = 10.7314$ (lbs/sq in)$(ft^3/lb\ mole)(°R)^{-1}$ Matthews and Hurd values

$R = 0.0036695$ (Amagat)$(°K)^{-1}$ Kvalnes and Gaddy values

The Amagat dimension used here for the PV product is defined as the ratio of the observed PV product to the PV product at standard conditions of 0°C and 1 atmosphere. The density at standard conditions used in these calculations is 0.7168 gm/liter.

Selected tabular values from these references are given in the tables on the following page.

(Continued on following page.)

SELECTED P-V-T VALUES OF METHANE

Matthews and Hurd

Selected Values of Specific Volume for Methane

Superheated Vapor Volumes, (cu.ft./lb.)

Press.	Temperature (°F)										
psia	-240°F	-200°F	-180°F	-160°F	-140°F	-120°F	-100°F	-80°F	-60°F	-40°F	0°F
10	14.39	17.15	18.52	19.87	21.28	22.62	23.97	25.33	26.69	28.02	30.72
20	7.04	8.47	9.17	9.86	10.56	11.25	11.94	12.61	13.29	13.97	15.32
30	4.60	5.57	6.06	6.53	6.99	7.45	7.91	8.37	8.83	9.28	10.19
40		4.12	4.49	4.85	5.21	5.56	5.91	6.25	6.60	6.94	7.63
60		2.678	2.934	3.184	3.429	3.670	3.91	4.14	4.37	4.60	5.06
80		1.954	2.153	2.348	2.539	2.725	2.903	3.080	3.255	3.432	3.78
100		1.518	1.684	1.847	2.002	2.155	2.301	2.444	2.588	2.729	3.014
150			1.052	1.172	1.283	1.391	1.495	1.597	1.695	1.793	1.989
200				0.830	0. 3	1.010	1.092	1.172	1.247	1.324	1.475
250				.621	.702	0.779	0.850	0.918	0.981	1.043	1.166
300					.553	.624	.687	.747	.802	0.856	0.961
400					.3614	.4267	.482	.532	.579	.623	.704
500						.3000	.3566	.402	.443	.481	.551
600						.1958	.2687	.3145	.3521	.386	.448
300							.1441	.1969	.2359	.2674	.3202
1000								.1262	.1650	.1957	.2438
1500									.0870	.1069	.1453

Matthews and Hurd

Saturated Liquid and Vapor Volumes for Methane

Temp.	Press.	Liquid Volume	Vapor Volume
°F	psia	cu.ft./lb.	cu.ft./lb.
-280	4.90	0.036 35	24.04
-270	8.44	.036 98	14.61
-260	13.80	.037 66	9.31
-250	21.71	.038 39	6.13
-240	32.4	.039 15	4.24
-230	46.4	.039 99	3.04
-220	64.5	.040 92	2.23
-200	115.7	.043 06	1.281
-180	191.5	.045 75	.773
-170	240.0	.047 45	.610
-160	297.0	.049 44	.483
-150	364	.051 97	.381
-140	440	.055 24	.3008
-130	527	.059 99	.2318
-120	627	.069 61	.1613

Kvalnes and Gaddy

Selected Values of PV for Methane

PV (Amagat)

Press.	Temperature			
atm.	-70°C	-50°C	-25°C	0°C
40	0.5244	0.6547	0.7873	0.9065
50	.4425	.6069		.8833
60	.3366	.5551	.7243	.8611
70	.2633	.5059		
80	.2556	.4604	.6551	.8199
90		.4266		
100	.2808	.4088	.6167	.7853
140	.3543	.4304	.5801	.7457
160	.3915	.4601	.5891	.7425
200	.4656	.5269	.6319	.7631
250	.5567	.6142	.7066	.8184
300	.6458	.7025	.7879	.8886
400	.8185	.8750	.9561	1.0468
500	.9867	1.0433	1.1221	1.2086
600	1.1487	1.2071	1.2862	1.3709

PV = 1 Amagat, at 0°C and 1 atm.

1 "PV Amagat" = 0.7168 $\frac{\text{liter atm.}}{\text{gm}}$

THERMAL CONDUCTIVITY INTEGRALS of SOLIDS at LOW TEMPERATURES

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Thermal Conductivity Integrals for Lithium, Sodium, Potassium Rubidium and Cesium 13.111

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Thermal Conductivity Integrals for Silver and Gold 13.112-2

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Thermal Conductivity Integrals for Lanthanum, Cerium, and Uranium. . 13.131

Thermal Conductivity Integrals for Aluminum, Callium, Indium and Thallium 13.132

Thermal Conductivity Integrals for Titanium, Zirconium and Hafnium . 13.141

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Thermal Conductivity Integrals for Vanadium, Niobium, and Tantalum . 13.151

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Thermal Conductivity Integrals for Chromium, Molybdenum and Tungsten 13.161

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(Continued)

PREFACE to the THERMAL CONDUCTIVITY INTEGRALS of SOLIDS at LOW TEMPERATURES

The thermal conducti ity integrals for metallic solids are presented in this section as a function of temperature for the range from 4 to 300°K. The thermal conductivity integral is defined from the Fourier equation for steady unidirectional conduction which is:

$$Q = \lambda A \frac{dT}{dL}$$

where:

Q = rate of heat conduction, negative in the direction of increasing length

λ = thermal conductivity

A = cross sectional area of the heat conduction path, and normal to the direction of heat flow

$\frac{dT}{dL}$ = temperature gradient along the path at the section under consideration

T = temperature

L = length

For a constant cross section area this may be reduced to:

$$Q \frac{L}{A} = \int_{T_1}^{T_2} \lambda \, dT$$

where T_1 and T_2 are the temperatures at any two points along the path of the heat flow.

The thermal conductivity integrals tabulated in this section are values of:

$$\int_{T_o}^{T_L} \lambda \, dT$$

where T_o and T_L are temperatures along a heat flow path communicating between heat reservoirs at $T_o = 4°K$ and T_L at length L from T_o. The heat flow along a conductor of constant cross section area A, through length L, may then be determined from the difference of the thermal conductivity integrals, i.e.,

$$Q \frac{L}{A} = \int_{T_1}^{T_2} \lambda \, dT = \int_{T_o}^{T_2} \lambda \, dT - \int_{T_o}^{T_1} \lambda \, dT$$

(Continued on following page)

THERMAL CONDUCTIVITY INTEGRALS

CONTENTS (Continued)

Thermal Conductivity Integrals for Aluminum Alloys 13.232

Thermal Conductivity Integrals for Nickel Alloys 13.281

Thermal Conductivity Integrals for Miscellaneous Alloys. 13.291

Thermal Conductivity Integrals for Ferrous Alloys. 13.301

Thermal Conductivity Integrals for Glasses and Plastics. 13.501

(In calculating the values of the thermal conductivity integrals presented in this section, a linear interpolation was assumed between the temperature intervals tabulated on the data sheets.)

The sources of data used are the data sheets from Chapter 3 of Phase I, Part II, of this Compendium. Reference should be made to these data sheets for information on documents used as sources of data and for comments on sample analysis, composition and treatment. The bibliography with the cross-references for this section will also be found in Phase I, Part III.

Of the metals included, five become superconducting above 4°K. These metals and their transition temperatures are:

Metals	Index	Transition Temperature *
Lanthanum	13.131	4.8, 5.8°K
Lead	13.142-3	7.22°K
Niobium	13.151	8.7 - 8.9°K
Tantalum	13.151	4.38°K
Vanadium	13.151	4.89°K

The values of the thermal conductivity for these metals below the superconducting transition temperatures are for the normal state rather than the superconducting state.

Several of the data sheets include extrapolated values, and are so noted on the individual data sheets. The extrapolations are based on the characteristics of the thermal conductivity curves of metals in the same series classification. The estimated deviation of the thermal conductivity integrals over the extrapolated range is not more than 10% from the probable values.

* American Institute of Physics Handbook, McGraw-Hill Book Co. Inc., New York (1957) sec. 4, p. 49

THERMAL CONDUCTIVITY INTEGRALS

for LITHIUM, SODIUM, POTASSIUM, RUBIDIUM and CESIUM

Source of Data: Data Sheet 3.111: Thermal Conductivity of Lithium, Sodium, Potassium, Rubidium, and Cesium.

Comments: The curves for Lithium, Sodium, Potassium, Rubidium, and Cesium were extrapolated to 300°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable value.

$$Q = \frac{A}{L}\int_{T_o}^{T_L} \lambda\, dT; \qquad Q\,\frac{L}{A} = \int_{T_o}^{T_L} \lambda\, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K					$\int_{T_o}^{T_L} \lambda\, dT$ watts/cm				
	Na	K	Li	Rb	Cs	Na	K	Li	Rb	Cs
4	47.	6.6	2.9	1.87	1.12					
6	42.5	7.0	4.0	1.70	.92	89.5	13.6	6.9	3.57	2.04
8	30.	5.8	5.0	1.37	.77	162	26.4	15.9	6.64	3.73
10	22.	4.6	5.9	1.08	.68	214	36.8	26.8	9.09	5.18
15	10.0	2.6	7.5	.75	.62	294	54.8	60.3	13.7	8.43
20	5.6	1.63	7.4	.67	.62*	333	65.4	97.6	17.2	11.5
25	3.6	1.3	6.4	.63	.62*	356	72.7	132	20.5	14.6
30	2.6	1.2	5.3	.62	.62*	372	79.0	161	23.6	17.7
35	2.2	1.15	4.3	.62	.62*	384	84.8	185	26.7	20.8
40	1.85	1.11	3.5	.61	.62*	394	90.5	205	29.8	23.9
50	1.6	1.10	2.5	.61	.62*	411	102	235	35.9	30.1
60	1.47	1.10	1.8	.61	.62*	426	112	256	42.0	36.3
70	1.40	1.10	1.40	.61	.62*	441	124	272	48.1	42.5
76	1.38	1.10	1.28	.61*	.62*	449	130	280	51.7	46.2
80	1.37	1.10	1.20	.61*	.62*	454	134	285	54.2	48.7
90	1.35	1.10	1.07	.61*	.62*	468	146	297	60.3	54.9
100	1.35*	1.10*	1.0	.61*	.62*	482	156	307	66.4	61.1
120	1.35*	1.10*	.92	.61*	.62*	508	178	326	72.5	73.5
140	1.35*	1.10*	.87*	.61*	.62*	536	200	344	84.7	85.9
160	1.35*	1.10*	.85*	.61*	.62*	562	222	361	96.9	98.3
180	1.35*	1.10*	.83*	.61*	.62*	590	244	378	109	101
200	1.35*	1.10*	.80*	.61*	.62*	616	266	394	121	123
250	1.35*	1.10*	.78*	.61*	.62*	684	322	434	152	154
300	1.35*	1.10*	.75*	.61*	.62*	752	377	472	182	185

* Extrapolated Values

RLP/EGP/JRK/ALB Issued: 1-11-60

THERMAL CONDUCTIVITY INTEGRALS

for COPPERS

Source of Data: Data Sheet 3.112-1: Thermal Conductivity of Coppers.

Comments: The six curves were extrapolated to 300°K. The curve for O.F.H.C. was extrapolated to 4°K and the curve for (Pb)Cu was extrapolated to 6°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (6°K for [Pb]Cu and [Te]Cu; 4°K for all other Coppers)

Thermal Conductivity Integrals are on following page.

Temp. °K	Thermal Conductivity watts/cm-°K					
	Hi-Purity Annealed	Coalesced	Elect. T.P.	O.F.H.C.	(Pb) Cu	(Te) Cu
4	70	6.2	3.2	2.4*		
6	96	10.	4.8	3.7*	2.7*	2.2
8	120	14.	6.3	4.7*	3.6*	2.8
10	134	17.5	7.8	6.0*	4.5*	3.4
15	120	23	11	8.5*	6.3*	5.0
20	88	24	13	11 *	8 *	6.5
25	60	23	14	12	9.2	7.3
30	40	22	14	12	9.6	7.8
35	28	18.5	13	11	9.5	7.9
40	20	15	11.5	10	9	7.7
50	12	10	8.8	7.7	6.9	6.8
60	8.0	7.8	7.0	6.2	5.5	5.8
70	6.2	6.5	5.9	5.5	4.7	5,2
76	5.7	6.0	5.5	5.2	4.5	4.9
80	5.2	5.7	5.2	4.9	4.3	4.6
90	4.7	5.1	4.7	4.7	4.0*	4.3
100	4.5	4.8	4.5	4.5	3.8*	4.2
120	4.3	4.5	4.3	4.3	3.7*	4.0
140	4.2	4.3	4.2	4.2	3.6*	3.8
160	4.1	4.2	4.1	4.1	3.6*	3.8
180	4.0	4.2	4.0	4.0	3.6*	3.8
200	4.0	4.2	4.0	4.0	3.6*	3.8
250	4.0	4.2*	4.0	4.0	3.6*	3.8*
300	4.0*	4.2*	4.0*	4.0*	3.6*	3.8*

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for COPPERS (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm					
	Hi-Purity Annealed	Coalesced	Elect. T.P.	O.F.H.C.	(Pb) Cu	(Te) Cu
6	166	16.2	8.00	6.1		
8	382	40.2	19.1	14.5	6.3	5
10	636	71.7	33.2	25.2	14.4	11.2
15	1270	173	80.2	61.4	41.4	32.2
20	1790	290	140	110	77.2	60.9
25	2160	408	208	168	120	95.4
30	2410	520	278	228	167	133
35	2580	622	345	285	215	172
40	2700	705	406	338	261	211
50	2860	830	508	426	341	284
60	2960	919	587	496	403	347
70	3030	991	651	554	454	402
76	3070	1030	686	586	481	432
80	3090	1050	707	606	499	451
90	3140	1100	756	654	540	496
100	3180	1160	802	700	579	538
120	3270	1250	891	788	654	620
140	3360	1340	976	874	727	698
160	3440	1420	1060	956	799	774
180	3520	1510	1140	1040	871	850
200	3600	1590	1220	1120	943	926
250	3800	1800	1420	1320	1120	1120
300	4000	2000	1620	1520	1300	1310

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THERMAL CONDUCTIVITY INTEGRALS

for SILVER and GOLD

Source of Data: Data Sheet 3.112-2: Thermal Conductivity of Silver and Gold.

Comments: The curve for Silver 2 was extrapolated to 300°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm			
	Ag 1	Au 1	Au 2	Ag 2	Ag 1	Au 1	Au 2	Ag 2
4	140	17	1.2	.42				
6	180	24	1.9	.68	320	41.0	3.1	1.1
8	170	28	2.6	.95	670	93.0	7.6	2.73
10	150	28	3.2	1.3	990	149	13.4	4.98
15	98	22	4.2	1.8	1610	274	31.9	12.7
20	52	14	4.4	2.3	1980	364	53.4	23.0
25	29	10	4.3	2.5	2190	424	75.2	35.0
30	18	7.3	4.0	2.8	2310	467	95.9	48.2
35	13	5.9	3.8	2.9	2380	500	115	62.5
40	9.5	5.0	3.6	2.9	2440	528	134	77.0
50	6.3	4.0	3.2	2.9	2520	573	168	106
60	5.0	3.8	3.1	2.9	2570	612	199	135
70	4.5	3.5	3.1	2.9	2620	648	230	164
76	4.3	3.4	3.1	3.0	2650	669	249	182
80	4.2	3.3	3.1	3.1	2670	682	261	194
90	4.1	3.3	3.1	3.1	2710	715	292	224
100	4.1	3.2	3.1	3.2	2750	748	323	256
120	4.1	3.2	3.1	3.3	2830	812	385	321
140	4.1	3.2	3.1	3.5*	2910	876	447	389
160	4.1	3.1	3.1	3.7*	2990	939	509	461
180	4.1	3.1	3.1	3.8*	3080	1000	571	536
200	4.1	3.1	3.1	3.8*	3160	1060	633	612
250	4.1	3.1	3.1	3.8*	3360	1220	788	802
300	4.1	3.1	3.1	3.8*	3570	1370	943	992

* Extrapolated Values

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THERMAL CONDUCTIVITY INTEGRALS
for BERYLLIUM and MAGNESIUM

Source of Data: Data Sheet No. 3.121: Thermal Conductivity of Beryllium and Magnesium.

Comments: The four curves were extrapolated to 300°K and the curve for Beryllium 1 was also extrapolated to 4°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K for Beryllium 1, Magnesium 1 and Magnesium 2; 20°K for Beryllium 2)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm			
	Be 1	Mg 1	Mg 2	Be 2	Be 1	Mg 1	Mg 2	Be 2
4	10 *	4.7	2.8		26	12.5	7.1	
6	16 *	7.8	4.3		64	30.7	17.2	
8	22 *	10.4	5.8		111	53.1	30	
10	25 *	12	7.0		244	119	70.7	
15	28 *	14.2	9.3		388	189	119	
20	30 *	14	10	.59	534	254	167	3.28
25	28	12	9.3	.72	671	308	210	7.2
30	27	9.5 *	7.8	.85	804	350	246	11.8
35	26	7.5 *	6.4	.98	931	385	275	17.0
40	25	6.3 *	5.3	1.1	1170	439	320	29.2
50	23	4.5 *	3.8	1.35	1390	479	353	44.0
60	20	3.5 *	2.8	1.6	1580	510	379	61.0
70	18.4	2.8 *	2.3	1.8	1680	527	392	72.1
76	17.5	2.6 *	2.1	1.9	1750	538	400	79.9
80	16.5	2.5 *	1.9	2.0	1910	560	418	101
90	15.0	2.2 *	1.78	2.3	2050	581	436	125
100	13.5	1.9 *	1.70	2.5	2300	617	469	176
120	11.5*	1.7 *	1.63	2.6	2520	650	501	226
140	10.0*	1.63*	1.61	2.4 *	2700	682	534	272
160	8.5*	1.61*	1.61*	2.2 *	2860	715	566	313
180	7.3*	1.61*	1.61*	1.9 *	3000	747	598	350
200	6.5*	1.61*	1.61*	1.75*	3290	827	678	429
250	5.0*	1.61*	1.61*	1.4 *	3520	908	759	492
300	4.0*	1.61*	1.61*	1.15*				

* Extrapolated Values

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THERMAL CONDUCTIVITY INTEGRALS

for ZINC and CADMIUM

Source of Data: Data Sheet No. 3.122: Thermal Conductivity of Zinc and Cadmium. Mercury values were omitted due to lack of sufficient data.

Comments: The curves for Zinc and Cadmium were extrapolated to 4°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm	
	Cadmium	Zinc	Cadmium	Zinc
4	170*	4.3*		
6	48.0	8.1	218	12.4
8	19.0	10.5	285	31
10	10.0	11.5	314	53
15	3.7	8.8	348	104
20	2.2	6.6	363	142
25	1.75	4.8	373	171
30	1.50	3.5	381	192
35	1.40	2.70	388	207
40	1.30	2.20	395	219
50	1.25	1.70	408	239
60	1.20	1.45	420	254
70	1.15	1.40	432	269
76	1.13	1.37	438	277
80	1.10	1.35	443	282
90	1.08	1.32	454	296
100	1.05	1.30	465	309
120	1.03	1.30	485	335
140	.99	1.30	506	361
160	.97	1.30	525	387
180	.96	1.30	544	413
200	.95	1.30	564	439
250	.95	1.30	611	504
300	.95	1.30	659	569

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS
for LANTHANUM†, CERIUM and URANIUM

Source of Data: Data Sheet 3.131: Thermal Conductivity of Lanthanum, Cerium, and Uranium.

Comments: The curves for Lanthanum, Cerium and Uranium were extrapolated to 300°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

where:

Q = heat flow in watts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in watts/cm-°K
T = temperature in °K
T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm		
	Uranium	Lanthanum	Cerium	Uranium	Lanthanum	Cerium
4	.045	.0062	.0045			
6	.066	.0098	.0064	.111	.016	.011
8	.084	.0132	.0083	.261	.039	.026
10	.10	.017	.0101	.445	.069	.044
15	.135	.025	.0145	1.03	.174	.106
20	.158	.033	.019	1.76	.319	.189
25	.170	.039	.023*	2.58	.499	.294
30	.177	.045	.028*	3.45	.709	.422
35	.180	.050	.030*	4.34	.947	.567
40	.180	.055	.034*	5.24	1.21	.727
50	.181	.063*	.040*	7.05	1.80	1.10
60	.191	.070*	.047*	8.91	2.46	1.53
70	.220	.078*	.052*	11.0	3.20	2.03
76	.230	.081*	.054*	12.3	3.68	2.34
80	.240	.085*	.056*	13.2	4.01	2.56
90	.27	.091*	.060*	15.8	4.89	3.14
100	.29*	.098*	.065*	18.6	5.84	3.77
120	.31*	.108*	.072*	24.6	7.90	5.14
140	.34*	.115*	.078*	31.1	10.1	6.64
160	.37*	.122*	.083*	38.2	12.5	8.25
180	.40*	.13 *	.087*	45.9	15.0	9.95
200	.42*	.135*	.090*	54.1	17.7	11.7
250	.45*	.150*	.100*	75.8	24.8	16.5
300	.47*	.150*	.105*	98.8	32.3	21.6

* Extrapolated Values

† See second page of the preface.

THERMAL CONDUCTIVITY INTEGRALS

for ALUMINUM, GALLIUM, INDIUM and THALLIUM

Source of Data: Data Sheet 3.132: Thermal Conductivity of Aluminum, Gallium, Indium and Thallium.

Comments: The curves for Aluminum-1, Gallium, Indium and Thallium have been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Thermal Conductivity Integrals are on following page.

Temp. °K	Thermal Conductivity watts/cm-°K				
	Aluminum-1	Aluminum-2	Gallium	Indium	Thallium
4	31.5	.54	24.0	8.4	9.8
6	42	.84	26.0	8.2	4.4
8	52	1.2	28.0	6.3	2.3
10	60	1.45	23	4.4	1.5
15	68	2.2	12	2.4	.92
20	55	2.75	6.3	1.8	.72
25	39	3.2	4.2	1.45	.62
30	28.5	3.5	3.2	1.2	.57
35	21	3.75	2.6	1.1 *	.52
40	16	3.8	2.35	1.0 *	.505*
50	9.5	3.75	2.1 *	.9 *	.47 *
60	6.6	3.4	1.85*	.84*	.46 *
70	4.95	3.1	1.8 *	.8 *	.44 *
76	4.3	2.9	1.75*	.79*	.42 *
80	3.9	2.8	1.7 *	.77*	.42 *
90	3.35	2.6	1.65*	.73*	.42 *
100	3.0	2.4	1.55*	.72*	.42 *
120	2.7	2.3	1.50*	.70*	.40 *
140	2.5	2.2	1.4 *	.69*	.39 *
160	2.4	2.2	1.4 *	.68*	.39 *
180	2.35	2.2	1.4 *	.67*	.38 *
200	2.35	2.2	1.4 *	.66*	.38 *
250	2.35*	2.2	1.4 *	.66*	.38 *
300	2.35*	2.2	1.4 *	.66*	.38 *

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for ALUMINUM, GALLIUM, INDIUM and THALLIUM (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm				
	Aluminum-1	Aluminum-2	Gallium	Indium	Thallium
6	73.5	1.38	52	16.6	14.2
8	168	3.42	108	31.1	20.9
10	280	6.07	159	41.8	24.7
15	600	15.2	246	58.8	30.8
20	907	27.6	292	69.3	34.8
25	1140	42.4	318	77.4	38.2
30	1310	59.2	337	84.0	41.2
35	1430	77.3	352	89.8	43.9
40	1530	96.2	364	95.0	46.5
50	1650	134	386	104	51.3
60	1740	170	406	113	56.0
70	1790	202	424	121	60.5
76	1820	220	435	126	63.1
80	1840	232	442	129	64.7
90	1870	258	458	137	68.9
100	1900	284	474	144	73.1
120	1960	330	505	158	81.3
140	2010	376	534	172	89.2
160	2060	420	562	186	97.0
180	2110	464	590	199	105
200	2160	508	618	213	112
250	2270	618	688	246	131
300	2390	728	758	279	150

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THERMAL CONDUCTIVITY INTEGRALS
for TITANIUM, ZIRCONIUM and HAFNIUM

Source of Data: Data Sheet 3.141: Thermal Conductivity of Titanium, Zirconium and Hafnium.

Comments: The curves for Titanium, Zirconium and Hafnium have been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm		
	Zirconium	Titanium	Hafnium	Zirconium	Titanium	Hafnium
4	.120	.046	.036			
6	.180	.069	.058	.3	.115	.094
8	.24	.093	.079	.72	.277	.231
10	.29	.118	.10	1.25	.488	.410
15	.38	.172	.147	2.93	1.21	1.03
20	.44	.225	.18	4.98	2.20	1.84
25	.47	.28	.20	7.25	3.47	2.80
30	.46	.32	.22	9.58	4.97	3.84
35	.44	.34	.23	11.8	6.62	4.97
40	.40	.35	.24	13.9	8.34	6.08
50	.35*	.36	.25	17.7	11.9	8.53
60	.32*	.36	.25	21.0	15.5	11.0
70	.29*	.36	.26	24.1	19.1	13.6
76	.27*	.35	.26	25.8	21.2	15.1
80	.26*	.35	.27	26.8	22.6	16.2
90	.24*	.35	.27	29.3	26.1	18.9
100	.23*	.35	.27*	31.7	29.6	21.6
120	.22*	.35*	.27*	36.2	36.6	27.0
140	.22*	.35*	.27*	40.7	43.6	32.4
160	.21*	.35*	.27*	45.0	50.6	37.8
180	.21*	.35*	.27*	49.2	57.6	43.2
200	.21*	.35*	.27*	53.4	64.6	48.6
250	.21*	.35*	.27*	63.9	82.1	62.1
300	.21*	.35*	.27*	74.4	99.6	75.6

* Extrapolated Values

13.142-1

THERMAL CONDUCTIVITY INTEGRALS
for CARBONS

Source of Data: Data Sheet 3.142-1: Thermal Conductivity of Carbons.

Comments: The curve for Natural Graphite was extrapolated to 4°K; Pyrolytic Graphite to 6°K; and the curves for Pitch Bonded Graphite and Carbon Resistor to 10°K. The curve for Carbon Resistor was also extrapolated to 300°K on the upper end. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature given for each Carbon

Thermal Conductivity Integrals are on following page.

Temp. °K	Thermal Conductivity watts/cm-°K			
	Natural Graphite	Pitch Bonded Graphite	Pyrolytic Graphite	Carbon Resistor
4	.055*			
6	.13 *		.0013*	
8	.25		.0021	
10	.40	.0012*	.003	.0009*
15	.90	.005	.0073	.0018
20	1.60	.013	.011	.0029
25	2.5	.025	.016	.004
30	3.4	.038	.022	.005
35	4.0	.050	.030	.006
40	5.0	.069	.038	.007
50	5.9	.10	.056	.0085
60	6.2	.14	.078	.010
70	6.2	.19	.10	.011
76	6.1	.21	.12	.012
80	6.0	.24	.13	.0125
90	5.8	.29	.14	.013
100	5.5	.34	.15	.0135
120	4.8	.43	.18	.014*
140	4.0	.50	.19	.014*
160	3.5	.54	.21	.015*
180	3.0	.58	.23	.015*
200	2.6	.59	.24	.015*
250	1.8	.59	.27	.015*
300	1.4	.58	.29	.015*

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for CARBONS (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm			
	Natural Graphite	Pitch Bonded Graphite	Pryolytic Graphite	Carbon Resistor
6	.185			
8	.565		.00340	
10	1.22		.00850	
15	4.46	.0155	.0342	.00675
20	10.7	.0605	.080	.0185
25	21.0	.156	.148	.0358
30	35.7	.313	.242	.0582
35	54.2	.533	.372	.0558
40	76.7	.830	.542	.118
50	131	1.68	1.01	.196
60	192	2.88	1.68	.288
70	254	4.52	2.57	.393
76	291	5.72	3.23	.462
80	315	6.62	3.73	.511
90	374	9.28	5.08	.639
100	430	12.4	6.53	.771
120	533	20.1	9.83	1.05
140	621	29.4	13.5	1.31
160	696	39.8	17.5	1.62
180	761	51.0	21.9	1.92
200	817	62.7	26.6	2.22
250	927	92.2	39.4	2.97
300	1010	121	53.4	3.72

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THERMAL CONDUCTIVITY INTEGRALS
for SILICON and GERMANIUM

Source of Data: Data Sheet 3.142-2: Thermal Conductivity of Silicon and Germanium.

Comments: The curves for Silicon and Germanium were extrapolated to 300°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm	
	Silicon	Germanium	Silicon	Germanium
4	1.3	2.5		
6	3.0	5.0	4.30	7.50
8	5.3	7.5	12.6	20.0
10	7.5	9.5	25.4	37.0
15	11.4	12.5	72.6	92.0
20	12.5	12.0	132	153
25	12.5	10.4	195	209
30	12.0	8.8	256	257
35	11.2	7.4	314	298
40	10.4	6.4	368	332
50	9.0	4.9	465	389
60	7.8	3.9	549	433
70	6.8	3.25	622	468
76	6.5	2.9	662	487
80	6.2	2.7	687	498
90	5.5	2.3	746	523
100	5.0	2.0	798	545
120	4.3	1.63	891	581
140	3.8	1.35	972	611
160	3.3	1.18	1040	636
180	3.0	1.06*	1110	658
200	2.8	.95*	1160	679
250	2.3*	.80*	1290	722
300	2.0*	.70*	1400	760

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for TIN and LEAD†

Source of Data: Data Sheet 3.142-3: Thermal Conductivity of Tin and Lead.

Comments: The curve for Tin was extrapolated to 300°K; the curve for Lead was extrapolated to 4°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

Q = heat flow in watts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in watts/cm-°K
T = temperature in °K
T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm	
	Tin	Lead	Tin	Lead
4	25	20*		
6	24	7.0	48.0	27.0
8	14.9	3.3	86.0	37.3
10	9.1	1.8	110	42.4
15	4.0	.82	143	49.0
20	2.5	.59	159	52.5
25	2.2	.5	171	55.2
30	2.0	.47	181	57.6
35	1.9	.44	191	59.9
40	1.9*	.42	201	63.3
50	1.9*	.40	220	69.9
60	1.9*	.38	239	73.8
70	1.9*	.38	258	77.6
76	1.9*	.37	269	79.9
80	1.9*	.37	277	81.3
90	1.8*	.37	295	85.0
100	1.8*	.36	313	88.7
120	1.8*	.36	349	95.9
140	1.8*	.36	385	103
160	1.8*	.36	421	110
180	1.8*	.36	457	117
200	1.8*	.35	493	125
250	1.8*	.35	583	142
300	1.8*	.35	673	160

* Extrapolated Values † See second page of the preface.

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THERMAL CONDUCTIVITY INTEGRALS†
for VANADIUM, NIOBIUM and TANTALUM

Source of Data: Data Sheet 3.151: Thermal Conductivity of Vanadium, Niobium and Tantalum.

Comments: The curves for Vanadium, Niobium and Tantalum have been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm		
	Niobium	Tantalum	Vanadium	Niobium	Tantalum	Vanadium
4	.26	.15	.021			
6	.36	.23	.034	.620	.380	.055
8	.46	.30	.048	1.44	.910	.137
10	.55	.38	.062	2.45	1.59	.247
15	.72	.55	.093	5.62	3.92	.634
20	.84	.63	.120	9.52	6.86	1.17
25	.88	.68	.143	13.8	10.1	1.82
30	.87	.67	.164	18.2	13.5	2.59
35	.80	.65	.180	22.4	16.8	3.45
40	.74	.63	.196	26.2	20.0	4.39
50	.65	.60	.215	33.2	26.2	6.45
60	.58	.60	.225	39.3	32.2	8.65
70	.54	.60	.23	44.9	38.2	10.9
76	.53	.60	.235	48.1	41.8	12.3
80	.52	.60	.24	50.2	44.2	13.3
90	.51	.61	.245	55.4	50.2	15.7
100	.51*	.61	.245*	60.5	56.3	18.1
120	.50*	.61*	.245*	70.6	68.5	23.0
140	.50*	.62*	.245*	80.6	80.8	27.9
160	.50*	.63*	.25 *	90.6	93.3	32.9
180	.50*	.65*	.25 *	101	106	37.9
200	.50*	.66*	.25 *	110	119	42.9
250	.50*	.68*	.25 *	136	153	55.4
300	.50*	.69*	.25 *	160	187	67.9

* Extrapolated Values

† See second page of the preface.

THERMAL CONDUCTIVITY INTEGRALS

for ANTIMONY and BISMUTH

Source of Data: Data Sheet 3.152: Thermal Conductivity of Antimony and Bismuth.

Comments: The Thermal Conductivity curve for Antimony was extrapolated to 300°K; the curve for Bismuth was extrapolated to 4°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm	
	Bismuth	Antimony	Bismuth	Antimony
4	1.0*	.65		
6	2.0*	1.55	2.90	2.20
8	3.2*	2.4	8.00	6.10
10	4.5*	3.0	15.7	11.5
15	8.5*	3.9	48.2	28.7
20	10.3	3.8	95.2	48.0
25	8.0	3.6	141	66.4
30	6.7	3.5	178	84.2
35	5.7	3.4	209	101
40	5.0	3.3*	235	118
50	3.7	3.2*	279	151
60	3.0	3.1*	312	182
70	2.4	3.0*	339	213
76	2.2	3.0*	353	231
80	2.0	2.9*	362	242
90	1.8	2.9*	381	271
100	1.65	2.8*	398	300
120	1.47	2.7*	429	355
140	1.35	2.7*	457	409
160	1.3	2.7*	484	463
180	1.23	2.6*	509	516
200	1.2	2.6*	533	568
250	1.14	2.6*	592	698
300	1.09	2.6*	648	828

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for CHROMIUM, MOLYBDENUM and TUNGSTEN

Source of Data: Data Sheet 3.161: Thermal Conductivity of Chromium, Molybdenum and Tungsten.

Comments: The curve for Chromium was extrapolated to 300°K; the curve for Tungsten was extrapolated to 4°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm		
	Cr	Mb	W	Cr	Mb	W
4	1.62	.62	46*			
6	2.5	.90	67*	4.12	1.52	119
8	3.3	1.20	83*	9.92	3.62	282
10	4.0	1.50	100*	17.2	6.32	472
15	5.1	2.25	86	40.0	15.7	937
20	5.6	2.9	54	66.7	28.6	1290
25	5.7	3.4	28	95.0	44.3	1500
30	5.4	3.7	15	123	62.1	1600
35	5.0	3.75	9.0	149	80.7	1660
40	4.2	3.6	6.5	172	99.1	1700
50	3.2	3.2	4.2	209	133	1760
60	2.4	2.7	3.3	238	163	1790
70	2.0	2.3	2.8	260	188	1820
76	1.9	2.2	2.6	272	201	1840
80	1.8	2.1	2.5	280	210	1850
90	1.65	1.86	2.3	297	229	1880
100	1.53	1.74	2.2	313	247	1900
120	1.40	1.57	1.93	342	281	1940
140	1.35	1.47	1.85	370	311	1980
160	1.32*	1.41	1.80	396	340	2010
180	1.30*	1.40	1.78	422	368	2050
200	1.30*	1.38	1.76	448	396	2080
250	1.25*	1.37	1.70	512	464	2170
300	1.25*	1.37	1.70	575	533	2260

* Extrapolated Values

13.171

THERMAL CONDUCTIVITY INTEGRALS

for MANGANESE and RHENIUM

Source of Data: Sheet 3.171: Thermal Conductivity of Manganese and Rhenium.

Comments: The curves for Manganese and Rhenium were extrapolated to 300°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

Q = heat flow in watts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in watts/cm-°K
T = temperature in °K
T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm	
	Manganese	Rhenium	Manganese	Rhenium
4	.0094	7.0		
6	.0125	10.0	.0219	17.0
8	.0150	12.5	.0494	39.5
10	.0170	14.0	.0814	66.0
15	.021	13.0	.176	134
20	.025	8.5	.291	187
25	.028	5.0	.424	221
30	.030	3.0	.569	241
35	.033	2.0	.726	254
40	.036	1.4	.899	262
50	.040	.90	1.28	274
60	.044	.75	1.70	282
70	.049	.68	2.16	289
76	.051	.67	2.46	293
80	.052	.66	2.67	296
90	.056	.63	3.21	302
100	.059	.62*	3.78	308
120	.067*	.62*	5.04	321
140	.073*	.61*	6.44	333
160	.080*	.61*	7.97	345
180	.085*	.61*	9.62	357
200	.090*	.61*	11.4	370
250	.095*	.61*	16.0	400
300	.100*	.61*	20.9	430

* Extrapolated Values

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13.181

THERMAL CONDUCTIVITY INTEGRALS

for IRON, COBALT and NICKEL

Source of Data: Data Sheet 3.181: Thermal Conductivity of Iron, Cobalt and Nickel.

Comments: The curves for Cobalt and Nickel 1 were extrapolated to 300°K; the curve for Nickel 2 was extrapolated to 6°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (6°K for Nickel 2; 4°K for all others)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm			
	Ni 1	Co	Fe	Ni 2	Ni 1	Co	Fe	Ni 2
4	1.7	1.20	.72					
6	3.4	1.8	1.1	.1 *	5.10	3.00	1.82	
8	5.0	2.4	1.44	.14*	13.5	7.20	4.36	.240
10	6.2	3.0	1.8	.17*	24.7	12.6	7.60	.550
15	7.9	4.1	2.5	.27*	60.0	30.4	18.4	1.65
20	8.0	4.6	3.0	.35*	99.7	52.1	32.1	3.20
25	7.8	4.7	3.3	.42*	139	75.4	47.9	5.13
30	6.8	4.5	3.5	.48*	176	98.4	64.9	7.38
35	5.7	4.1	3.4	.53	207	120	82.1	9.90
40	4.7	3.7	3.3	.58	233	139	98.9	12.7
50	3.3	3.0	2.7	.65	273	173	129	18.8
60	2.6	2.5	2.3	.70	302	200	154	25.6
70	2.2	2.3	1.9	.73	326	224	175	32.7
76	2.0	2.1	1.8	.75	339	238	186	37.2
80	1.87	1.95	1.7	.76	347	246	193	40.2
90	1.70	1.81	1.5	.77	365	264	209	47.8
100	1.60	1.70	1.37	.78	381	282	223	55.6
120	1.45	1.60	1.19	.80	412	315	249	71.4
140	1.39	1.50	1.04	.80	440	346	271	87.4
160	1.33*	1.47	.95	.80	467	376	291	103
180	1.31*	1.42*	.90	.80	494	405	310	119
200	1.30*	1.40*	.88	.80	520	433	327	135
250	1.30*	1.37*	.83	.78	585	502	370	175
300	1.30*	1.35*	.81	.76	650	570	411	213

* Extrapolated Values

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THERMAL CONDUCTIVITY INTEGRALS

for RHODIUM, PALLADIUM, IRIDIUM and PLATINUM

Source of Data: Data Sheet 3.182: Thermal Conductivity of Rhodium, Palladium, Iridium and Platinum.

Comments: The thermal conductivity curve for Palladium has been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm			
	Rh	Ir	Pd	Pt	Rh	Ir	Pd	Pt
4	12	5.5	7.7	9.2				
6	16.7	8.0	9.8	12	29.0	13.5	17.5	21.2
8	22	10.2	11.0	13	68.0	31.7	38.3	46.2
10	26	12.2	11.3	12.2	116	54.1	60.6	71.4
15	36	16.6	9.2	8	271	126	112	122
20	37	19	6	4.7	454	215	150	154
25	30	17.5	4	3	621	306	175	173
30	22	13.8	3	2.2	751	385	192	186
35	14.5	9.7	2.3	1.7	842	445	206	196
40	10	7.1	1.8	1.4	904	487	216	203
50	5.7	4.6	1.2	1.1	982	545	231	216
60	3.7	3.3	1.0	.95	1030	585	242	226
70	2.9	2.6	.88	.86	1060	614	251	235
76	2.6	2.4	.85	.83	1080	629	256	240
80	2.4	2.2	.83	.81	1090	639	260	244
90	2.1	1.95	.81	.78	1110	659	268	251
100	1.88	1.76	.80	.76	1130	677	276	259
120	1.65	1.55	.80	.73	1170	710	292	274
140	1.55	1.50	.80	.72	1200	741	308	288
160	1.51	1.48	.79	.71	1230	771	324	303
180	1.50	1.48	.79*	.70	1260	800	340	317
200	1.50	1.48	.79*	.70	1290	830	356	331
250	1.50	1.48	.79*	.70	1360	904	396	366
300	1.50	1.48	.79*	.70	1440	978	436	401

* Extrapolated Values

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THERMAL CONDUCTIVITY INTEGRALS
for COPPER ALLOYS

Source of Data: Data Sheet 3.212-1: Thermal Conductivity of Copper Alloys.

Comments: For the data tabulated below, the curves have been extrapolated as follows: Phos. Deox. Copper to 4°K; Silicon Bronze to 6°K and 300°K; Manganin to 20°K; (Pb) Brass and Beryllium Copper to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K for German Silver, Beryllium Copper, [Pb] Brass and Phos. Deox. Copper; 6°K for Silicon Bronze; 20°K for Manganin)

Thermal Conductivity Integrals are on following page.

Temp. °K	Thermal Conductivity watts/cm-°K					
	Phos. Deox Copper	Silicon Bronze	Manganin	(Pb) Brass	Beryllium Copper	German Silver
4	.067*			.021	.019	.0068
6	.109	.006*		.032	.028	.0128
8	.152	.01 *		.044	.038	.02
10	.196	.015*		.056	.048	.028
15	.32	.025		.09	.076	.052
20	.53	.034	.046*	.122	.106	.073
25	.63	.043	.064*	.153	.133	.092
30	.72	.052	.08 *	.183	.162	.11
35	.81	.061	.09 *	.21	.186	.122
40		.07	.10 *	.24	.21	.133
50	.96	.083	.11 *	.28	.26	.148
60	1.08	.096	.12 *	.33	.3	.158
70	1.18	.108	.13 *	.37	.34	.162
76	1.2	.112	.13 *	.38	.35	.165
80	1.27	.118	.13 *	.405	.37	.167
90	1.35	.126	.135*	.44	.4 *	.169
100	1.41	.136*	.14 *	.47	.42*	.17
120	1.52	.15 *	.143	.53*	.48*	.173
140	1.62	.16 *	.15	.6 *	.54*	.178
160	1.72	.17 *	.156	.65*	.58*	.185
180	1.83	.18 *	.162	.7 *	.62*	.192
200	1.92	.19 *	.17	.75*	.65*	.205
250	2.1	.20 *	.194	.85*	.7 *	.23
300	2.2	.22 *	.22	.9 *	.80*	.24

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS
for COPPER ALLOYS (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm					
	Phos. Deox. Copper	Silicon Bronze	Manganin	(Fo) Brass	Beryllium Copper	German Silver
6	.176			.053	.047	.0196
8	.437	.016		.129	.113	.0524
10	.785	.041		.229	.189	.100
15	2.08	.141		.594	.499	.300
20	3.95	.288		1.12	.954	.613
25	6.35	.481	.275	1.81	1.55	1.02
30	9.25	.718	.535	2.65	2.29	1.53
35	12.6	1.00	1.06	3.63	3.16	2.11
40	16.4	1.33	1.54	4.76	4.15	2.75
50	25.3	2.09	2.58	7.36	6.50	4.15
60	35.5	2.99	3.74	10.4	9.30	5.68
70	46.8	4.01	4.98	13.9	12.5	7.28
76	53.9	4.67	5.76	16.2	14.6	8.26
80	58.9	5.13	6.28	17.7	16.0	8.93
90	72.0	6.35	7.61	22.0	19.9	10.6
100	85.8	7.66	8.98	26.5	24.0	12.3
120	115	10.5	11.8	36.5	33.0	15.7
140	146	13.6	14.7	47.8	43.2	19.2
160	180	16.9	17.8	60.3	54.4	22.9
180	215	20.4	21.0	73.8	66.4	26.6
200	253	24.1	24.3	88.3	79.1	30.6
250	353	33.9	33.4	128	113	41.5
300	461	44.4	43.8	172	150	53.2

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THERMAL CONDUCTIVITY INTEGRALS
for COPPER-NICKEL and SILVER ALLOYS

Source of Data: Data Sheet 3.212-2: Thermal Conductivity of Copper-Nickel and Silver Alloys.

Comments: The curves for Cu-Ni (annealed), Cu-Ni (cold) and Ag-Solder were extrapolated to 300°K. The curve for Ag-Solder was also extrapolated to 4°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable value.

$$Q = \frac{A}{L}\int_{T_o}^{T_L} \lambda\, dT; \qquad Q\,\frac{L}{A} = \int_{T_o}^{T_L} \lambda\, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_o}^{T_L} \lambda\, dT$ watts/cm			
	Ag Solder	Cu-Ni Anneal.	Cu-Ni Cold	Constantan	Ag Solder	Cu-Ni Anneal.	Cu-Ni Cold	Constantan
4	.022*	.011	.0083	.0080				
6	.037*	.023	.016	.0158	.059	.034	.024	.024
8	.052*	.038	.027	.026	.148	.095	.067	.066
10	.068*	.057	.037	.036	.268	.190	.131	.128
15	.10 *	.106	.07	.063	.688	.353	.399	.375
20	.124	.16	.103	.088	1.25	1.02	.831	.753
25	.142	.21	.137	.108	1.92	1.94	1.43	1.24
30	.16	.25	.17	.12	2.67	3.09	2.20	1.81
35	.18	.28	.20	.132	3.52	4.42	3.12	2.44
40	.20	.32	.23	.14	4.47	1.92	4.20	3.12
50	.23	.35	.28	.15	6.62	9.27	6.75	4.57
60	.27	.37	.32	.16	9.12	12.9	9.75	6.12
70	.30	.38	.34	.165	12.0	16.6	13.0	7.75
76	.33	.38	.36	.169	13.9	18.9	15.1	8.75
80	.34	.38	.37	.170	15.2	20.4	16.6	9.43
90	.37	.38*	.38*	.170	18.7	24.2	20.4	11.1
100	.40	.38*	.40*	.170	22.6	28.0	24.3	12.8
120	.45	.39*	.42*	.171	31.1	35.7	32.5	16.2
140	.50	.39*	.42*	.174	40.6	43.5	40.9	19.7
160	.54	.39*	.42*	.180	51.0	51.3	49.3	23.2
180	.58	.39*	.42*	.183	62.2	59.1	57.7	26.9
200	.60	.40*	.42*	.19	74.0	67.0	66.1	30.6
250	.65*	.40*	.42*	.21	105	87.0	87.1	40.6
300	.68*	.40*	.42*	.23	138	107.0	108.	51.6

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for ALUMINUM ALLOYS

Source of Data: Data Sheet 3.232: Thermal Conductivity of Aluminum Alloys.

Comments: The Thermal Conductivity curves for 4 S, 75 S and 2024-T4 have been extrapolated to 4°K. The curve for 5154-0 has been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

Q = heat flow in watts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in watts/cm-°K
T = temperature in °K
T_o = initial temperature (4°K)

The Thermal Conductivity Integrals are on the following page.

Temp. °K	Thermal Conductivity watts/cm-°K							
	1100-F	6063-T5	3003-F	4 S	5052-0	5154-0	75 S	2024-T4
4	.55	.34	.11	.053*	.049	.041	.037*	.03*
6	.83	.51	.165	.078*	.07	.062	.057*	.05
8	1.12	.69	.23	.105*	.093	.085	.078*	.067
10	1.4	.86	.27	.13 *	.12	.108	.10 *	.083
15	2.2	1.3	.42	.20 *	.19	.163	.15 *	.127
20	2.8	1.7	.56	.27 *	.25	.23	.20 *	.165
25	3.3	2.0	.70	.34	.32	.28	.25	.20
30	3.6	2.3	.82	.41	.38	.33	.31	.24
35	3.8	2.6	.95	.48	.44	.38	.36	.28
40	3.9	2.7	1.05	.54	.50	.43	.40	.32
50	3.7	2.8	1.20	.62	.59	.51	.48	.38
60	3.4	2.7	1.30	.70	.68	.59	.55	.45
70	3.1	2.5	1.38	.77	.73	.66	.61	.51
76	2.9	2.4	1.40	.80	.77	.68	.64	.54
80	2.8	2.3	1.41	.81	.79	.70	.66	.56
90	2.6	2.2	1.45	.87	.84	.75	.70	.61
100	2.5	2.1	1.50	.90	.89	.80	.75	.65
120	2.3	2.05	1.51	.98	.96	.88*	.83	.73
140	2.25	2.0	1.54	1.06	1.04	.96*	.90	.80
160	2.20	2.0	1.58	1.11	1.08	1.01*	.96	.87
180	2.20	2.0	1.60	1.18	1.16	1.10*	1.00	.93
200	2.10	2.0	1.60	1.24	1.20	1.14*	1.05	.98
250	2.10	2.0	1.60	1.37	1.33	1.27*	1.10	1.10
300	2.10	2.0	1.60	1.48	1.42	1.38*	1.10	1.20

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS for ALUMINUM ALLOYS (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm							
	1100-F	6063-T5	3003-F	4 S	5052-O	5154-O	75-S	2024-T4
6	1.38	.850	.275	.131	.119	.103	.094	.080
8	3.33	2.05	.670	.314	.282	.250	.229	.197
10	5.85	3.60	1.17	.549	.495	.443	.407	.347
15	14.9	9.00	2.90	1.37	1.27	1.12	1.03	.872
20	27.4	16.5	5.34	2.55	2.37	2.10	1.91	1.60
25	42.6	25.8	8.50	4.07	3.80	3.38	3.03	2.51
30	59.9	36.5	12.3	5.95	5.55	4.90	4.43	3.61
35	78.4	48.8	16.7	8.17	7.60	6.68	6.11	4.91
40	97.6	62.0	21.7	10.7	9.95	7.70	8.01	6.41
50	136	89.5	33.0	16.5	15.4	12.4	12.4	9.91
60	171	117	45.5	23.1	21.7	17.9	17.6	14.1
70	204	143	58.9	30.5	28.8	24.2	23.6	18.9
76	222	158	67.2	35.2	33.3	28.2	27.1	22.0
80	233	167	72.8	38.4	36.4	30.9	29.7	24.2
90	260	190	87.1	46.8	44.6	38.2	36.5	30.1
100	286	211	102	55.7	53.2	45.9	43.8	36.3
120	334	253	132	74.5	71.7	62.7	59.6	50.1
140	379	293	162	94.9	91.7	81.1	76.9	65.4
160	424	333	194	117	113	101	95.5	82.1
180	468	373	225	139	135	122	115	100
200	511	413	257	164	159	144	136	119
250	616	513	337	229	222	205	189	171
300	721	613	417	300	291	271	244	229

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THERMAL CONDUCTIVITY INTEGRALS
for NICKEL ALLOYS

Source of Data: Data Sheet 3.281: Thermal Conductivity of Nickel Alloys.

Comments: The curve for Inconel (annealed) has been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (6°K for Contracid; 4°K for all other Nickel Alloys)

Thermal Conductivity Integrals are on following page.

Temp. °K	Thermal Conductivity watts/cm-°K				
	Monel (Annealed)	Monel (Drawn)	Inconel (Annealed)	Inconel (Drawn)	Contracid
4	.0085	.0043	.0048	.00252	
6	.0150	.0080	.0085	.0046	.0036
8	.022	.0126	.0130	.0068	.0052
10	.030	.0174	.0175	.0092	.0067
15	.051	.030	.029	.016	.011
20	.070	.043	.041	.023	.0185
25	.088	.057	.053	.029	.031
30	.100	.069	.063	.036	.041
35	.110	.080	.072	.043	.049
40	.120	.090	.080	.050	.055
50	.133	.110	.094	.062	.062
60	.143	.120	.103	.073	.067
70	.150	.130	.110	.085	.070
76	.155	.135	.115	.090	.072
80	.160	.140	.118	.095	.073
90	.165	.147	.120	.105*	.075
100	.170	.152	.123	.113*	.078
120	.180	.163	.127	.127*	.081
140	.186	.173	.129	.137*	.084
160	.191	.182	.130	.146*	.089
180	.200	.190	.132	.152*	.092
200	.210	.198	.135	.160*	.096
250	.220	.210	.145	.170*	.108
300	.230	.220	.152	.180*	.118

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS

for NICKEL ALLOYS (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm				
	Monel (Annealed)	Monel (Drawn)	Inconel (Annealed)	Inconel (Drawn)	Contracid
6	.0235	.0123	.0133	.00712	
8	.0605	.0329	.0348	.0185	.00880
10	.112	.0629	.0653	.0345	.0207
15	.315	.181	.182	.0975	.0650
20	.618	.364	.356	.195	.139
25	1.01	.614	.592	.325	.262
30	1.48	.929	.882	.488	.442
35	2.01	1.30	1.22	.685	.667
40	2.58	1.73	1.60	.918	.927
50	3.85	2.73	2.47	1.48	1.51
60	5.23	3.88	3.45	2.15	2.16
70	6.69	5.13	4.52	2.94	2.84
76	7.61	5.92	5.19	3.47	3.29
80	8.24	6.47	5.66	3.84	3.56
90	9.86	7.91	6.85	4.84	4.30
100	11.5	9.40	8.06	5.93	5.06
120	15.0	12.6	10.6	8.33	6.65
140	18.7	15.9	13.1	11.0	8.30
160	22.5	19.5	15.7	13.8	10.0
180	26.4	23.2	18.3	16.8	11.8
200	30.5	27.1	21.0	19.9	13.7
250	41.2	37.3	28.0	28.1	18.8
300	52.5	48.0	35.4	36.9	24.5

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THERMAL CONDUCTIVITY INTEGRALS

for MISCELLANEOUS ALLOYS

Source of Data: Data Sheet 3.291: Thermal Conductivity of Miscellaneous Alloys.

Comments: The curves for Miscellaneous Alloys have been extrapolated to 300°K. The curves for Lead - 44% Tin and Roses's Metal have been extrapolated to 4°K, while the curve for Titanium has been extrapolated to 15°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

Q = heat flow in watts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in watts/cm-°K
T = temperature in °K
T_o = initial temperature (15°K for Titanium, 4°K for all other Miscellaneous Alloys)

Thermal Conductivity Integrals are on the following page.

Temp. °K	Thermal Conductivity watts/cm-°K					
	Lead-44% Tin	Rose's Metal	Titanium	Lead-50% Indium	Wood's Metal	Soft Solder
4	.08 *	.0092*		.0088	.04	.16
6	.123*	.02		.0116	.072	.265
8	.16 *	.028		.0146	.10	.36
10	.19 *	.0335		.0175	.118	.42
15	.255	.0435	.0112*	.0245	.15	.52
20	.29	.0505	.0177	.032	.17	.55
25	.32	.056	.023	.037	.18	.57
30	.34	.059	.027	.043	.188	.57
35	.37	.063	.0295	.049	.196	.56
40	.38	.066	.032	.054	.20	.54
50	.42	.0715	.037	.064	.21	.52
60	.425	.077	.04	.073	.22	.51
70	.44	.081	.043	.082	.22	.51
76	.44	.083	.045	.089	.225	.52
80	.445*	.085	.046	.093	.225	.525
90	.46 *	.088	.048	.104	.23	.53
100	.465*	.091	.051	.118	.235	.54*
120	.47 *	.097	.054	.152	.235*	.55*
140	.47 *	.104	.057	.195	.235*	.56*
160	.47 *	.111	.06	.25	.235*	.56*
180	.47 *	.12	.063	.32	.24*	.56*
200	.48 *	.128	.065	.38	.24*	.56*
250	.48 *	.15	.074	.62	.24*	.57*
300	.48 *	.17*	.088*	.9*	.24*	.57*

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS
for MISCELLANEOUS ALLOYS (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm					
	Lead-44% Tin	Rose's Metal	Titanium	Lead 50% Indium	Wood's Metal	Soft Solder
6	.203	.0292		.0204	.112	.425
8	.486	.0772		.0466	.284	1.05
10	.836	.139		.0787	.502	1.83
15	1.95	.331		.184	1.17	4.18
20	3.31	.566	.0722	.325	1.97	6.86
25	4.84	.832	.174	.497	2.85	9.66
30	6.49	1.12	.299	.697	3.77	12.5
35	8.26	1.42	.440	.927	4.73	15.3
40	10.1	1.75	.594	1.18	5.72	18.1
50	14.1	2.43	.939	1.77	7.77	23.4
60	18.4	3.18	1.32	2.46	9.92	28.5
70	22.7	3.97	1.74	3.23	12.1	33.6
76	25.3	4.46	2.00	3.75	13.4	36.7
80	27.1	4.80	2.18	4.11	14.4	38.8
90	31.6	5.66	2.66	5.10	16.6	44.1
100	36.2	6.56	3.15	6.21	19.0	49.4
120	45.6	8.44	4.20	8.91	23.6	60.3
140	55.0	10.4	5.31	12.4	28.4	71.4
160	64.4	12.6	6.48	16.8	33.0	82.6
180	73.8	14.9	7.71	22.5	37.8	93.8
200	83.3	17.4	8.99	29.5	42.6	105
250	107	24.3	12.5	54.5	54.6	133
300	131	32.3	16.5	92.5	66.6	162

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THERMAL CONDUCTIVITY INTEGRALS
for FERROUS ALLOYS

Source of Data: Data Sheet 3.301: Thermal Conductivity of Ferrous Alloys.

Comments: In the table of values below, all the thermal conductivity curves for Ferrous Alloys, with the exception of Stainless, have been extrapolated. Of the extrapolated curves, all have been extrapolated to 4°K, and all except SAE 1020 and SAE 4130 have been extrapolated to 300°K. It is estimated that the extrapolated values deviate no more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

Q = heat of flow in watts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in watts/cm-°K
T = temperature in °K
T_o = initial temperature (4°K)

Thermal Conductivity Integrals are on the following page.

Temp. °K	Thermal Conductivity watts/cm-°K								
	SAE 1020	MILD 0.1% C	SAE 1095	SAE 4130	410	4% Al	13% Cr Quenched	Stain-less	24% Ni
4	.030*	.025*	.011*	.0075*	.0045*	.0045*	.0032*	.0024	.0018*
6	.058*	.050*	.019*	.013 *	.0070*	.0070*	.0055*	.0039	.0033*
8	.085*	.073*	.027*	.018 *	.010 *	.010 *	.0080*	.0057	.0050*
10	.115*	.100*	.035*	.023 *	.013 *	.013 *	.010 *	.0077	.0067*
15	.180*	.157	.060*	.040 *	.020 *	.020	.0165	.0132	.0115
20	.24 *	.22	.080*	.060 *	.035 *	.033	.024	.0195	.0165
25	.28	.27	.108	.078	.050	.045	.032	.026	.021
30	.32	.31	.130	.100	.070	.054	.040	.033	.025
35	.37	.34	.157	.120	.090	.060	.048	.040	.029
40	.40	.37	.180	.137	.108	.066	.056	.047	.032
50	.48	.42	.22	.170	.135	.080	.070	.058	.039
60	.53	.48	.26	.195	.157	.092	.082	.068	.045
70	.57	.51	.29	.22	.177	.108	.095	.076	.051
76	.59	.53	.30	.23	.183	.115	.100	.080	.054
80	.60	.54	.31	.24	.19	.120	.105	.083	.057
90	.61	.57	.33	.27	.20	.135	.113	.090	.062
100	.63	.59*	.34	.27	.21	.150	.120	.095	.068
120	.65	.60*	.37	.30	.23	.160*	.140*	.103	.077*
140	.65	.60*	.38	.32	.24	.180*	.150*	.110	.085*
160	.65	.60*	.40	.33	.25	.190*	.160*	.120	.090*
180	.65	.60*	.41	.34	.255	.20 *	.165*	.123	.100*
200	.65	.60*	.43	.35	.26	.21 *	.17 *	.13	.107*
250	.65	.60*	.45	.35	.27	.22 *	.18 *	.14	.120*
300	.65	.60*	.45*	.35	.28*	.23 *	.19 *	.15	.130*

* Extrapolated Values

THERMAL CONDUCTIVITY INTEGRALS
for Ferrous Alloys (cont.)

Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$, watts/cm								
	SAE 1020	Mild 0.1% C	SAE 1095	SAE 4130	410	4% Al	13% Cr Quenched	Stain-less	24% Ni
6	.088	.075	.03	.0205	.0115	.0115	.0087	.0063	.00510
8	.231	.198	.076	.0515	.0285	.0285	.0222	.0159	.0134
10	.431	.371	.138	.0925	.0515	.0515	.0402	.0293	.0251
15	1.17	1.01	.376	.250	.134	.134	.106	.0816	.0706
20	2.22	1.96	.726	.500	.272	.266	.208	.163	.141
25	3.52	3.18	1.20	.845	.484	.462	.348	.277	.234
30	5.02	4.63	1.79	1.29	.784	.709	.528	.424	.349
35	6.74	6.26	2.51	1.84	1.18	.994	.748	.607	.484
40	8.67	8.03	3.35	2.48	1.68	1.31	1.01	.824	.637
50	13.1	12.0	5.35	4.02	2.89	2.04	1.64	1.35	.992
60	18.1	16.5	7.75	5.84	4.35	2.90	2.40	1.98	1.41
70	23.6	21.4	10.5	7.92	6.02	3.90	3.28	2.70	1.89
76	27.1	24.6	12.3	9.27	7.10	4.57	3.87	3.17	2.21
80	29.5	26.7	13.5	10.2	7.85	5.04	4.28	3.49	2.43
90	35.5	32.2	16.7	12.8	9.80	6.31	5.37	4.36	3.02
100	41.7	38.0	20.0	15.4	11.8	7.74	6.53	5.28	3.67
120	54.5	49.9	27.1	21.2	16.2	10.8	9.13	7.26	5.12
140	67.5	61.9	34.6	27.4	21.0	14.2	12.0	9.39	6.74
160	80.5	73.9	42.4	33.8	25.8	17.9	15.1	11.7	8.49
180	93.5	85.9	50.5	40.6	30.9	21.8	18.4	14.1	10.4
200	107	97.9	58.9	47.4	36.1	25.9	21.7	16.6	12.5
250	139	128	80.9	65.0	49.3	36.7	30.5	23.4	18.1
300	172	158	103	82.4	63.1	47.9	39.7	30.6	24.4

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THERMAL CONDUCTIVITY INTEGRALS

for GLASSES and PLASTICS

Source of Data: Data Sheet 3.501: Thermal Conductivity of Glasses and Plastics.

Comments: The curves for Teflon, Nylon, and Perspex were extrapolated to 300°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable value.

$$Q = \frac{A}{L}\int_{T_o}^{T_L} \lambda dT; \qquad Q\,\frac{L}{A} = \int_{T_o}^{T_L} \lambda dT$$

Where:

Q = heat flow in milliwatts
A = cross sectional area in cm^2
L = length in cm
λ = thermal conductivity in milliwatts/cm-°K
T = temperature in °K
T_o = initial temperature (4°K)

Temp. °K	Thermal Conductivity milliwatts/cm-°K				$\int_{T_o}^{T_L} \lambda dT$ milliwatts/cm			
	glass	teflon	perspex	nylon	glass	teflon	perspex	nylon
4	.97	.46	.58	.125				
6	1.14	.67	.60	.196	2.11	1.13	1.18	.321
8	1.19	.82	.60	.29	4.43	2.62	2.38	.807
10	1.20	.96	.61	.38	6.81	4.4	3.59	1.48
15	1.3	1.22	.63	.67	13.1	9.85	6.69	4.10
20	1.46	1.41	.75	.98	20.0	16.4	10.1	8.23
25	1.68	1.60	.97	1.28*	27.9	23.9	14.4	13.9
30	1.9	1.74	1.18*	1.5 *	36.8	32.3	19.6	20.8
35	2.2	1.86	1.35*	1.78*	47.1	41.3	25.9	29.0
40	2.4	1.95	1.50*	1.99*	58.6	50.8	33.0	38.5
50	2.9	2.1	1.80*	2.4 *	84.6	71.6	49.5	60.4
60	3.4	2.2	1.95*	2.7 *	115	93.6	68.3	85.9
70	3.9	2.3	2.10*	2.8 *	151	116	88.5	113
76	4.2	2.3	2.15*	2.9 *	175	130	101.	131
80	4.4	2.35	2.20*	3.0 *	194	139	110.	142
90	5.0	2.4 *	2.25*	3.1 *	240	163	132.	173
100	5.5	2.45*	2.25*	3.2 *	292	187	155.	204
120	6.4	2.45*	2.30*	3.3 *	408	237	200.	269
140	7.3	2.5 *	2.35*	3.4 *	542	287	247.	336
160	7.9	2.55*	2.40*	3.5 *	694	338	294.	405
180	8.5	2.60*	2.40*	3.5 *	858	390	342.	475
200	9.0	2.60*	2.40*	3.5 *	1030	442	390.	545
250	9.8	2.60*	2.40*	3.5 *	1500	572	510.	720
300	10.2	2.60*	2.40*	3.5 *	1990	702	630.	895

* Extrapolated Values

RLF/EGP/JRK Issued: 1-12-60

ENTROPY of NEON

Sources of Data:

Yendall, E. F., Advances in Cryogenic Engineering, 4, Plenum Press, New York (1960) pp. 47-64

Yendall, E. F., Private communication to Dr. K. D. Timmerhaus, University of Colorado (June 1, 1960)

Rossini, F. D., Selected Values of Thermodynamic Properties, Ser. III, Natl. Bur. Standards (Mar. 1, 1954)

Other References:

Crommelin, C. A., Martinez, J. P. and Onnes, H. K., Koninkl. Akad. Wetenschap. Amsterdam Proc. 27, 1316-26 (1919)

Onnes, H. K. and Crommelin, C. A., Communs. Phys. Lab. Univ. Leiden No. 147d (1915)

Comments:

The calculated values of entropy and enthalpy for the following tables and graph are based on the experimental P-V-T measurements by Crommelin, Martinez and Onnes as represented by an equation of state by Yendall and the zero pressure specific heat as reported by Rossini. The modified Benedict-Webb-Rubin equation of state, determined by Yendall and reported in Advances in Cryogenic Engineering, was primarily based on these experimental data points which cover a temperature range from 55° to 300°K with pressures from 20 to 90 atmospheres. Improved coefficients for this equation were supplied by Yendall in a private communication. These revised coefficients for the equation of state were then used for the P-V-T relationships in calculating values of entropy and enthalpy for the temperature range from 55° to 300°K with pressures from 0.5 to 90 atmospheres.

To ascertain the probable accuracy of the P-V-T relationships, a graphical study was made of the 103 experimental pressure, volume, temperature data reported by Crommelin, et al. This study employed the method of graphical residuals, i.e., a term expressing, the difference between the experimentally determined volumes from an ideal volume. The order of magnitude of these residuals is sufficiently small to provide a comparison to five significant figures over the entire range of values. This study indicated a random scatter of the fourth significant figure of this data, indicating the experimental accuracy of the orignal data is limited to three significant figures.

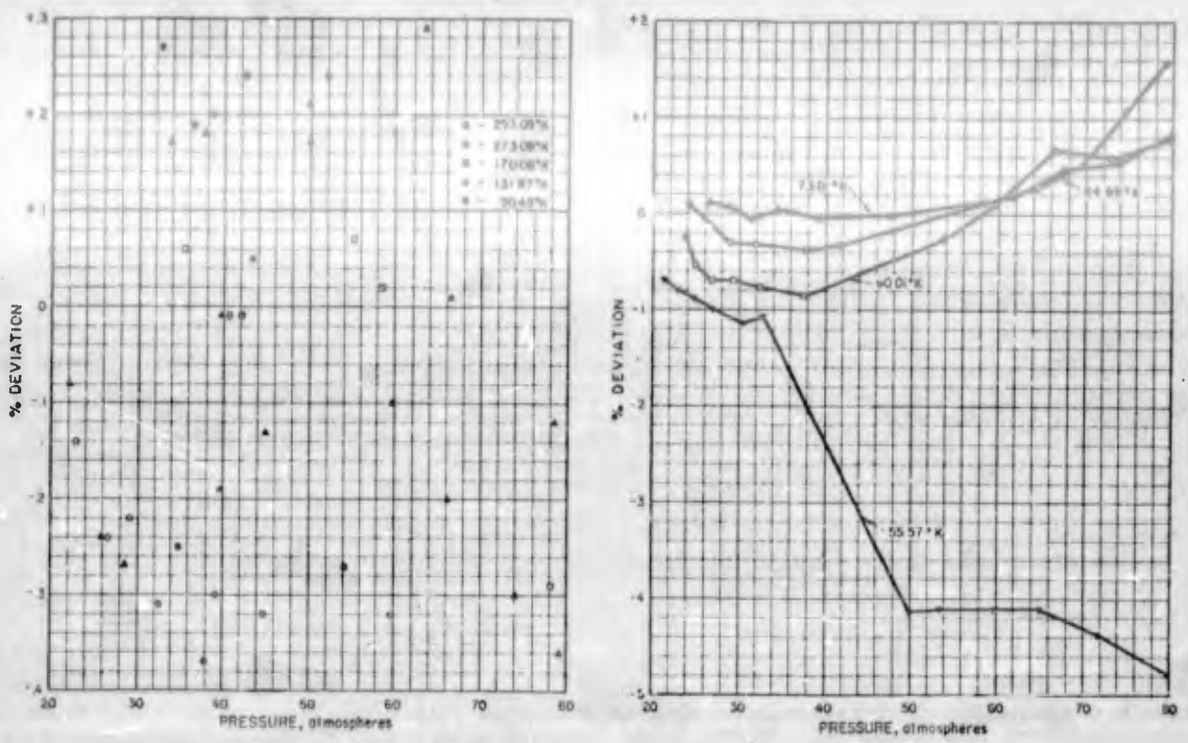
A comparison was made between the experimental pressures reported by Crommelin, et al., and the pressures calculated from Yendall's equation of state. The results of this study (see graph below) indicate good agreement between the experimental data and the calculated values, except at 55.57°K. A comparison of calculated pressures by this equation with the pressures at the experimental points of Crommelin, et al., was also made by Yendall, for which he reports a mean

ENTROPY of NEON (Cont.)

Comments: (cont.)

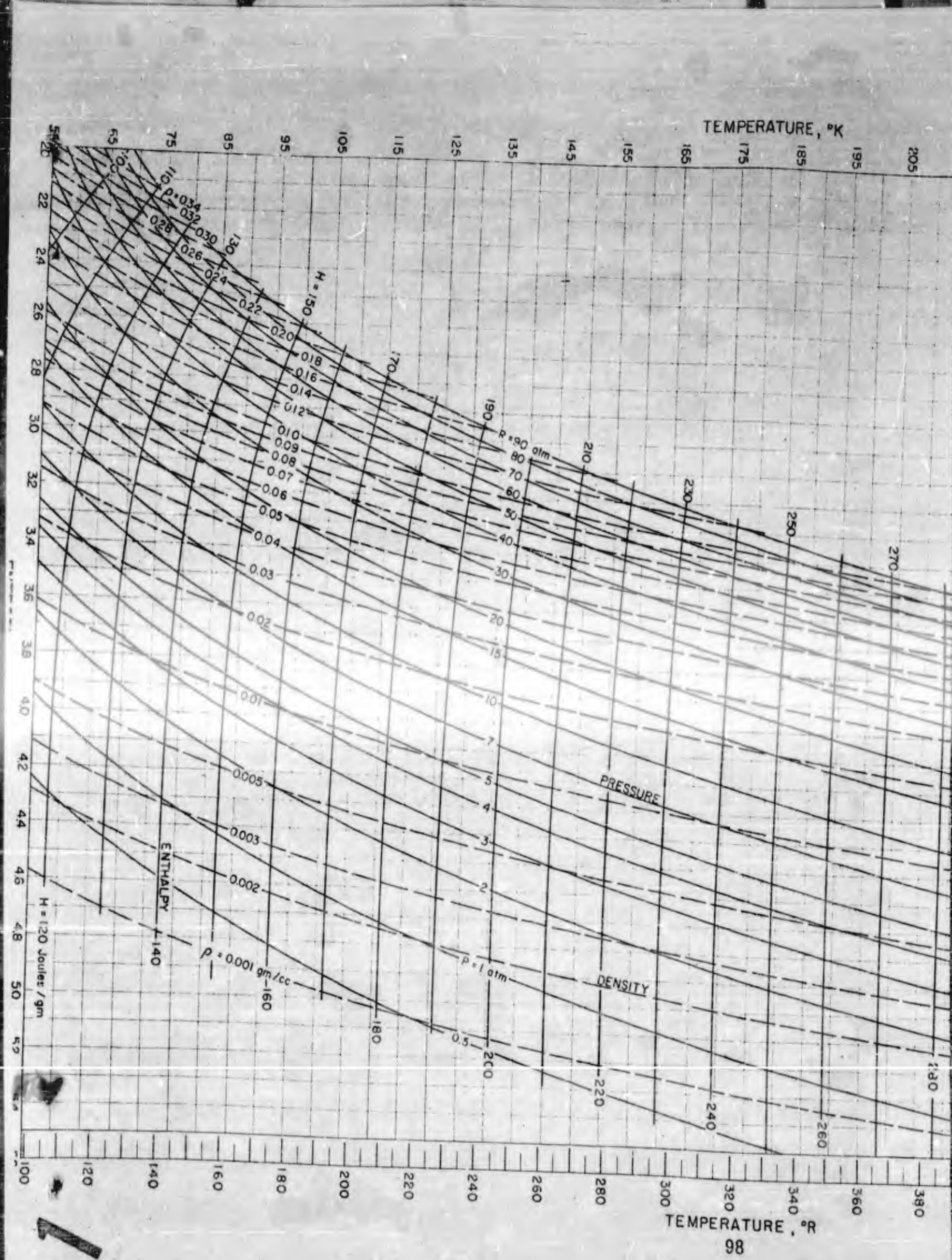
percentage deviation of 0.57%. These comparisons and the study of the data as discussed above, both indicated a departure in the original data at 55°K from the general pattern as compared to values of 60°K and higher. It therefore, seems valid to assume that there is basis for doubt in the relative accuracy of the values at 55.57°K as reported by Crommelin, et al.

The calculation of the entropy and enthalpy with the equations listed below makes use of the zero pressure specific heat and the analogy between the real and ideal gas in the limit as the pressure approaches zero. The experimental data by Crommelin, et al., the basis for the equation of state, does not contain data below approximately 20 atmospheres pressure; therefore this calculation of the entropy and enthalpy represents an extrapolation of the equation of state from 20 atmospheres to zero pressure. The nature of the equation of state, i.e., it reduces to the ideal gas equation in the limit as the pressure approaches zero, and a study of the behavior of the P-V-T data predicted by the equation at low pressures indicate that this extrapolation is reasonable and prudent.

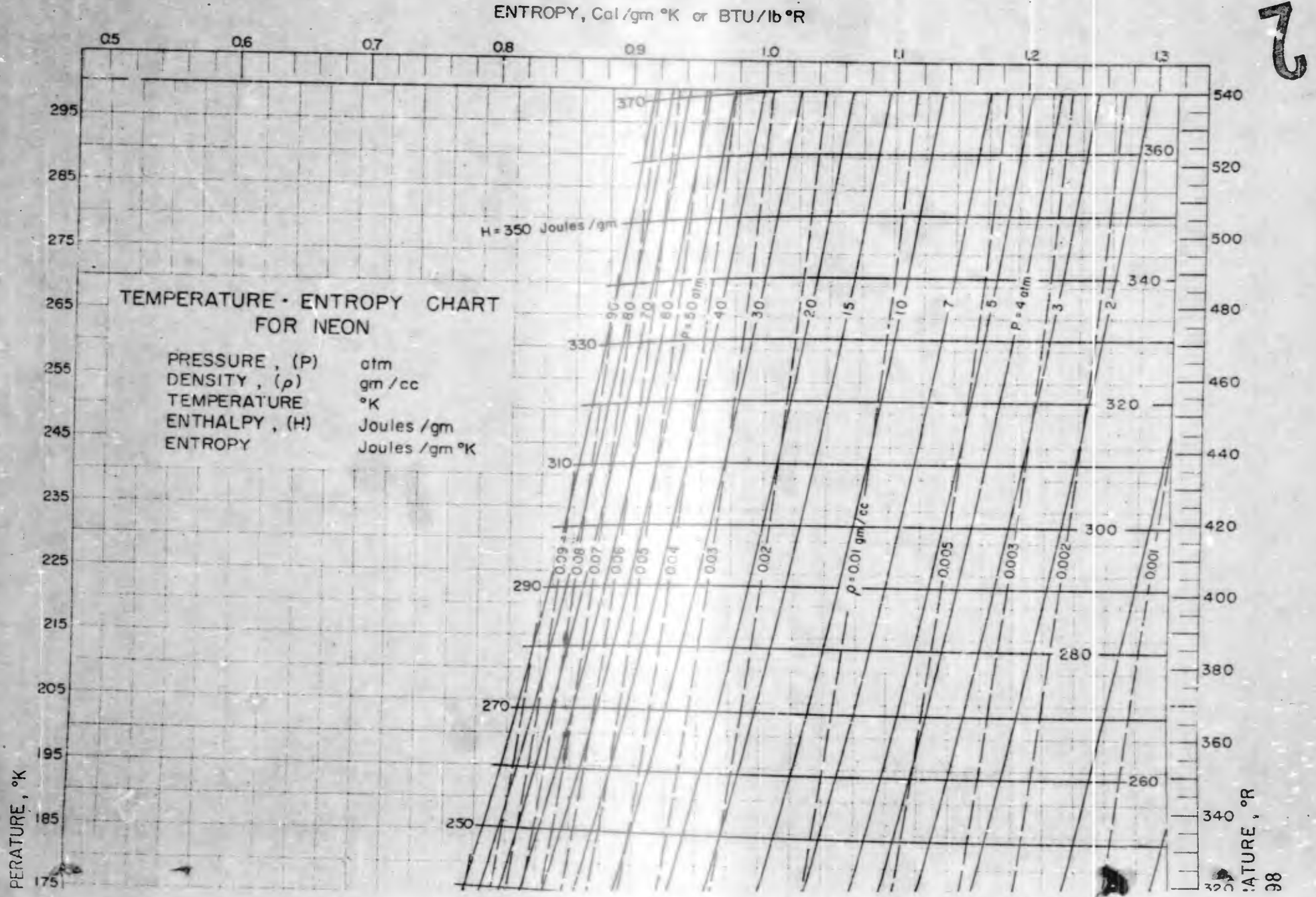


COMPARISON of PRESSURES from YENDALL'S EQUATION WITH DATA by CROMMELIN, ET AL.

$$\% \text{ Deviation} = \frac{P_{Yend.} - P_{Crom.}}{P_{Crom.}}$$


TEMPERATURE, °K
TEMPERATURE, °R
PRESSURE
DENSITY
ENTHALPY
P = 90 atm
P = 1 atm
H = 150
H = 120 Joules / gm
ρ = 0.001 gm/cc

14.003


ENTROPY, Cal/gm °K or BTU/lb °R
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
TEMPERATURE · ENTROPY CHART FOR NEON
PRESSURE , (P) atm
DENSITY , (ρ) gm/cc
TEMPERATURE °K
ENTHALPY , (H) Joules/gm
ENTROPY Joules/gm °K
H = 350 Joules/gm
P = 50 atm
P = 4 atm
ρ = 0.01 gm/cc
TEMPERATURE, °K
TEMPERATURE, °R

THERMODYNAMIC PROPERTIES OF NEON

(ρ = density, gm/cc ; h = enthalpy, joules/gm ; s = entropy, joules/gm°K)

Temp. °K		Pressure, atmospheres																Temp. °K
		0.5	1	2	3	4	5	7	10	15	20	30	40	50	60	70	80	90		
55	ρ	.002244	.004505	.009078	.01372	.01843	.02322	.03300	.04833	.07563	.1055	.1744	.2561	.3560	.4568	.5456	.6178	.6782	ρ	55
	h	116.8	116.5	115.9	115.4	114.8	114.2	113.1	111.3	108.2	105.0	98.22	90.79	83.13	76.21	70.83	66.97	64.20	h	
	s	4.236	3.947	3.654	3.480	3.354	3.254	3.101	2.931	2.724	2.563	2.301	2.091	1.881	1.710	1.575	1.473	1.394	s	
60	ρ	.002055	.004122	.008290	.01250	.01676	.02107	.02984	.04337	.06700	.09207	.1469	.2091	.2751	.3453	.4146	.4794	.5377	ρ	60
	h	122.0	121.7	121.3	120.8	120.3	119.9	118.9	117.5	115.0	112.5	107.3	101.9	96.47	91.26	86.55	82.52	79.20	h	
	s	4.327	4.038	3.747	3.574	3.450	3.353	3.203	3.038	2.842	2.692	2.461	2.275	2.114	1.972	1.849	1.744	1.656	s	
65	ρ	.001896	.003800	.007631	.01149	.01539	.01932	.02728	.03946	.06046	.08234	.1286	.1766	.2312	.2854	.3398	.3926	.4423	ρ	65
	h	127.8	127.6	126.6	126.2	125.8	125.4	124.6	123.4	121.4	119.3	115.1	110.9	106.7	102.7	98.85	95.41	92.35	h	
	s	4.410	4.122	3.832	3.660	3.537	3.441	3.294	3.133	2.943	2.801	2.587	2.419	2.276	2.155	2.045	1.951	1.866	s	
70	ρ	.001760	.003525	.007072	.01064	.01424	.01785	.02515	.03627	.05526	.07481	.1156	.1582	.2024	.2474	.2923	.3365	.3793	ρ	70
	h	132.3	132.2	131.8	131.5	131.2	130.8	130.2	129.1	127.4	125.7	122.3	118.8	115.4	112.1	109.0	106.2	103.5	h	
	s	4.486	4.199	3.910	3.739	3.617	3.522	3.376	3.216	3.033	2.896	2.692	2.536	2.407	2.296	2.198	2.110	2.032	s	
75	ρ	.001642	.003288	.006591	.009911	.01325	.01660	.02335	.03380	.05099	.06875	.1053	.1430	.1815	.2204	.2592	.2973	.3345	ρ	75
	h	137.5	137.4	137.1	136.8	136.5	136.2	135.6	134.8	133.3	131.8	128.9	126.0	123.2	120.5	117.9	115.5	113.2	h	
	s	4.558	4.271	3.982	3.812	3.691	3.596	3.452	3.296	3.114	2.981	2.784	2.636	2.515	2.411	2.320	2.239	2.166	s	
80	ρ	.001539	.003083	.006173	.009277	.01239	.01552	.02181	.03132	.04740	.06372	.09703	.1310	.1655	.2000	.2343	.2681	.3011	ρ	80
	h	142.7	142.6	142.3	142.1	141.8	141.5	141.0	140.3	139.0	137.8	135.3	132.8	130.4	128.1	125.9	123.9	122.0	h	
	s	4.625	4.338	4.050	3.880	3.759	3.665	3.521	3.367	3.188	3.057	2.866	2.723	2.608	2.509	2.424	2.347	2.279	s	
85	ρ	.001448	.002898	.005805	.008720	.01164	.01457	.02046	.02935	.04432	.05946	.09045	.1213	.1525	.1838	.2148	.2453	.2751	ρ	85
	h	147.9	147.7	147.5	147.3	147.1	146.9	146.4	145.7	144.6	143.5	141.4	139.3	137.2	135.2	133.4	131.5	129.9	h	
	s	4.687	4.401	4.113	3.944	3.823	3.729	3.586	3.434	3.255	3.127	2.940	2.802	2.690	2.596	2.514	2.442	2.376	s	
90	ρ	.001367	.002736	.005478	.008227	.01098	.01374	.01928	.02765	.04165	.05578	.08431	.1131	.1418	.1705	.1989	.2268	.2541	ρ	90
	h	153.0	152.9	152.7	152.5	152.3	152.1	151.7	151.2	150.2	149.2	147.3	145.5	143.7	142.0	140.4	138.9	137.4	h	
	s	4.746	4.460	4.172	4.003	3.883	3.789	3.647	3.495	3.320	3.192	3.008	2.873	2.764	2.673	2.594	2.524	2.461	s	
95	ρ	.001295	.002591	.005187	.007788	.01039	.01300	.01823	.02611	.03930	.05257	.07926	.1061	.1328	.1593	.1856	.2114	.2366	ρ	95
	h	158.2	158.1	157.9	157.7	157.6	157.4	157.0	156.5	155.7	154.8	153.1	151.5	150.0	148.5	147.1	145.7	144.5	h	
	s	4.802	4.516	4.228	4.060	3.940	3.846	3.705	3.553	3.379	3.253	3.071	2.938	2.832	2.743	2.665	2.593	2.530	s	
100	ρ	.001230	.002461	.004926	.007394	.009865	.01234	.01729	.02475	.03722	.04974	.07485	.09997	.1250	.1495	.1742	.1983	.2219	ρ	100
	h	163.3	163.3	163.1	162.9	162.8	162.6	162.3	161.9	161.1	160.3	158.9	157.4	156.1	154.8	153.5	152.4	151.3	h	
	s	4.855	4.569	4.282	4.113	3.993	3.900	3.759	3.603	3.434	3.309	3.130	2.999	2.894	2.807	2.732	2.666	2.607	s	
110	ρ	.001118	.002237	.004475	.006715	.008957	.01120	.01569	.02243	.03368	.04494	.06745	.08988	.1121	.1341	.1558	.1771	.1980	ρ	110
	h	173.7	173.6	173.5	173.3	173.2	173.1	172.8	172.5	171.8	171.2	170.1	168.9	167.8	166.8	165.9	165.0	164.1	h	
	s	4.953	4.667	4.380	4.212	4.095	4.000	3.859	3.709	3.537	3.413	3.236	3.106	3.007	2.923	2.850	2.787	2.730	s	
120	ρ	.001025	.002050	.004101	.006152	.008203	.01026	.01436	.02052	.03078	.04103	.06148	.08179	.1019	.1218	.1413	.1606	.1794	ρ	120
	h	184.0	183.9	183.8	183.7	183.6	183.5	183.3	183.0	182.5	182.0	181.0	180.1	179.3	178.5	177.8	177.1	176.4	h	
	s	5.043	4.757	4.471	4.303	4.183	4.090	3.950	3.801	3.630	3.507	3.332	3.206	3.107	3.024	2.954	2.892	2.837	s	
130	ρ	.0009460	.001892	.003784	.005676	.007568	.009459	.01324	.01891	.02835	.03777	.05653	.07513	.09354	.1117	.1296	.1472	.1644	ρ	130
	h	194.3	194.2	194.2	194.1	194.0	193.9	193.7	193.5	193.1	192.7	191.9	191.2	190.5	189.9	189.3	188.7	188.3	h	
	s	5.126	4.840	4.553	4.385	4.266	4.174	4.034	3.885	3.714	3.592	3.419	3.294	3.196	3.115	3.046	2.985	2.931	s	
140	ρ	.0008784	.001757	.003513	.005269	.007024	.008779	.01229	.01754	.02629	.03501	.05235	.06954	.08652	.1033	.1198	.1360	.1519	ρ	140
	h	204.6	204.5	204.5	204.4	204.3	204.3	204.1	203.9	203.6	203.3	202.6	202.1	201.5	201.0	200.6	200.2	199.8	h	
	s	5.202	4.916	4.630	4.462	4.343	4.251	4.111	3.962	3.792	3.671	3.499	3.375	3.276	3.198	3.130	3.070	3.017	s	
150	ρ	.0008199	.001640	.003278	.004917	.006554	.008191	.01146	.01636	.02451	.03263	.04877	.06475	.08054	.09612	.1115	.1266	.1414	ρ	150
	h	214.9	214.9	214.8	214.8	214.7	214.6	214.5	214.4	214.1	213.8	213.3	212.8	212.4	212.0	211.7	211.4	211.1	h	
	s	5.273	4.987	4.701	4.534	4.414	4.322	4.182	4.034	3.866	3.744	3.572	3.449	3.353	3.274	3.206	3.147	3.095	s	
160	ρ	.0007686	.001537	.003073	.004608	.006143	.007677	.01074	.01533	.02296	.03056	.04565	.06061	.07538	.08994	.1043	.1184	.1323	ρ	160
	h	225.2	225.2	225.1	225.1	225.0	225.0	224.9	224.8	224.5	224.3	223.9	223.5	223.2	222.9	222.7	222.4	222.3	h	
	s	5.340	5.054	4.766	4.600	4.481	4.389	4.249	4.101	3.932	3.812	3.641	3.518	3.423	3.344	3.277	3.219	3.167	s	
170	ρ	.0007234	.001446	.002892	.004337	.005781	.007224	.01011	.01442	.02160	.02875	.04294	.05698	.07086	.08455	.09805	.1113	.1244	ρ	170
	h	235.5	235.5	235.5	235.4	235.4	235.3	235.3	235.1	235.0	234.8	234.5	234.2	233.9	233.7	233.5	233.4	233.3	h	
	s	5.402	5.116	4.830	4.663	4.544	4.452	4.312	4.164	3.995	3.875	3.705	3.583	3.488	3.410	3.343	3.285	3.234	s	
180	ρ	.0006832	.001366	.002731	.004096	.005459	.006822	.009544	.01362	.02039	.02714	.04053	.05378	.06687	.07979	.09253	.1051	.1174	ρ	180
	h	245.8	245.8	245.8	245.7	245.7	245.7	245.6	245.5	245.4	245.2	245.0	244.8	244.6	244.5	244.3	244.3	244.2	h	
	s	5.461	5.175	4.889	4.722	4.603	4.511	4.371	4.224	4.055	3.935	3.765	3.643	3.549	3.471	3.405	3.347	3.295	s	
190	ρ	.0006473	.001294	.002587	.003880	.005171	.006462	.009040	.01290	.01931	.02570	.03838	.05092	.06332	.07556	.08764	.09953	.1112	ρ	190
	h	256.1	256.1	256.1	256.1	256.0	256.0	256.0	255.9	255.8	255.7	255.5	255.3	255.2	255.1	255.1	255.0	255.0	h	
	s	5.517	5.231	4.945	4.778	4.659	4.567	4.427	4.280	4.111	3.991	3.822	3.700	3.606	3.529	3.463	3.405	3.353	s	

	h	[illegible]	[illegible]	157.9	157.7	157.6	157.4	157.0	156.5	155.7	154.8	153.1	151.5	150.0	146.5	147.1	145.7	144.5	h
	s	4.832	[illegible]	4.228	[illegible]	3.940	3.846	3.705	3.553	3.379	3.253	3.071	2.938	2.832	2.743	2.663	2.593	2.533	s
95																			
	p	.001250	[illegible]	.004926	.007394	.009865	.01234	.01729	.02479	.03732	.04974	.07485	.09997	.1250	.1498	.1742	.1989	.2239	p
100	h	163.3	163.3	163.1	162.9	162.8	162.6	162.3	161.9	161.1	160.3	158.9	157.4	156.1	154.8	153.5	152.1	151.3	h
	s	4.835	4.569	4.382	4.113	3.993	3.900	3.759	3.608	3.434	3.309	3.130	2.999	2.894	2.807	2.732	2.666	2.607	s
100																			
	p	.001118	.002237	.004475	.006715	.008957	.01120	.01569	.02243	.03368	.04494	.06745	.08996	.1121	.1341	.1558	.1771	.1980	p
110	h	173.7	173.5	173.5	173.3	173.2	173.1	172.8	172.5	171.9	171.2	170.1	168.9	167.9	166.8	165.9	165.0	164.1	h
	s	4.953	4.687	4.330	4.212	4.093	4.000	3.859	3.709	3.537	3.413	3.236	3.108	3.007	2.923	2.850	2.787	2.730	s
110																			
	p	.001025	.002050	.004101	.006152	.008203	.01026	.01436	.02052	.03078	.04103	.06148	.08179	.1019	.1213	.1413	.1606	.1794	p
120	h	184.0	183.9	183.8	183.7	183.6	183.5	183.3	183.0	182.5	182.0	181.0	180.1	179.3	178.5	177.8	177.1	176.4	h
	s	5.043	4.757	4.471	4.303	4.183	4.090	3.950	3.801	3.630	3.507	3.332	3.206	3.107	3.024	2.954	2.892	2.837	s
120																			
	p	.0009460	.001892	.003784	.005676	.007568	.009459	.01324	.01892	.02835	.03777	.05653	.07513	.09354	.1117	.1296	.1472	.1644	p
130	h	194.3	194.2	194.2	194.1	194.0	193.9	193.7	193.5	193.1	192.7	192.9	191.2	190.5	189.9	189.3	188.7	188.3	h
	s	5.128	4.840	4.553	4.385	4.266	4.174	4.034	3.889	3.714	3.592	3.419	3.294	3.196	3.115	3.046	2.985	2.931	s
130																			
	p	.0008784	.001757	.003513	.005269	.007024	.008779	.01229	.01754	.02629	.03501	.05235	.06954	.08658	.1033	.1196	.1360	.1519	p
140	h	204.6	204.6	204.5	204.4	204.3	204.3	204.1	203.9	203.6	203.3	202.6	201.9	201.3	200.6	200.2	199.8	199.4	h
	s	5.202	4.916	4.630	4.462	4.343	4.251	4.111	3.962	3.792	3.671	3.499	3.375	3.278	3.193	3.130	3.070	3.017	s
140																			
	p	.0008199	.001640	.003278	.004917	.006554	.008191	.01146	.01636	.02451	.03263	.04877	.06475	.08054	.09612	.1115	.1266	.1414	p
150	h	214.9	214.9	214.8	214.8	214.7	214.6	214.5	214.4	214.1	213.8	213.3	212.8	212.4	212.0	211.7	211.4	211.1	h
	s	5.273	4.987	4.701	4.534	4.414	4.322	4.182	4.034	3.886	3.744	3.572	3.449	3.353	3.274	3.208	3.147	3.095	s
150																			
	p	.0007636	.001537	.003073	.004608	.006142	.007677	.01074	.01535	.02296	.03056	.04566	.06061	.07538	.08994	.1043	.1184	.1323	p
160	h	225.2	225.2	225.1	225.1	225.0	225.0	224.9	224.8	224.5	224.3	223.9	223.5	223.2	222.9	222.7	222.4	222.3	h
	s	5.340	5.054	4.768	4.600	4.481	4.389	4.249	4.101	3.928	3.802	3.641	3.518	3.423	3.344	3.277	3.219	3.167	s
160																			
	p	.0007234	.001446	.002892	.004337	.005781	.007224	.01011	.01446	.02160	.02875	.04304	.05696	.07086	.08455	.09805	.1113	.1244	p
170	h	235.5	235.5	235.5	235.4	235.4	235.3	235.3	235.1	234.9	234.8	234.5	234.2	233.9	233.7	233.5	233.4	233.3	h
	s	5.402	5.116	4.830	4.663	4.544	4.452	4.312	4.164	3.995	3.875	3.705	3.583	3.485	3.410	3.343	3.285	3.234	s
170																			
	p	.0006832	.001366	.002731	.004096	.005459	.006822	.009544	.01382	.02039	.02714	.04053	.05378	.06687	.07979	.09253	.1051	.1174	p
180	h	245.8	245.8	245.8	245.7	245.7	245.7	245.6	245.5	245.4	245.2	245.0	244.8	244.6	244.5	244.3	244.3	244.2	h
	s	5.461	5.175	4.889	4.722	4.603	4.511	4.371	4.224	4.054	3.935	3.765	3.643	3.549	3.471	3.405	3.347	3.296	s
180																			
	p	.0006473	.001294	.002587	.003880	.005171	.006462	.009040	.01309	.01931	.02570	.03838	.05092	.06332	.07556	.08764	.09953	.1112	p
190	h	256.1	256.1	256.1	256.1	256.0	256.0	256.0	255.9	255.8	255.7	255.5	255.3	255.2	255.1	255.1	255.0	255.0	h
	s	5.517	5.231	4.945	4.778	4.659	4.567	4.427	4.280	4.111	3.991	3.822	3.700	3.606	3.529	3.463	3.406	3.355	s
190																			
	p	.0006149	.001229	.002458	.003686	.004912	.006138	.008587	.01225	.01834	.02441	.03645	.04836	.06014	.07177	.08325	.09456	.1057	p
200	h	266.4	266.4	266.4	266.4	266.4	266.4	266.3	266.3	266.2	266.1	266.0	265.9	265.8	265.8	265.8	265.8	265.7	h
	s	5.570	5.284	4.998	4.831	4.712	4.620	4.480	4.333	4.164	4.045	3.875	3.754	3.660	3.583	3.518	3.461	3.410	s
200																			
	p	.0005856	.001171	.002341	.003510	.004678	.005846	.008178	.01167	.01747	.02324	.03471	.04605	.05727	.06835	.07929	.09008	.1007	p
210	h	276.8	276.7	276.7	276.7	276.7	276.7	276.6	276.6	276.5	276.4	276.4	276.3	276.4	276.4	276.4	276.5	276.5	h
	s	5.620	5.334	5.048	4.881	4.762	4.670	4.531	4.383	4.215	4.095	3.926	3.806	3.712	3.635	3.570	3.513	3.463	s
210																			
	p	.0005590	.001118	.002234	.003350	.004466	.005580	.007806	.01114	.01667	.02213	.03313	.04396	.05467	.06526	.07571	.08602	.09619	p
220	h	287.1	287.1	287.0	287.0	287.0	287.0	287.0	287.0	286.9	286.9	286.9	286.8	286.9	286.9	287.0	287.1	287.2	h
	s	5.668	5.382	5.096	4.929	4.810	4.718	4.579	4.431	4.263	4.144	3.975	3.854	3.761	3.684	3.619	3.562	3.512	s
220																			
	p	.0005347	.001069	.002137	.003205	.004271	.005337	.007466	.01065	.01595	.02122	.03159	.04205	.05230	.06243	.07244	.08232	.09205	p
230	h	297.4	297.4	297.4	297.3	297.3	297.3	297.3	297.3	297.3	297.3	297.3	297.4	297.4	297.6	297.7	297.9	297.9	h
	s	5.714	5.428	5.142	4.975	4.856	4.764	4.625	4.477	4.309	4.190	4.021	3.901	3.807	3.731	3.666	3.609	3.559	s
230																			
	p	.0005124	.001024	.002048	.003071	.004093	.005115	.007155	.01021	.01528	.02033	.03037	.04030	.05013	.05985	.06945	.07893	.08829	p
240	h	307.7	307.7	307.7	307.7	307.7	307.7	307.7	307.6	307.6	307.7	307.7	307.8	307.8	308.0	308.1	308.3	308.5	h
	s	5.758	5.472	5.186	5.019	4.900	4.808	4.669	4.521	4.353	4.234	4.065	3.945	3.852	3.776	3.711	3.654	3.605	s
240																			
	p	.0004919	.0009835	.001966	.002948	.003930	.004910	.006869	.009801	.01467	.01952	.02915	.03870	.04814	.05747	.06670	.07582	.08482	p
250	h	318.0	318.0	318.0	318.0	318.0	318.0	318.0	318.0	318.0	318.1	318.2	318.3	318.3	318.6	318.8	319.0	319.2	h
	s	5.800	5.514	5.228	5.061	4.942	4.850	4.711	4.563	4.396	4.276	4.108	3.988	3.895	3.818	3.754	3.697	3.648	s
250																			
	p	.0004730	.0009457	.001891	.002835	.003778	.004721	.006605	.009424	.01411	.01877	.02804	.03721	.04630	.05528	.06417	.07295	.08162	p
260	h	328.3	328.3	328.3	328.3	328.3	328.3	328.3	328.3	328.4	328.4	328.5	328.6	328.8	328.9	329.1	329.3	329.6	h
	s	5.840	5.554	5.269	5.101	4.983	4.890	4.752	4.604	4.436	4.317	4.149	4.029	3.930	3.859	3.795	3.739	3.689	s
260																			
	p	.0004555	.0009106	.001821	.002730	.003639	.004546	.006359	.009073	.01359	.01808	.02700	.03584	.04460	.05326	.06182	.07029	.07865	p
270	h	338.6	338.6	338.6	338.6	338.6	338.6	338.6	338.7	338.7	338.8	338.9	339.0	339.2	339.4	339.6	339.9	340.1	h
	s	5.879	5.593	5.307	5.140	5.022	4.929	4.790	4.643	4.475	4.356	4.188	4.068	3.975	3.899	3.834	3.778	3.729	s
270																			
	p	.0004392	.0008781	.001756	.002632	.003509	.004384	.006133	.008732	.01310	.01743	.02604	.03457	.04302	.05138	.05965	.06783	.07591	p
280	h	348.9	348.9	348.9	348.9	348.9	348.9	349.0	349.0	349.0	349.1	349.3	349.4	349.6	349.8	350.1	350.3	350.6	h
	s	5.916	5.631	5.345	5.178	5.059	4.967	4.828	4.681	4.513	4.394	4.226	4.106	4.013	3.937	3.872	3.817	3.767	s
280																			
	p	.0004041	.0008478	.001695	.002542	.003388	.004233	.005922	.008450	.01168	.01683	.02515	.03339	.04155	.04963	.05762	.06553	.07335	p
290	h	359.2	359.2	359.2	359.2	359.2	359.2	359.3	359.3	359.4	359.5	359.6	359.8	360.0	360.3	360.5	360.8	361.1	h
	s	5.953	5.667	5.381	5.214	5.095	5.003	4.864	4.717	4.549	4.430	4.262	4.143	4.050	3.974	3.909	3.853	3.804	s
290																			
	p	.0004099	.0008196	.001639	.002457	.003275	.004092	.005725	.008169	.01223	.01627	.02431	.03228	.04015	.04799	.05573	.06339	.07096	p
300	h	369.5	369.5	369.5	369.5	369.6	369.6	369.6	369.6	369.7	369.8	370.0	370.2	370.4	370.7	371.0	371.3	371.6	h
	s	5.985	5.702	5.416	5.249	5.130	5.038	4.899	4.752	4.584	4.465	4.297	4.178	4.085	4.009	3.945	3.889	3.839	s
300																			

15.000

VELOCITY of SOUND IN CRYOGENIC FLUIDS

CONTENTS

Velocity of Sound in Liquid Helium 15.001

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Velocity of Sound in Gaseous Nitrogen 15.004

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Velocity of Sound in Gaseous Argon 15.009

Velocity of Sound in Liquid Methane 15.010

Velocity of Sound in Gaseous Methane 15.010

VELOCITY of SOUND in LIQUID HELIUM

Sources of Data:

Atkins, K. R. and Stasior, R. A.; Can. J. Phys. 31, 1156 (1953)

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Findlay, J. C., Pitt, A., Smith, H. G. and Wilhelm, J. O.; Phys. Rev. 54, 506 (1938)

Findlay, J. C., Pitt, A., Smith, H. G. and Wilhelm, J. O.; Phys. Rev. 56, 122 (1939)

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Comments:

The values of velocity of sound reported here are for ordinary sound in He^4 and do not include the velocities of second sound also associated with liquid helium. The data for the velocity of sound tabulated below and illustrated on the graph are from the references listed above as sources of data. The data for the Saturated Liquid (liquid at the boiling point) listed in Table I, are from the paper by Findlay, et al. with additional data for Helium II listed in Table II from the paper by Chase. The values for pressures from 2.5 to 70 atm. tabulated in Table III are from the paper by Atkins and Stasior. Additional data in Tables IV, V, VI, VII illustrate the variation of the velocity of sound as a function of frequency. These data are from the two papers by Van Itterbeek, Forrez and Teirlinck.

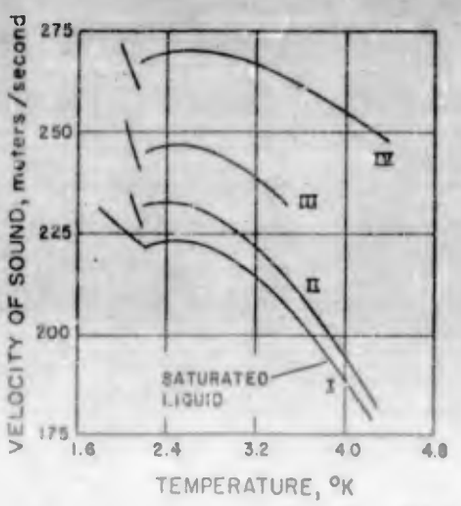
It will be noted that the graph indicates a discontinuity at the λ point (phase boundary between Helium I and Helium II). The work of Findlay, Pitt, Smith and Wilhelm showed a drop in the velocity of sound in liquid Helium I as the λ point (2.19°K) was approached, and below the λ point the velocity rose again, as illustrated on the graph, however, no discontinuous decrease in velocity was noted. However, Ehrenfest's thermodynamic relations for a phase change of the second order (one involving no latent heat) require that there be a discontinuity in the velocity of sound at this point. The authors concluded that this failure to show

(Continued on following page)

VELOCITY OF SOUND in LIQUID HELIUM (Cont.)

Comments: (cont.)

a decrease was due to the formation of bubbles. In order to check this theory they repeated the experiment using pressures up to five atmospheres in order to prevent the formation of bubbles. Under these conditions the predicted discontinuity was observed, as illustrated below.



The Velocity of Sound in Liquid Helium under Various Pressures

I - Vapor Pressure
II - 1 Atmosphere
III - 2.47 Atmospheres
IV - 5.5 Atmospheres

Pellam and Squire, working at normal evaporation pressures found no discontinuity, and concluded that their results were due to the lack of higher pressures as used in the experiments of Findlay et al. On strictly theoretical grounds, using numerous assumptions, Pippard concluded that the anomalous behavior at the λ point was due to inclusions of He II in He I immediately above the λ point, and inclusions of He I in He II immediately below the λ point. Pippard also stated that these inclusions should have a mean radius of 2.1×10^{-7} cm, each consisting of about 850 atoms, in order to explain the curves. In this way the absence of the discontinuity required by Ehrenfest could be accounted for. Atkins and Osborne determined the velocities below the λ point. Atkins and Chase determined the velocity curve both above and below the λ point and found no discontinuity. Their velocities were slightly lower than those of Findlay et al. near the λ point. Atkins and Stasior observed no discontinuities for the series of velocity-temperature curves at constant pressure reported here. The work of Chase published in 1953 and in 1956 is in close agreement with that of Findlay et al.

Van Itterbeek, Forrez and Teirlinck made measurements on the velocity of sound in liquid helium in the neighborhood of 1°K with frequencies of 200, 500, 600, 800, and 1500 kilocycles per second. A small minimum was observed at 800 kilocycles per second for the velocity as a function

(Continued on following page)

VELOCITY of SOUND in LIQUID HELIUM (Cont.)

Comments: (cont.)

of frequency which does not appear at the boiling point. These values are tabulated in Tables IV and V. Van Itterbeek, Forrez and Teirlinck in a second article made the observations listed in Table VI, and stated that the velocity as a function of frequency is constant to within one part in 2400, and that the velocity seems to be constant as a function of temperature. At the boiling point they found no difference in the velocity using two frequencies, as shown in Table VII.

Table I. The Velocity of Sound for Saturated Liquid*

Temperature °K	Velocity m/sec
He I	
4.22	179.8
4.0	189.2
3.6	206.5
2.5	223.3
2.20	221.2
He II	
2.18	221.7
2.0	225.3
1.76	231.4

* Findlay, Pitt, Smith and Wilhelm

Table II. Velocity of Sound in Helium II*

Temp. °K	Velocity (m/sec)	Temp. °K	Velocity (m/sec)
1.3	236.73	1.9	229.47
1.4	236.35	2.0	226.68
1.5	235.66	2.05	224.90
1.6	234.61	2.10	222.72
1.7	233.28	2.15	220.20
1.8	231.70	2.179	218.00

* Chase

(Continued on following page)

VELOCITY of SOUND in LIQUID HELIUM (Cont.)

Comments: (cont.)

Table III. The Velocity of First Sound in Liquid Helium*

Velocity of Sound, m/sec

Temp. °K	Pressure, atm.											
	Vapor Press.	2.5	5	10	15	20	25	30	40	50	60	70
1.25	237	257	273	300	326	346	365					
1.50	235	256	272	299	325	345	362					
1.75	233	252	270	298	323	342	355					
1.80	232	251	269	297	321	339	352					
1.90	229	249	267	295	318	333	348	372				
2.00	227	247	265	292	312	336	358	379				
2.10	222	240	259	288	317	340	361	382				
2.20	219	240	259	293	322	344	366	385	419			
2.25	220	242	261	295	323	345	367	[illegible]	420			
2.50	222	244	265	298	326	348	369	[illegible]	422	451		
3.00	218	242	264	298	327	349	370	[illegible]	423	452	481	510
3.50	206	230	256	296	325	349	370	389	423	452	481	510
4.00	190	216	246	290	321	347	369	388	423	452	481	510
4.20	180	206	241	285	318	345	368	387	422	452	481	510

Values above the line in the table are for Helium II, and below the line for Helium I.

* Atkins and Stasior

Table IV. Variation of Velocity of Sound with Frequency*

Temp. °K	Press. mm Hg	Vel. m/sec	Frequency Kc/sec	Temp. °K	Press. mm Hg	Vel. m/sec	Frequency Kc/sec
1.076	.241	238.05	218.59	1.116	.336	237.75	218.63
1.108	.315	238.05	218.56	1.123	.357	238.05	218.56
1.081	.250	237.75	513.12	1.116	.336	237.40	813.76
1.081	.250	237.75	512.76	1.146	.420	237.22	813.44
1.081	.250	237.57	624.01	1.123	.357	237.78	1449.28
1.090	.273	237.48	800.33	1.123	.357	237.69	1476.05
1.076	.241	237.81	1484.92	1.116	.336	237.64	1476.05
1.099	.294	237.68	1476.05				

* Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 63 (1957)

(Continued on following page)

VELOCITY of SOUND in LIQUID HELIUM (Cont.)

Comments: (cont.)

Table V. Variation of Velocity of Sound with Frequency, for Saturated Liquid*

Temp. °K	Pressure mm Hg	Velocity m/sec	Velocity** m/sec	Frequency Kc/sec
4.221	763.3	180.38	180.32	1469.92
4.216	761.2	180.39	180.18	1484.78
4.222	764.3	180.08	180.05	814.45
4.223	765.1	179.91	179.91	799.83
4.222	764.3	180.68	180.65	623.60
4.218	761.5	180.37	180.22	512.70
4.214	758.50	180.51	180.24	218.33
4.226	767.41	180.01	180.10	218.21

* Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 63 (1957)

** Corrected to 4.223°K

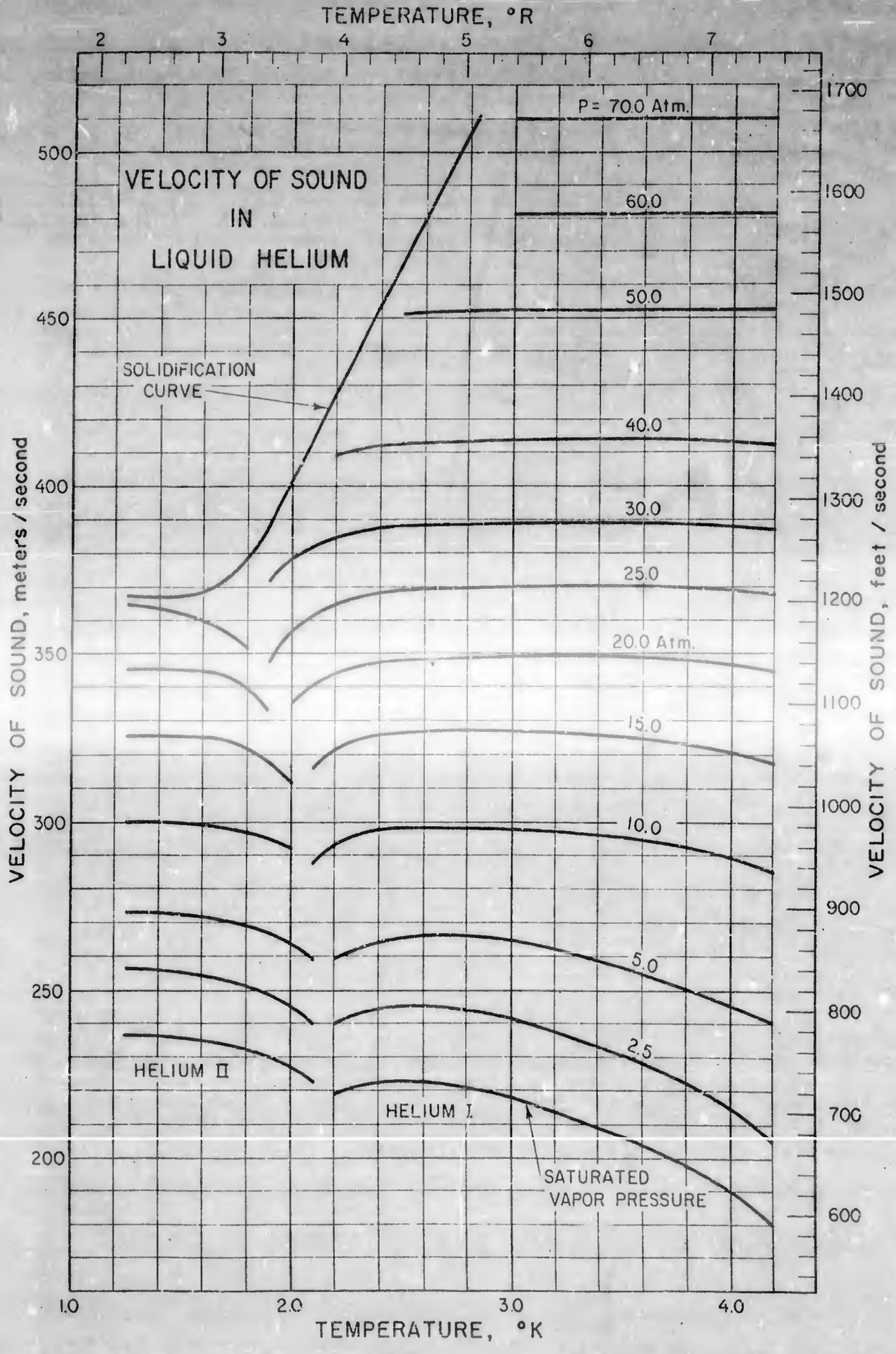
Table VI. Variation of Velocity of Sound with Frequency**

Temp. °K	Press. mm Hg	Velocity m/sec	Frequency Kc/sec	Temp. °K	Press. mm Hg	Velocity m/sec	Frequency Kc/sec
0.985	.105	238.51	218.24	0.985	.105	237.63	226.212
0.985	.105	238.35	218.012	0.985	.105	237.63	523.03
0.985	.105	238.27	211.257	0.985	.105	237.53	800.374
0.985	.105	237.81	226.385	0.997	.146	237.73	1455.76
0.985	.105	237.65	226.241				

Table VII. Velocity of Sound at 4.223°K**

Frequency Kc/scc	Velocity m/sec
217.97	180.69
226.706	180.49
226.485	180.75
226.706	180.59

** Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 905 (1957)


TEMPERATURE, °R
2
3
4
5
6
7
VELOCITY OF SOUND
IN
LIQUID HELIUM
P = 70.0 Atm.
60.0
50.0
40.0
30.0
25.0
20.0 Atm.
15.0
10.0
5.0
2.5
SOLIDIFICATION
CURVE
HELIUM II
HELIUM I
SATURATED
VAPOR PRESSURE
VELOCITY OF SOUND, meters / second
500
450
400
350
300
250
200
VELOCITY OF SOUND, feet / second
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
1.0
2.0
3.0
4.0
TEMPERATURE, °K

15.001

VELOCITY of SOUND in GASEOUS HELIUM

Sources of Data:

Van Itterbeek, A. and Keesom, W. H., Communs. Phys. Lab. Univ. Leiden Commun. No. 209c (1930); Wis-en Natuurk. Tijdschr. 5, 69 (1930)

Keesom, W. H. and Van Itterbeek, A., Koninkl. Ned. Akad 34, 204 (1931); Communs. Phys. Lab. Univ. Leiden Commun. No. 213b (1931)

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Other References:

Keesom, W. H. and Van Itterbeek, A., Koninkl. Ned Akad. Wetenschapen, Proc. 33, 440 (1930); Communs. Phys. Lab. Univ. Leiden Commun. No. 209a (1930)

Comments:

The values of the velocity of sound in gaseous helium are presented here as functions of temperature and pressure, from temperatures of 2.078°K to 290°K, and pressures from 0 to 1 atmosphere. The velocity of sound at the vapor pressure at various temperatures is also given. The data tabulated below and illustrated on the graphs are from the references listed above under "Sources of Data".

The data illustrated in the graph of velocity of sound versus temperature and tabulated below are from Keesom and Van Itterbeek; Van Itterbeek and Keesom; Van Itterbeek and Van Doninck; Van Itterbeek and Thys; and Schneider and Thiessen. All of the above investigators report that all values were obtained at nearly atmospheric pressures. No mention is made by any of the above authors of the purity of the experimental samples used. The data reported by Keesom and Van Itterbeek are estimated by the authors to have a maximum error of 0.1%. The frequency of the sound used is not given. Van Itterbeek and Keesom report a maximum error in their observations of 0.15%, and again no mention is made of the frequency of the sound used. Van Itterbeek and Van Doninck report a frequency of 523.78 kilocycles per second used in their determinations of velocity of sound, but they make no specific claims on the accuracy of their data. Schneider and Thiessen; and Van Itterbeek and Thys used ultrasonics of unreported frequency in their experiments and did not estimate the accuracy of their observations.

Van Itterbeek and Forrez; and Van Itterbeek and De Laet report velocities of sound at various constant temperatures below 5°K as a function of

(Continued on following page)

VELOCITY of SOUND in GASEOUS HELIUM (Cont.)

Comments: (cont.)

pressure. These data are tablulated below and illustrated in the graph of velocity of sound versus pressure, together with the velocity of sound at the vapor pressure as reported by Van Itterbeek and De Laet. Van Itterbeek and Forrez report using a quartz crystal with a frequency of 510 kilocycles per second to propagate the sound waves through their experimental sample. Using audible sound, Van Itterbeek and De Laet measured the velocity of sound in helium gas at very low temperatures and pressures. Using these data they extrapolated the velocity of sound to the vapor pressure at various temperatures. A graphical comparison was made between Keesom and Van Itterbeek's observations at 4.247°K and Van Itterbeek's values at 4.228°K. The agreement between these two sets of data is very good. No information is given by any of the investigators mentioned above as to the purity of their experimental samples.

The units of the velocity of sound in helium gas used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Helium
as a Function of Temperature
near One Atmosphere Pressure

Temperature °K	Velocity m/sec
Van Itterbeek & Keesom	
15.181	229.1
17.186	244.2
18.424	253.1
20.429	266.2
20.519	266.2
Van Itterbeek & Thys	
290.6	997.0
Keesom & Van Itterbeek	
4.247	103.94

Temperature °K	Velocity m/sec
Van Itterbeek & Van Doninck	
20.3	265.9
75	509.9
80	526.9
85	542.9
90	559.5
90.2	559.5
Schneider & Thiessen	
194.99	822.5
273.1	973.9

(Continued on following page)

VELOCITY of SOUND in GASEOUS HELIUM (Cont.)

Comments: (cont.)

Velocity of Sound in Gaseous Helium as a Function of Pressure

Van Itterbeek and De Laet

Pressure atm.	Velocity m/sec
4.228°K	
0	121.00
.0195	120.87
.0346	120.69
.0528	120.47
.0837	120.01
.1285	119.34
.1804	118.54
.2305	117.75
.2991	116.63
.3700	115.46
.4459	113.94
.5513	112.16
.6330	110.55
.7538	107.95
.8828	104.78
3.760°K	
0	114.12
.0153	114.11
.0255	113.92
.0378	113.70
.0873	112.80
.1227	112.10
.1724	111.12
.2923	108.63
.3534	107.21
.3944	106.25
.4291	105.41
.5048	103.34
.5563	101.86
3.184°K	
0	105.01
.0350	104.28
.0708	103.33
.1098	102.29
.1514	101.10
.1913	99.88
.2487	98.04
2.824°K	
0	98.89
.0231	98.24
.0341	98.03
.0437	97.74
.0683	96.94
.1074	95.58
.1482	94.05
2.642°K	
0	95.65
.0169	95.55
.0207	95.46
.0285	95.19
.0390	94.76
.0508	94.27
.0669	93.63
.0813	93.15
.0923	92.66
.1156	91.72
2.259°K	
0	88.44
.0226	87.92
.0269	87.80
.0335	87.56
.0391	87.28
.0455	87.00
.0506	86.76
2.218°K	
0	87.64
.0256	87.11
.0314	86.70
.0382	86.24
.0446	85.70
2.078°K	
0	84.85
.0182	84.25
.0245	83.93
.0298	83.59

Van Itterbeek and Forrez

Pressure atm.	Velocity m/sec
3.582°K	
0	111.3
.1275	109.1
.1653	108.8
.2143	108.2
3.582°K	
.2517	106.5
.3206	105.6
.3876	104.1
.4318	102.5
.5204	100.0

(Continued on following page)

VELOCITY of SOUND in GASEOUS HELIUM (Cont.)

Comments: (cont.)

Velocity of Sound in Helium Gas
at the Vapour Pressure

Van Itterbeek and De Lact		
Temperature °K	Pressure atm.	Velocity m/sec
4.228	1.0116	101.96
3.760	0.6288	99.62
3.184	0.3118	95.37
2.824	0.1823	92.62
2.642	0.1336	90.08
2.259	0.0615	86.12
2.218	0.0558	84.83
2.078	0.0392	82.71

RDM/FEEG/RS Issued: 4/17/61

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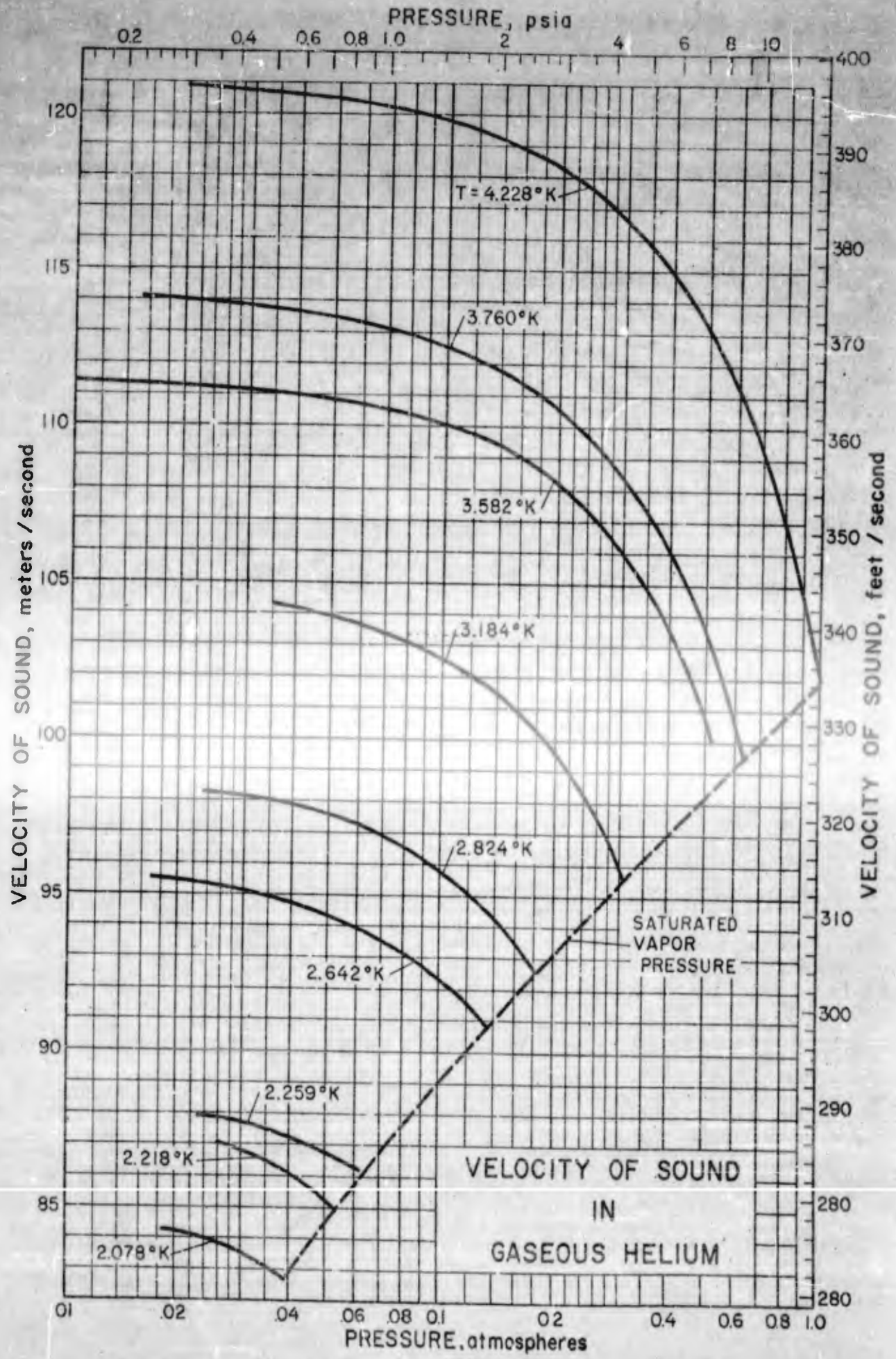
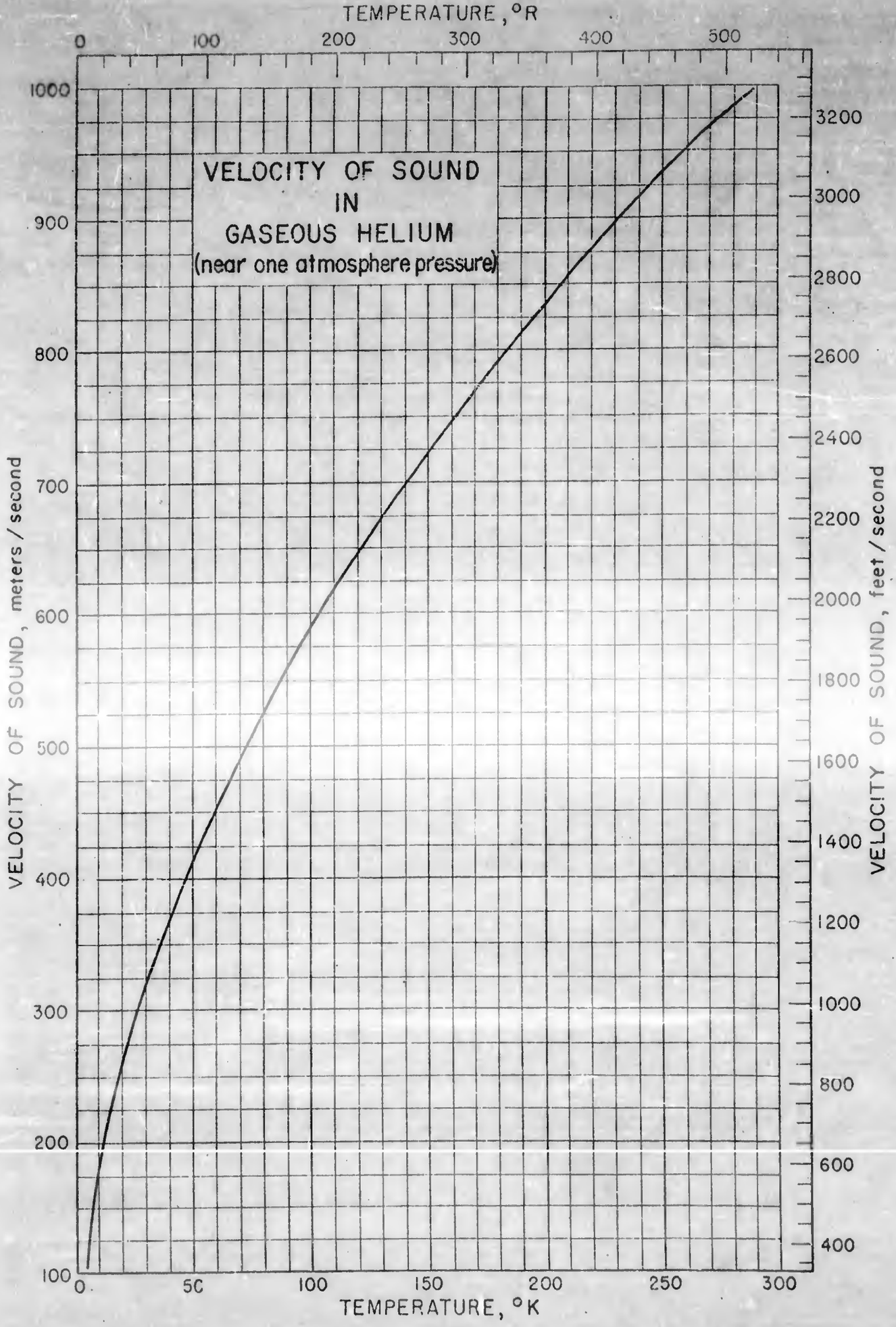

PRESSURE, psia
0.2
0.4
0.6
0.8
1.0
2
4
6
8
10
400
390
380
370
360
350
340
330
320
310
300
290
280
280
120
115
110
105
100
95
90
85
T = 4.228°K
3.760°K
3.582°K
3.184°K
2.824°K
2.642°K
2.259°K
2.218°K
2.078°K
SATURATED
VAPOR
PRESSURE
VELOCITY OF SOUND
IN
GASEOUS HELIUM
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
.01
.02
.04
.06
.08
0.1
0.2
0.4
0.6
0.8
1.0
PRESSURE, atmospheres


TEMPERATURE, °R
0
100
200
300
400
500
VELOCITY OF SOUND
IN
GASEOUS HELIUM
(near one atmosphere pressure)
VELOCITY OF SOUND, meters / second
1000
900
800
700
600
500
400
300
200
100
VELOCITY OF SOUND, feet / second
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
0
50
100
150
200
250
300
TEMPERATURE, °K

VELOCITY of SOUND in LIQUID HYDROGEN

Sources of Data:

Galt, J. K.; J. Chem. Phys. 16, 505 (1948)

Pitt, A. and Jackson, W. J.; Can. J. Research 12, 686 (1935)

Van Itterbeek, A. and Verhaegen, L.; Nature 163, 399 (1949)

Other References:

Van Itterbeek, A., Van den Berg, G. J. and Limburg, W.; Physica 20, 307 (1954)

Verhaegen, L.; Verhandel. Koninkl. Vlaam. Akad. Wetenschap. Belge. K. Wetenschap. 38, (1952) 65 pp.

Comments:

The values of velocity of sound presented here on the graph are for both equilibrium and normal liquid hydrogen. Isolated values of velocity of sound in liquid parahydrogen and various ortho-para concentrations are given. The data for the velocity of sound tabulated below and illustrated on the graph are from the references listed above as "Sources of Data". The temperature range of the data is 14.8 to 21.0°K.

Pitt and Jackson found the velocity of sound in liquid hydrogen at 20.4°K to be 1127 m/sec. Galt working at 17°K ±1° found a sonic series of values between 14 and 21°K as shown in the following table. Pitt and Jackson used frequencies of 427 kc/sec, Galt used 44.4 mc/sec, and Van Itterbeek and Verhaegen used 523 kc/sec. Pitt and Jackson and Galt's values are compared to the values of Van Itterbeek and Verhaegen on the accompanying graph.

Van Itterbeek and Verhaegen					
Saturation Pressure					
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
21.0	1150	18.2	1251	16.5	1265
20.8	1173	18.0	1260	16.3	1274
20.4	1229	17.4	1278	14.8	1340
20.4	1190	16.7	1271		

The ortho-para concentration of the liquid is not reported for the above values, and no statement is made regarding the age of the liquid hydrogen at the time the measurements were made. Van Itterbeek and Verhaegen, without stating the age of the hydrogen at the beginning of their measurements, observed a change of velocity at the normal boiling point for about 53 minutes, and during that time recorded an increase

(Continued on following page)

VELOCITY of SOUND in LIQUID HYDROGEN (Cont.)

Comments: (cont.)

from about 1140 m/sec to 1240 m/sec. They state that this increase with time is not due to a temperature drift, but probably to a transformation of the normal to parahydrogen in the liquid phase. They also assume that a value of 1340 m/sec at 14.8°K corresponds to a more complete transformation into parahydrogen, and that Galt's value of 1187 m/sec at 17°K ±1° was for normal hydrogen.

Verhaegen reported 1130 m/sec for normal hydrogen and 1237 m/sec for parahydrogen at 20.4°K. Van Itterbeek, Van den Berg and Limburg noted the catalytic effect of ultrasonic waves speeding up the transformation from normal to parahydrogen. With a frequency of 1 mc/sec they found a velocity of 1129 m/sec and with 3 mc/sec parahydrogen gave a value of 1230 m/sec, both at 20.4°K.

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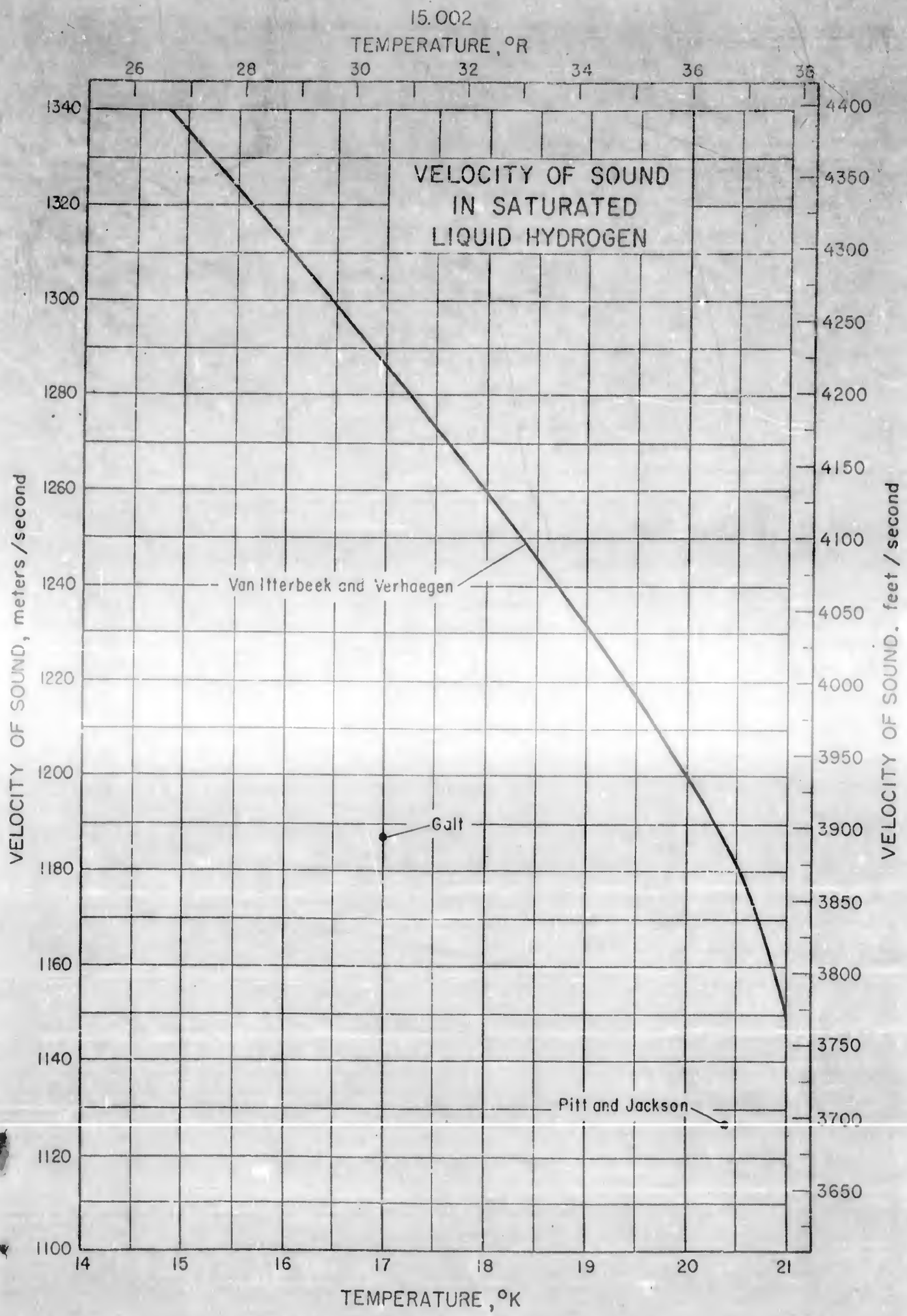

TEMPERATURE, °R
26
28
30
32
34
36
38
VELOCITY OF SOUND IN SATURATED LIQUID HYDROGEN
VELOCITY OF SOUND, meters/second
1340
1320
1300
1280
1260
1240
1220
1200
1180
1160
1140
1120
1100
VELOCITY OF SOUND, feet/second
4400
4350
4300
4250
4200
4150
4100
4050
4000
3950
3900
3850
3800
3750
3700
3650
Van Itterbeek and Verhaegen
Galt
Pitt and Jackson
14
15
16
17
18
19
20
21
TEMPERATURE, °K

VELOCITY of SOUND in GASEOUS HYDROGEN

Sources of Data:

Brown, E. H.; J. Research Natl. Bur. Standards 64C, 25-36 (Jan.- Mar.1960)

Cornish, R. E. and Eastman, E. D.; J. Am. Chem. Soc. 50, 1, 627 (1928)

Van Itterbeek, A. and Van Doninck, W.; Ann. phys. 19, 88 (1944)

Van Itterbeek, A. and Vermaelen, R.; Physica 9, 345 (1942)

Van Itterbeek, A. and Keesom, W. H.; Koninkl. Ned. Akad. Wetenschap 34, 988 (1931); Communs. Phys. Lab. Univ. Leiden No. 216c (1931)

Wooley, H. W., Scott, R. B., and Brickwedde, F. G.; J. Research NBS 41, 379 (1948) RP 1932

Other References:

Clark, A. L. and Katz, L.; Can. J. Research 21. 1 (1943)

Darrow, K. K.; Phys. Rev. 7, 413 (1916)

Dulong, P. L.; Ann. Chim. et Phys. 41, 113 (1829)

Grüneisen, E. and Merkel, E.; Ann. Physik. 66, 344 (1921)

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564, (1955) 488 pp.

Low, J. W.; Ann. Physik. 52, 641 (1894)

Michels, A., Wassenaar, T. and Wolkers, G. J.; Appl. Sci. Research A5, 121 (1955)

Pitt, A., and Jackson, W. J.; Can. J. Research 12, 686 (1935)

Regnault, V.; Compt. rend. 66, 209 (1868)

Sturm, J.; Ann. Physik. 14, 822 (1904)

Thiesen, M.; Ann. Physik. 24, 401 (1907)

Van Itterbeek, A.; Communs. Kamerlingh Onnes Lab. Univ. Leiden Suppl. No. 70b (1932)

Van Itterbeek, A. and Mariens, P.; Physica 4, 207 (1937)

Van Itterbeek, A. and Mariens, P.; Physica 4, 609 (1937)

Van Itterbeek, A. and Van Paemel, O.; Physica 5, 845 (1938)

Zoch, I. B.; Ann. Physik. 128, 497 (1866)

Comments:

The values of the velocity of sound in hydrogen are presented here as functions of pressure, density and temperature. The data illustrated in the three graphs and tabulated below are from the references listed above under "Sources of Data". The first graph is from E.H. Brown's paper and illustrates the velocity of sound as a function of temperature for densities of 0 to 500 Amagat at temperatures between 15° and 300°K. These data were calculated by Brown using the relation $Mc^2/RT = (\partial\rho Z/\partial\rho)_T + 1/C_v (\partial TZ/\partial T)^2_\rho$; where R is the gas constant; M the molecular weight; T the temperature; ρ the density; C_v the specific heat at constant volume; Z the compressibility factor; and c the velocity of sound for the real gas. The data used by Brown in these calculations are the

(Continued on following page)

VELOCITY of SOUND in GASEOUS HYDROGEN (Cont.)

Comments: (cont.)

P-V-T and specific heat values from Woolley, Scott and Brickwedde and are for the normal hydrogen (75% ortho, 25% parahydrogen). The results are presented here on the graph in the form of c/c^o, where c^o is the velocity of sound in the ideal gas and is given by: $c^o = \sqrt{RT\gamma^o M}$. selected values of c^o are given in the accompanying table.

The second graph illustrates the variation of velocity of sound as a function of temperature, at near atmosphere pressure, from the normal boiling point (T = 20.39°K) to 400°K. These data are tabulated below from the several references. The third graph illustrates the variation of velocity of sound as a function of pressure, for a pressure range of 0 to 1.0 atmospheres with temperatures from 17° to 20°K. The data from the paper by Van Itterbeek and Keesom are illustrated on this plot. The isotherms of velocity of sound versus pressure were extrapolated to the vapor pressures as derived from data reported by Woolley, Scott and Brickwedde. These smoothed isotherms represent the experimental points with a maximum deviation of 0.5 m/sec except on the 18.60°K isotherm where a maximum deviation of 2 m/sec occurred. The values of the velocity of sound at zero pressure have been calculated for the ideal gas, i.e., $c = \sqrt{RT\gamma}$, where c is the velocity of sound, R is the gas constant, T is the temperature and γ is the ratio of specific heats.

The measurements from the several sources illustrated in these two graphs employed a variety of experimental methods using widely differing frequencies. The hydrogen was of uncertain ortho-para composition, and of uncertain purity, but the results produced by the several experimenters are generally consistent.

The units of the velocity of sound in gaseous hydrogen used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665), density in Amagats (density, gm/cm^3 = density, Amagat x 8.9885 x 10^{-5}) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Hydrogen

as a Function of Temperature

Cornish and Eastman			
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
372.52	1466.30	203.63	1099.00
369.40	1461.10	182.41	1046.30
333.31	1389.30	165.58	1001.60
308.96	1337.70	145.64	947.15
294.27	1307.10	135.71	920.00
269.02	1251.50	81.12	738.00
238.23	1181.70		

(Continued on following page)

VELOCITY of SOUND in GASEOUS HYDROGEN (Cont.)

Comments: (cont.)

Velocity of Sound in Gaseous Hydrogen
as a Function of Temperature

Van Itterbeek and Vermaelen			
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
293.0	1307.6	100	807.6
283	1285.6	90	768.6
273	1262.5	80	730.0
253	1215.4	75	711.5
233	1165.3	60	641.0
213	1115.2	50	585.7

Velocity of Sound in Gaseous Hydrogen.
as a Function of Pressure

Van Itterbeek and Keesom					
Press. atm.	Velocity m/sec	Press. atm.	Velocity m/sec	Press. atm.	Velocity m/sec
20.42°K		.3951	363.9	.2608	353.2
.9295	358.9*	.2738	365.7	.1116	355.9
.7981	361.4	.1527	368.3	17.85°K	
.7814	361.6	19.38°K		.3621	342.1
.6463	364.6	.6395	352.4	.3126	342.9
.6078	365.5	.5852	354.0	.2539	344.3
.4013	369.0	.5323	354.8	.1978	345.7
.2847	371.0	.4006	357.5	.1403	347.3
.2567	371.5	.3011	359.4	17.17°K	
.1723	372.8	.1993	361.4	.2690	338.0
.1533	373.2	.1109	363.0	.2113	339.1
19.91°K		18.60°K		.1726	339.7
.8028	356.1	.4021	350.9	.1311	340.5
.6686	358.3	.3540	351.1	.1042	341.2
.5275	361.3				

(Continued on following page)

VELOCITY of SOUND in GASEOUS HYDROGEN (Cont.)

Comments: (cont.)

The various experimental methods employed and the results obtained by researchers over the last century or more are of interest.

The work of P. L. Dulong on the velocity of sound, published in 1829, was based on the experimental determination of the frequency of vibration produced in the same tube when filled successively with various gases. He assumed that these frequencies were directly proportional to the velocities of sound in the different gases. Letting V and n be the velocity and frequency when the tube was filled with air, and V_1 and n_1 the values when filled with the gas being studied, we have $V/V_1 = n/n_1$. Adopting the value of 333 m/sec for air at 0°C and 1 atm. he arrived at a value of 1269.5 m/sec for hydrogen.

Regnault published a critical review of all possible sources of error in the case of sound traveling in tubes up to 100 mm length and of varying diameters. From his experiments he concluded that both the velocity and the intensity of sound decrease as the tube diameter decreases. Assuming the velocity in dry air at 0°C to be 331.37 m/sec, he gives the velocity in hydrogen to be 3.801 times as large, namely 1259.5 m/sec. Zoch's value of 1286 m/sec is obviously too large. Low's value of 1236 m/sec at 15°C, he himself questions. Sturm used a tube having a 21 mm diameter, and arrived at a value of 1257.8 m/sec at 18°C.

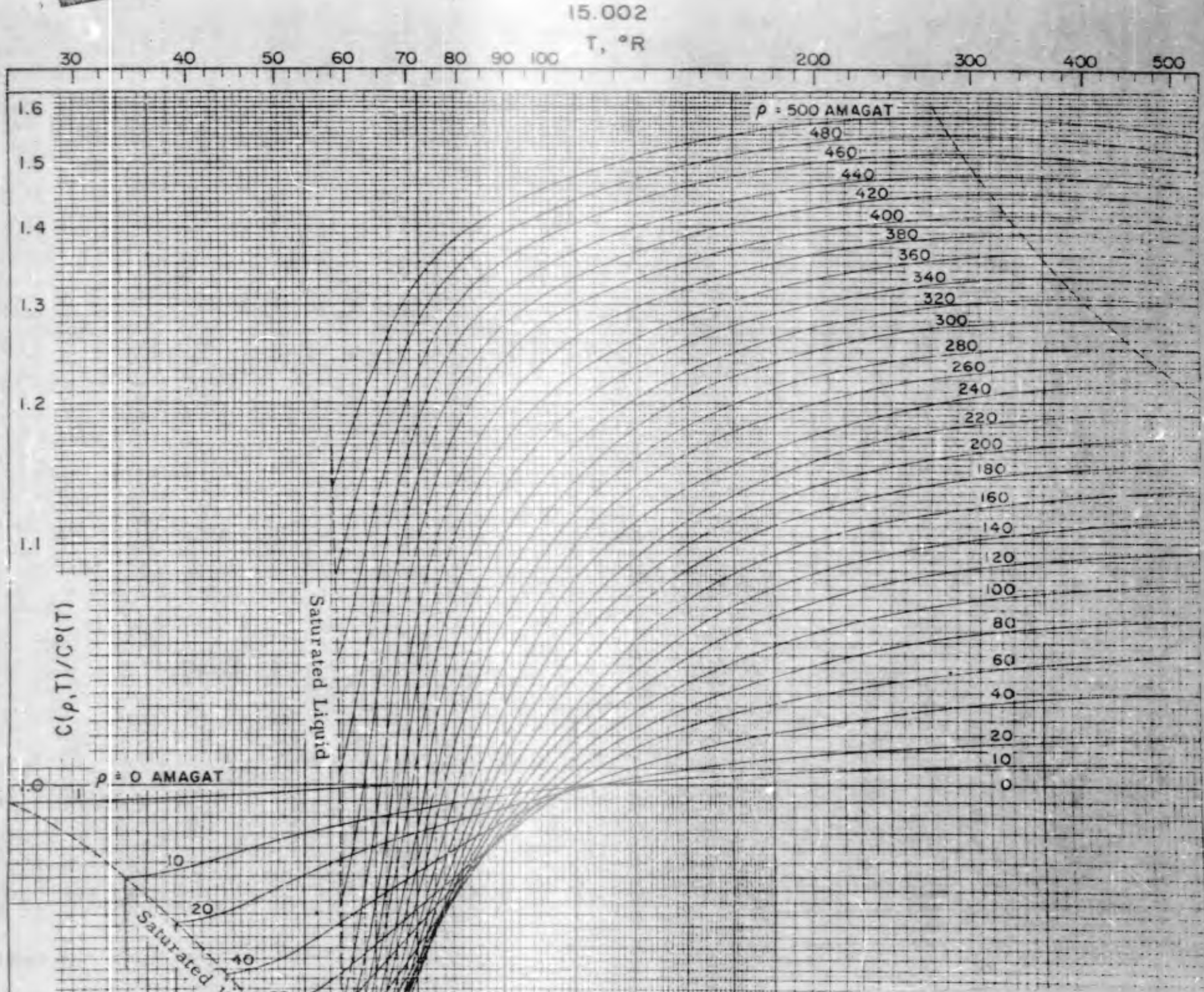
One cause of the variation of the velocity of sound when measured with different frequencies may be found in the relaxation time. A. L. Clark and L. Katz state in a footnote:

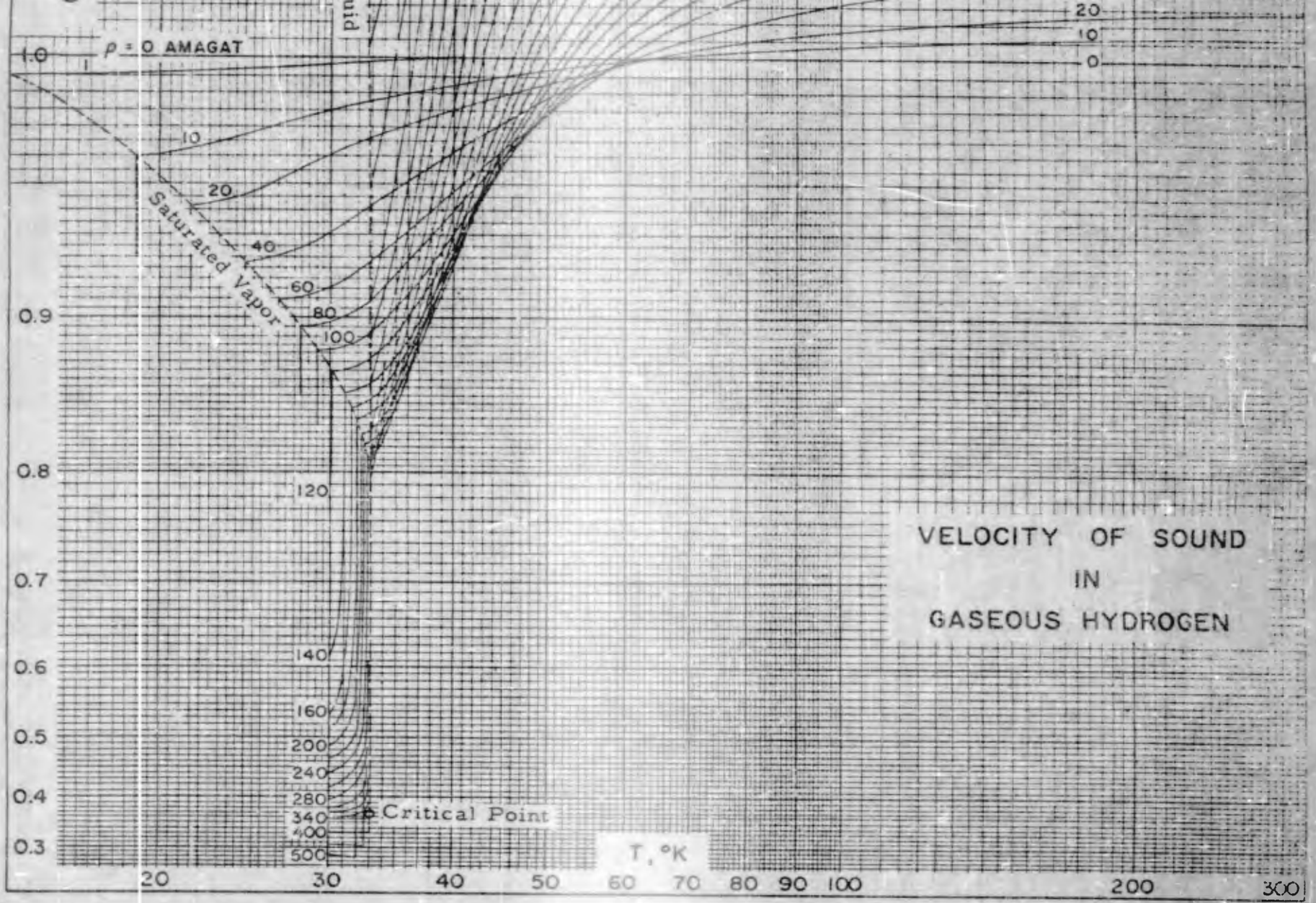
> "When kinetic energy is given to a group of molecules, the time required for this energy to be distributed among the vibrational degrees of freedom is known as the relaxation time. Dispersion of sound with frequency is the phenomenon which occurs when the frequency is so great as to be comparable to the relaxation time. This phenomenon appears as a change of velocity of sound, change of the ratio of specific heats of the gas, and of some related quantities."

Darrow, using frequencies from 400 to 2000 cycles/sec concluded that the velocity in hydrogen was 3.792 times as great as in air. By interpolation of the data published in 1955 by Michels, Wassenaar and Wolkers, we find the velocity in air at 0°C and 1 atm. to be 331.54 m/sec. Using this value, Darrow's value for hydrogen becomes 1257.19 m/sec. Grüneisen and Merkel give as the most probable value 1260.6 at 0° and 357.0 at -252.9°C using 427 kc/sec frequency. Van Itterbeek and Mariens used a piezo-quartz crystal having a frequency of 304.4 kc/sec and arrived at a value of 0°C of 1256 m/sec.

Cornish and Eastman used resonance tubes and audible frequencies up to 10,000 cycles per second using an adaptation of Thiesen's method. After applying certain corrections to Grüneisen and Merkel's data, they suggest as a best value at 0°C, 1260.9 m/sec.

In view of all this it is remarkable that Dulong in 1829 arrived at a figure of 1269 lying in the range of present day values, which in the case of Pitt and Jackson are as high as 1286 m/sec.


T, °R
30
40
50
60
70
80
90
100
200
300
400
500
1.6
1.5
1.4
1.3
1.2
1.1
C(ρ,T)/C°(T)
ρ = 500 AMAGAT
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
10
0
Saturated Liquid
ρ = 0 AMAGAT
10
20
40
Saturated


VELOCITY OF SOUND
IN
GASEOUS HYDROGEN
ρ = 0 AMAGAT
Saturated Vapor
Critical Point
T, °K
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10
20
40
60
80
100
120
140
160
200
240
280
340
400
500
20
30
40
50
60
70
80
90
100
200
300

SONIC VELOCITY c(ρ,T) OF NORMAL HYDROGEN*

Calculated from the data of H. W. Woolley, R. B. Scott, F. G. Brickwedde, "Compilation of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-para Modifications," J. Research NBS 41, 379 (1958) RP 1932, by means of the formula

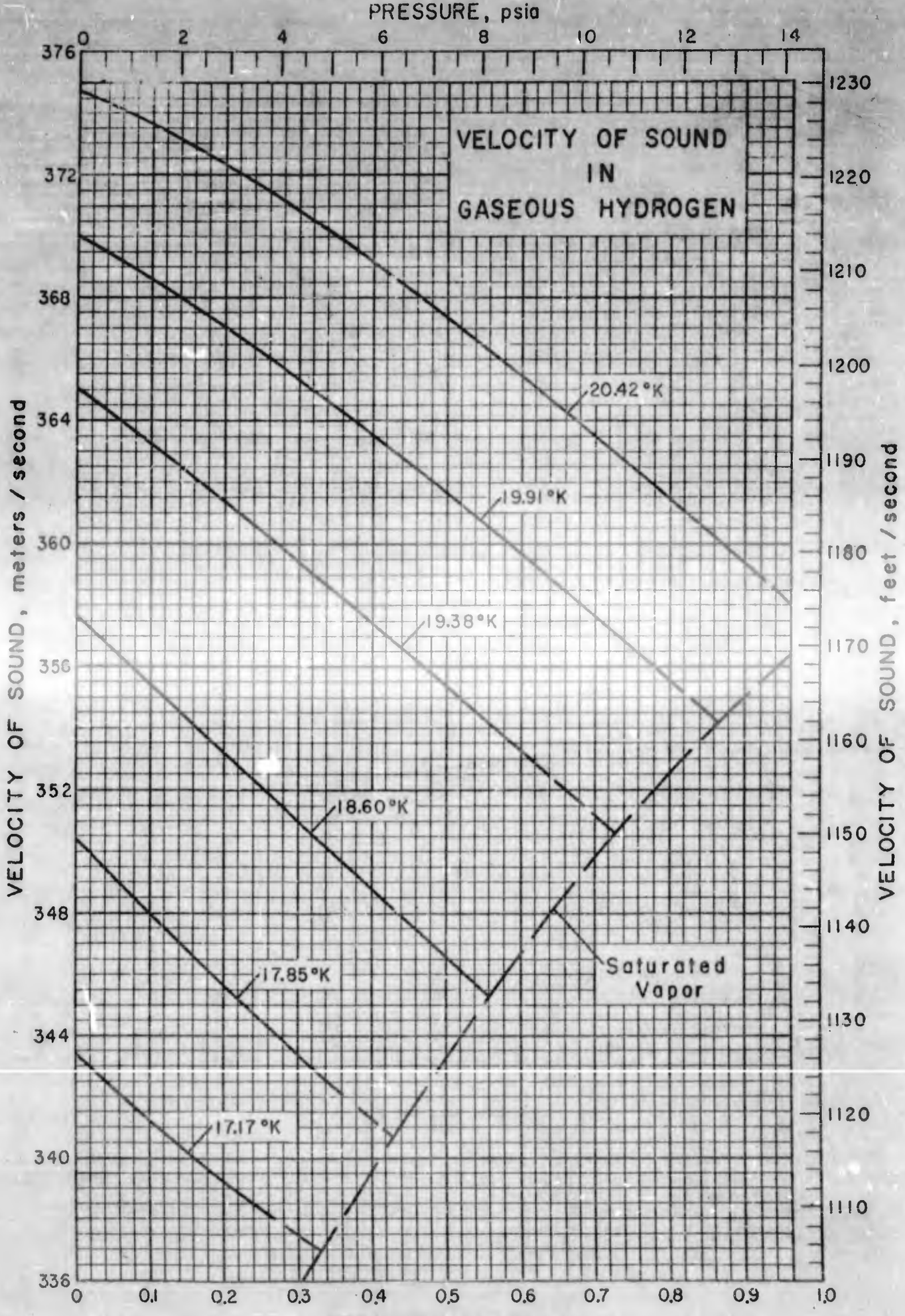
$$\frac{Mc^2}{RT} = \left(\frac{\partial \rho Z}{\partial \rho}\right)_T + \frac{R}{c_v}\left(\frac{\partial T Z}{\partial T}\right)_\rho^2.$$

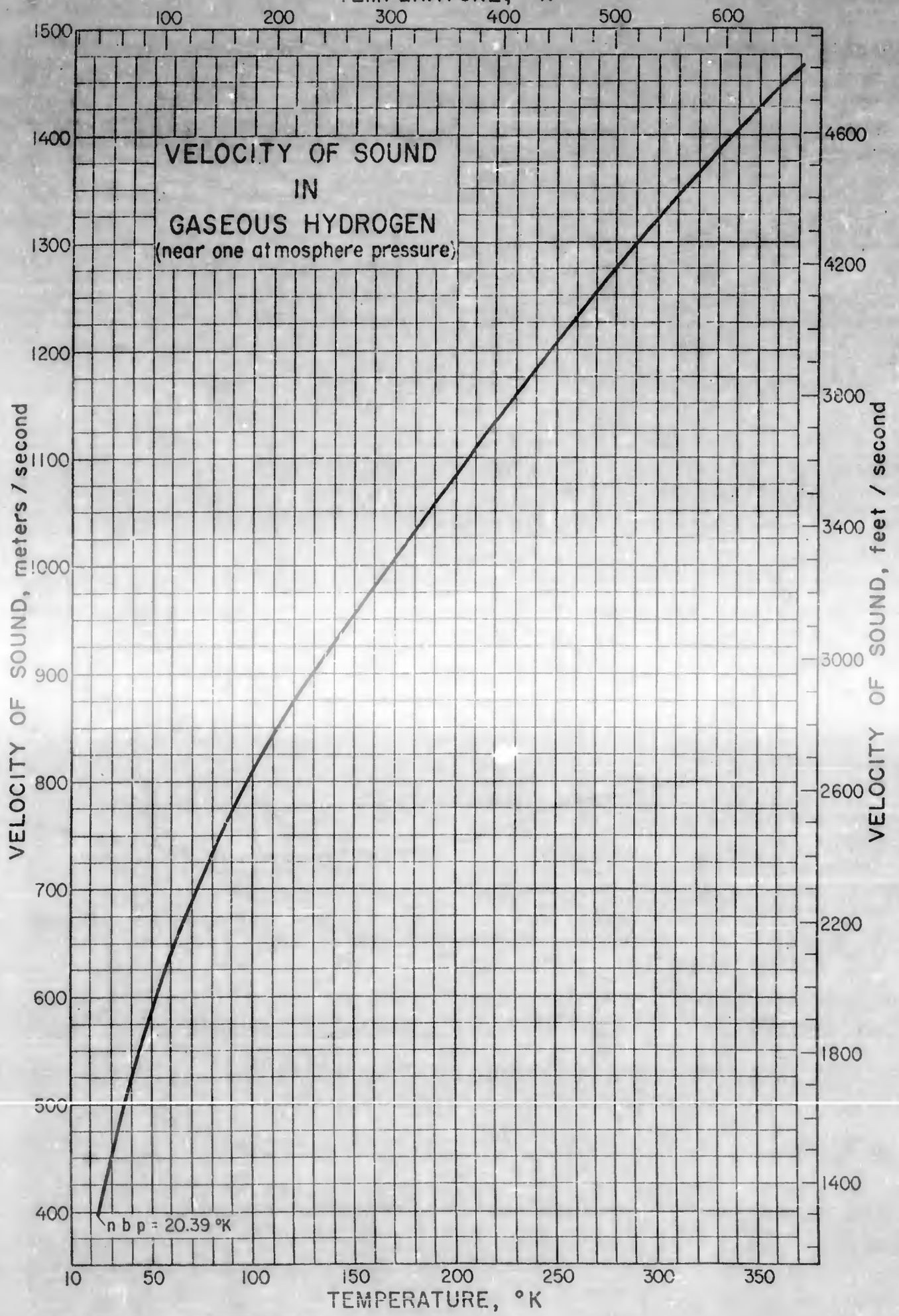
Sonic Velocity $c^o(T) = \sqrt{\frac{R}{M} T\gamma^o(T)}$ of Normal Hydrogen in the Perfect Gas State

T°K	c^o m/sec.	T°K	c^o m/sec.
20	370.8	56	619.4
22	388.8	58	630.1
24	406.1	60	640.6
26	422.7	65	665.7
28	438.7	70	689.4
30	454.1	75	711.8
32	469.0	80	733.0
34	483.4	85	753.1
36	497.4	90	772.3
38	511.0	95	790.6
40	524.3	100	808.1
42	537.2	150	959.2
44	549.8	200	1089
46	562.1	250	1208
48	574.1	300	1318
50	585.8	400	1519
52	597.3	500	1697
54	608.5	600	1858

*from Edmund H. Brown, Expansion Engines for hydrogen liquefiers, J. Research NBS 64C, 25 (January-March 1960).

15.002


PRESSURE, psia
0
2
4
6
8
10
12
14
VELOCITY OF SOUND
IN
GASEOUS HYDROGEN
20.42°K
19.91°K
19.38°K
18.60°K
17.85°K
17.17°K
Saturated
Vapor
VELOCITY OF SOUND, meters / second
376
372
368
364
360
356
352
348
344
340
336
VELOCITY OF SOUND, feet / second
1230
1220
1210
1200
1190
1180
1170
1160
1150
1140
1130
1120
1110
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PRESSURE, atmospheres


TEMPERATURE, °R
100
200
300
400
500
600
VELOCITY OF SOUND
IN
GASEOUS HYDROGEN
(near one atmosphere pressure)
VELOCITY OF SOUND, meters / second
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
VELOCITY OF SOUND, feet / second
4600
4200
3800
3400
3000
2600
2200
1800
1400
n b p = 20.39 °K
10
50
100
150
200
250
300
350
TEMPERATURE, °K

15.003

VELOCITY of SOUND in GASEOUS NEON

Source of Data:

Keesom, W. H. and Van Lammeren, J. A.; Physica 1, 1161 (1934)

Other References:

Grennspan, M. J.; Acoust. Soc. Am. 28, 644 (1956)

Keesom, W. H. and Van Itterbeek, A.; Proc. Acad. Sci. Amsterdam 33, 440 (1930); Communs. Phys. Lab. Univ. Leiden No. 209a (1930)

Skudrzyk, E.; Acta Phys. Austriaca 2, 148 (1949)

Van Itterbeek, A. and Mariens, P.; Physica 7, 125 (1940)

Van Itterbeek, A. and Thys, L.; Physica 5, 889 (1938)

Comments:

The values of the velocity of sound in gaseous neon are given here as functions of pressure and temperature for temperatures from 26.25°K to 273.1°K at various pressures between 0 and 0.9825 atmospheres. The 26.25°K isotherm on the plot of the velocity of sound versus pressure has been terminated at the point of saturation. All the data tabulated below are from Keesom and Van Lammeren listed above under "Sources of Data".

The values of velocity of sound by Keesom and Van Lammeren are the average values from measurements at several frequencies in the audible sound range. The error caused by the resonator (heat conduction and viscosity) in the experimental apparatus was corrected by means of the Kirchhoff-Helmholtz formula as reported by Keesom and Van Itterbeek. No estimate is made of the accuracy of the measurements or the purity of the neon gas used.

The values of the velocity of sound at 0 pressure were calculated for the ideal gas, i.e., $c = \sqrt{RT\gamma}$ where c is the velocity of sound, R is the gas constant, T is the temperature and γ is the specific heat ratio. The 26.25°K isotherm has been terminated at the saturated vapor pressure.

The units of the velocity of sound in neon gas used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 890.665) and the velocity of sound in meters per second.

(Continued on following page)

VELOCITY of SOUND in GASEOUS NEON (Cont.)

Comments: (cont.)

Velocity of Sound in Gaseous Neon
as a Function of Temperature

Keesom and Van Lammeren		
Temp. °K	Pressure atm.	Velocity m/sec
273.1	0.8626	433.4
170.0	0.9822	342.2
90.24	0.9581	249.3
74.11	0.8152	225.7
62.54	0.9784	207.1

Velocity of Sound in Gaseous Neon
as a Function of Pressure

Keesom and Van Lammeren			
Pressure atm.	Velocity m/sec	Pressure atm.	Velocity m/sec
27.80°K		26.25°K	
0.9825	134.9	0.6760	131.9
0.8053	135.6	0.5063	132.6
0.6024	136.3	0.4113	133.0
0.4514	136.8	0.2763	133.5
0.2859	137.3		
0.1376	138.1		

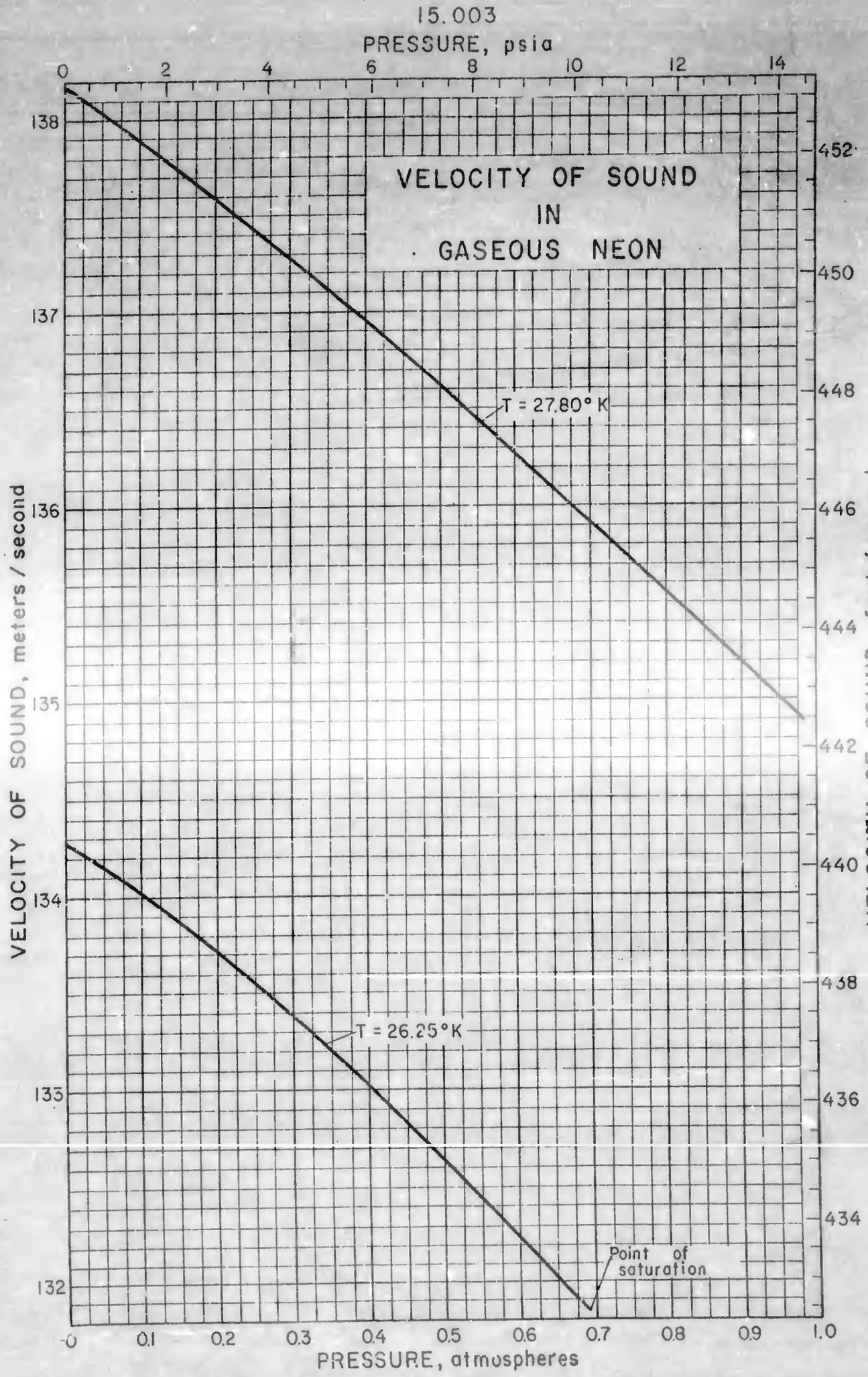
Van Itterbeek and Thys made measurements of the velocity of sound in neon gas using a sound wave with a frequency of 304.4 kilocycles per second; whereas Keesom and Van Lammeren had used audible sound. From these measurements they calculated the value of the velocity of sound at 0°C and 1 atmosphere pressure in neon gas as 434.9 m/sec, differing slightly from the value of 433.4 m/sec reported by Keesom and Van Lammeren. Van Itterbeek and Thys conclude that their own neon contained a small amount of hydrogen.

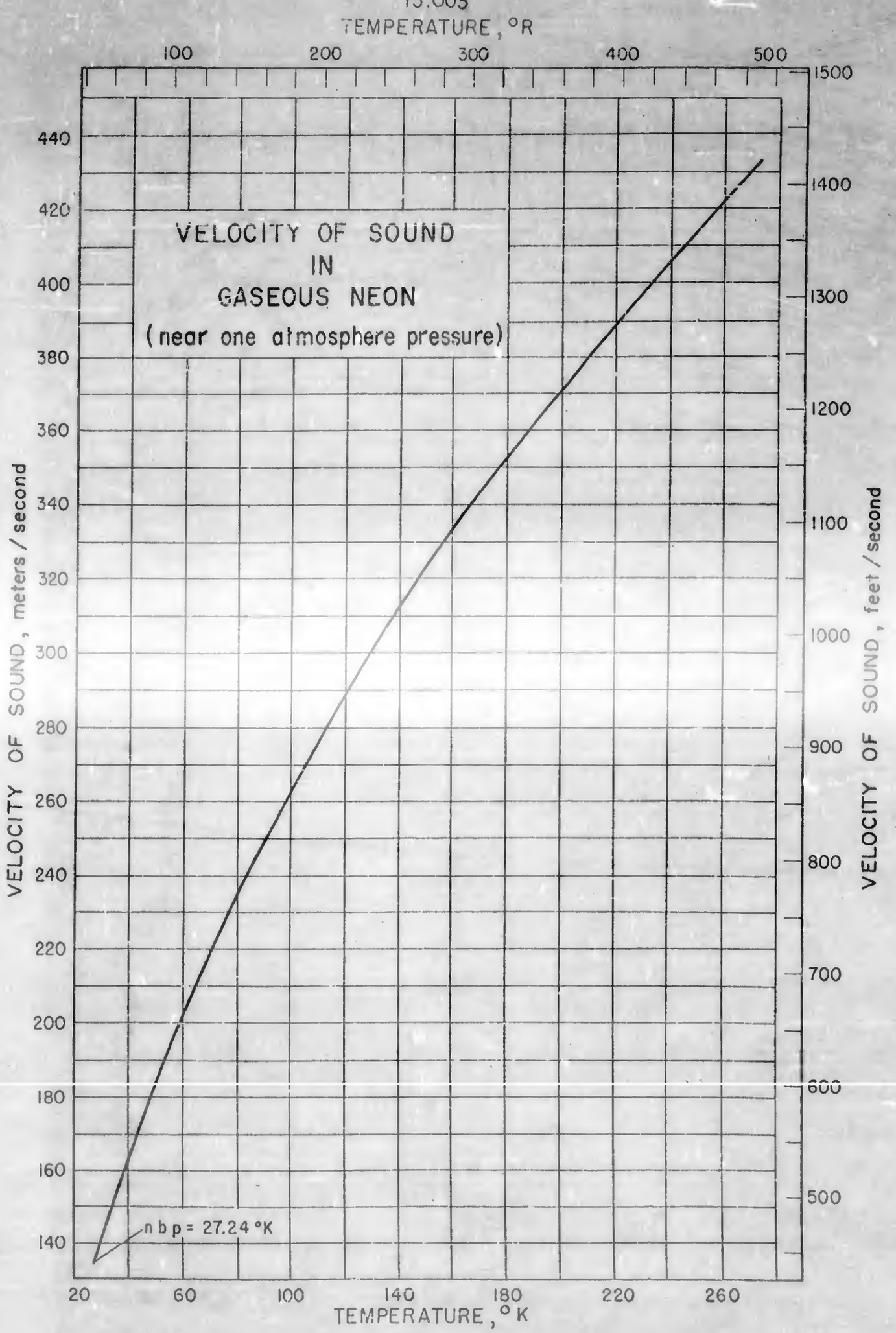
Van Itterbeek and Mariens made measurements on carbon dioxide to which small amounts (0.28%) of neon had been added to study the effect of this impurity.

Skudrzyk derived relations of absorption and velocity of sound and compared them with the classical hypothesis of Stokes. The specific behavior of helium and neon was also explained.

Greenspan measured the speed and attenuation of sound at 11 megacycles in helium, neon, argon, krypton, and xenon at various pressures between atmospheric and a few mm Hg, and compared the results with existing theories.

15.003


PRESSURE, psia
0
2
4
6
8
10
12
14
VELOCITY OF SOUND
IN
GASEOUS NEON
T = 27.80° K
T = 26.25° K
Point of saturation
VELOCITY OF SOUND, meters / second
138
137
136
135
134
133
132
VELOCITY OF SOUND, feet / second
452
450
448
446
444
442
440
438
436
434
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PRESSURE, atmospheres


TEMPERATURE, °R
100
200
300
400
500
1500
1400
1300
1200
1100
1000
900
800
700
600
500
VELOCITY OF SOUND
IN
GASEOUS NEON
(near one atmosphere pressure)
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
n b p = 27.24 °K
20
60
100
140
180
220
260
TEMPERATURE, °K

VELOCITY of SOUND in LIQUID NITROGEN

Sources of Data:

Van Itterbeek, A., de Bock, A. and Verhaegen, L.; Physica 15, 624 (1949)

Van Itterbeek, A., and Van Dael, W.; Bull. inst. intern. froid. Annexe 1958-1, 295 (1958)

Other References:

Hirschlaff, E.; Proc. Cambridge Phil. Soc. 34, 296 (1938)

Liepmann, H. W.; Helv. Phys. Acta. 12, 421 (1939)

Galt, J. K; J. Chem. Phys. 16, 505 (1948)

Van Itterbeek, A., Van den Berg, G. J. and Limburg, W.; Physica 20, 307 (1954)

Venkatasubramanian, F. S.; J. Indian Inst. Sci. 37, 227 (1955)

Comments:

The velocity of sound in liquid nitrogen is presented here as a function of pressure and temperature between the temperatures of 64.5°K and 90.25°K at various pressures from 1 to 67 atmospheres. The data tabulated below and illustrated on the graphs are from the references listed above under "Sources of Data".

The data by Van Itterbeek, de Bock and Verhaegen tabulated below are illustrated in the graph of the velocity of sound versus temperature. The authors report these values as being observed at the pressures of the saturated liquid with sound having a frequency of 535 kilocycles per second. No mention is made of the purity of the sample used or the estimated accuracy of the measurements taken.

The data illustrated in the graph of the velocity of sound in liquid nitrogen versus pressure at constant temperature are from Van Itterbeek and Van Dael. These isotherms terminate on the low pressure end at saturation as indicated on the graph, and therefore should not be extrapolated to lower pressures. The authors report sound frequency of 528.58 kc/sec used to take the measurements at 77.40°K and sound of 519.00 kc/sec used to take the measurements at 90.25°K. No mention is made by the investigators as to the purity of the sample or the estimated accuracy of the measurements.

The units of the velocity of sound in liquid nitrogen used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

(Continued on following page)

VELOCITY of SOUND in LIQUID NITROGEN (Cont.)

Comments: (cont.)

Velocity of Sound in Liquid Nitrogen
at Saturation Pressures as a Function of Temperature

Van Itterbeek, de Bock and Verhaegan			
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
64.5	1009.6	70.2	945.8
65.4	1002.5	71.9	921.3
66.4	998.2	74.7	907.2
67.5	964.7	77.5	857.1

Velocity of Sound in Liquid Nitrogen
as a Function of Pressure

Van Itterbeek and Van Dael			
Pressure atm.	Velocity m/sec	Pressure atm.	Velocity m/sec
77.40°K		8.3	735.7
4.2	861.6	10.2	737.3
9.2	863.2	15.5	743.3
13.9	868.0	15.9	743.0
31.8	881.2	19.2	743.4
42.0	885.4	24.8	753.2
42.1	889.1	28.8	756.2
49.6	894.7	32.3	759.7
51.9	896.5	38.6	769.2
54.1	898.1	39.3	767.4
60.9	902.0	39.3	768.7
66.7	907.1	43.7	775.4
90.25°K		44.2	773.9
4.6*	731.2	47.4	777.7
8.1	732.3	49.3	780.7
		55.7	787.5

* Value appears on both graphs

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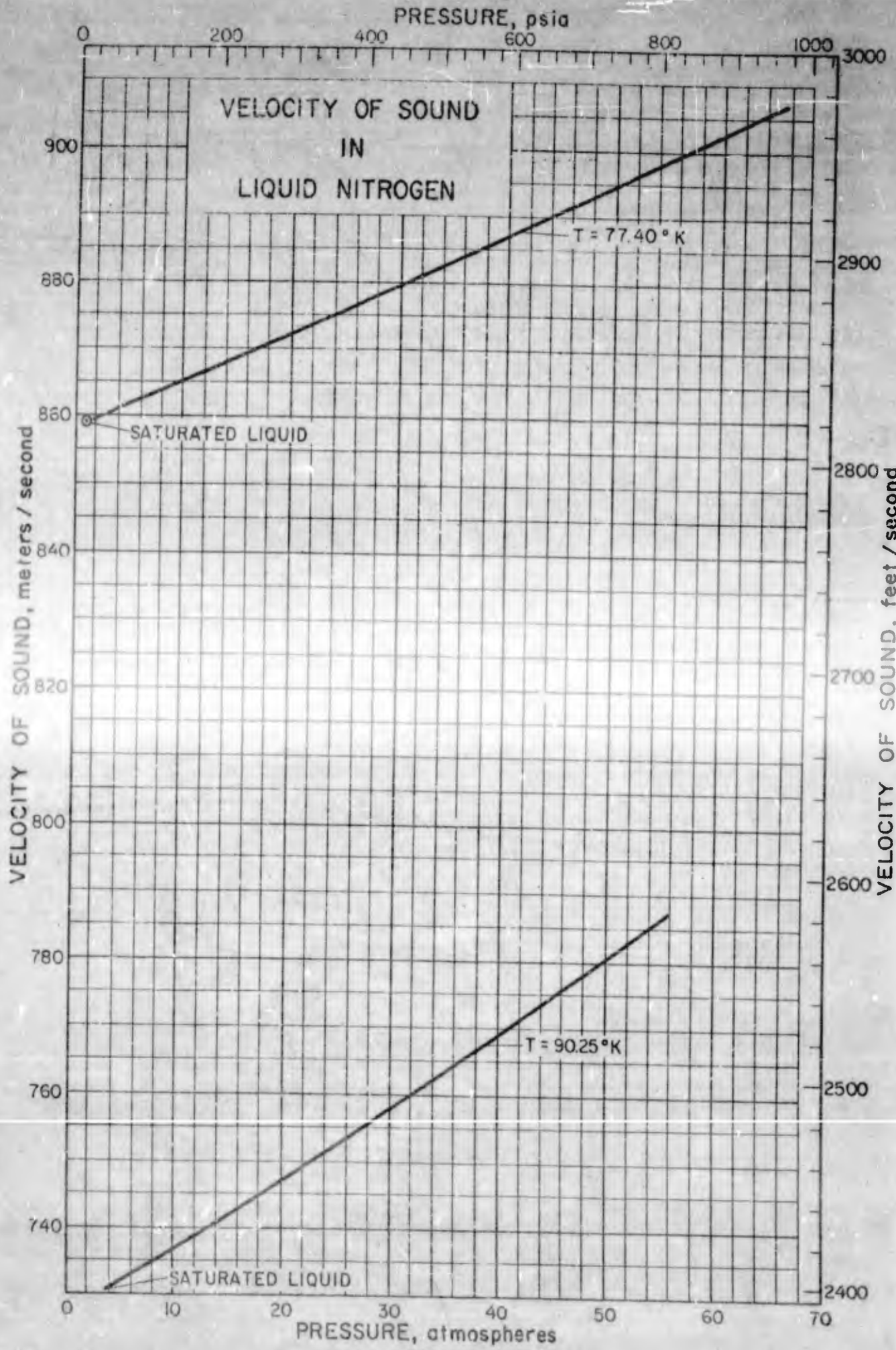
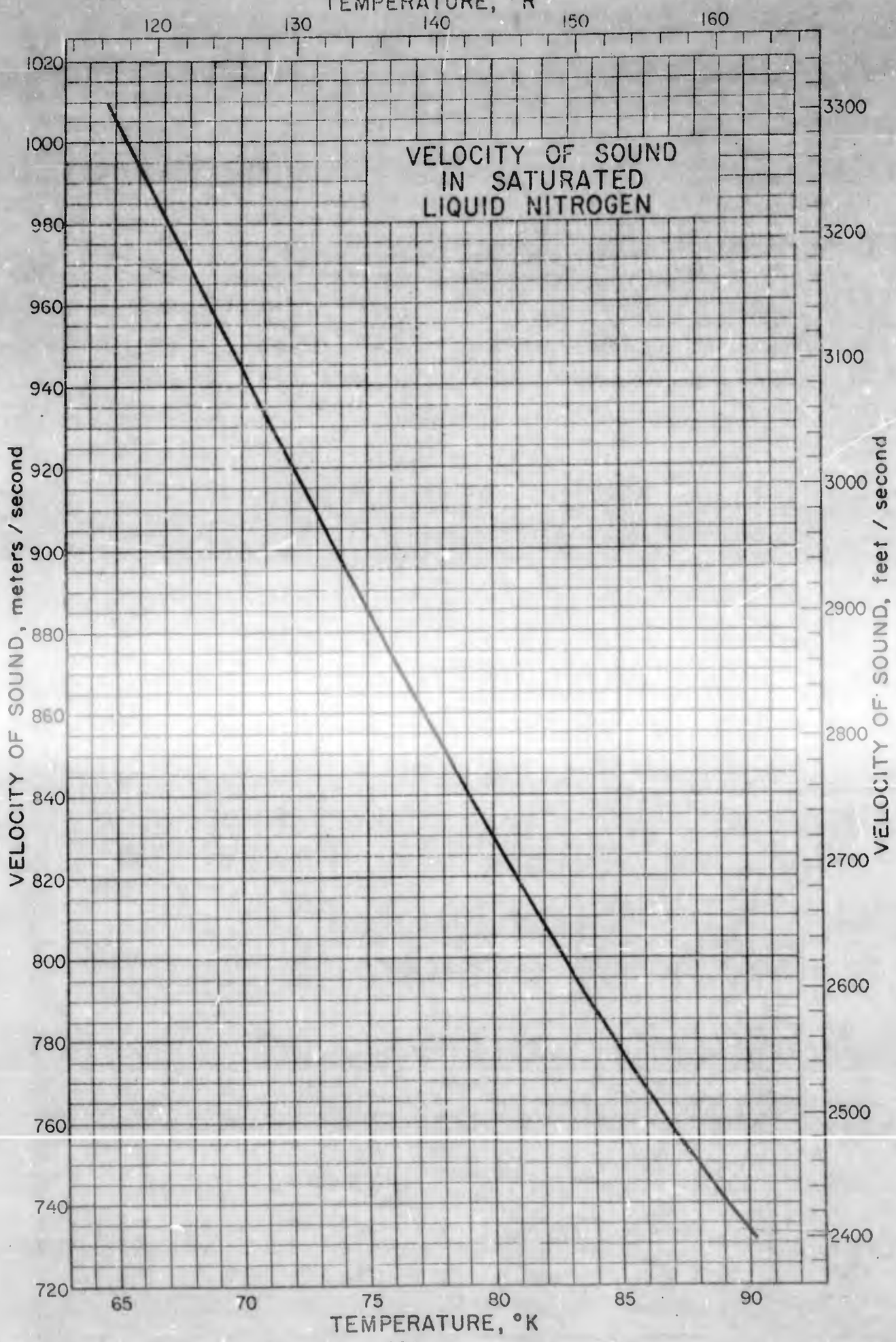
15.004


PRESSURE, psia
0
200
400
600
800
1000
3000
VELOCITY OF SOUND
IN
LIQUID NITROGEN
900
880
860
840
820
800
780
760
740
T = 77.40 °K
SATURATED LIQUID
T = 90.25 °K
SATURATED LIQUID
VELOCITY OF SOUND, meters / second
2900
2800
2700
2600
2500
2400
VELOCITY OF SOUND, feet / second
0
10
20
30
40
50
60
70
PRESSURE, atmospheres


TEMPERATURE, °R
120
130
140
150
160
VELOCITY OF SOUND
IN SATURATED
LIQUID NITROGEN
VELOCITY OF SOUND, meters / second
1020
1000
980
960
940
920
900
880
860
840
820
800
780
760
740
720
VELOCITY OF SOUND, feet / second
3300
3200
3100
3000
2900
2800
2700
2600
2500
2400
65
70
75
80
85
90
TEMPERATURE, °K

VELOCITY of SOUND in GASEOUS NITROGEN

Sources of Data:

Keesom, W. H. and Van Lammeren, J. A.; Koninkl. Akad. Amsterdam, Proc. 35, 727 (1932)

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564 (1955) 488 pp.

Lunbeck, R. J., Michels, A. and Wolkers, G. J.; Appl. Sci. Research A3, 197 (1952)

Other References:

Foley, A. L., International Critical Tables of Numerical Data, Physics, Chemistry and Technology VI, 1st Edition Published for the National Research Council by the McGraw-Hill Book Co., Inc. (1929) p. 46

Van Itterbeek, A. and Mariens, P.; Physica 4, 207 (1937)

Shilling, W. G. and Partington, J. R.; Phil. Mag. 6, 920 (1928)

Hodge, A. H.; J. Chem. Phys. 5, 974 (1937)

Colwell, R. C. and Gibson, L. H.; J. Acoust. Soc. Am. 12, 436 (1941)

Van Itterbeek, A. and Van Doninck, W.; Ann. phys. 19, 88 (1944)

Michels, A., Lunbeck, R. J. and Wolkers, G. J.; Physica 17, 801 (1951)

Dixon, H. B., Campbell, C. and Parker, A.; Proc. Roy. Soc. (London) A100, 1 (1921)

Comments:

The values of the velocity of sound in gaseous nitrogen are given here as functions of temperature and pressure. Three graphs are given with accompanying tabular data. The first graph illustrates the velocity of sound in nitrogen near one atmosphere pressure, versus temperature between 77.395°K (the normal boiling point) and 280°K. The final two graphs present the velocity of sound in nitrogen versus pressure, with pressures of 0 to 1 atmosphere and 0 to 3000 atmospheres, respectively. The data illustrated in the graphs and tabulated below are from the references listed above under "Sources of Data". The data illustrated in the plot of velocity of sound as a function of temperature and in the graph of the velocity of sound as a function of pressure between 0 and 1 atmosphere are from Keesom and Van Lammeren; and Hilsenrath, et al. The values of the velocity of sound at 0 pressure were calculated for the ideal gas, i.e., $c = \sqrt{RT\gamma}$, where c is the velocity of sound, R is the gas constant, T is the temperature, and γ is the specific heat ratio. The data by Hilsenrath, et al., are reported by the authors as the velocity of sound at low frequency. A comparison of these data with experimental values appears in National Bureau of Standards Circular 564, and indicates an agreement with the experimental values of less than 1% maximum deviation. Hilsenrath, et al., present their data as ratios in the form of a/a_o, where a is the value of the velocity of

(Continued on following page)

VELOCITY of SOUND in GASEOUS NITROGEN (Cont.)

Comments: (Cont.)

low frequency sound at a given temperature and pressure, and a_o (a_o = 336.96 m/sec) is the velocity of sound at 0°C and 1 atmosphere of pressure. All values from Hilsenrath, et al., tabulated here have been converted to specific values of velocity of sound. Keesom and Van Lammeren make no mention of the frequency of the sound used in their determinations but do claim 0.15% accuracy in their measurements. All of the above data are for a pressure of approximately 1 atm.

The data by Lunbeck, Michels and Wolkers tabulated below and illustrated in the plot of the velocity of sound in nitrogen gas as a function of pressure between 0 and 3000 atmospheres were calculated by the authors from a correlation of their own experimental data. The authors estimate a maximum error in these calculations of 10%. However, in the temperature range reported here, the maximum error should be substantially smaller.

The units of the velocity of sound in nitrogen gas used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16° K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Nitrogen as a Function of Pressure*

Press.	Velocity, m/sec					
atm.	-125°C	-100°C	-75°C	-50°C	-25°C	0°C
0	248.1	268.2	286.9	304.6	321.1	337.0
10	241	264	285	304	322	338
30	229	260	284	306	324	342
50	230	261	286	310	329	346
100	362	298	310	326	345	362
200	566	462	415	404	405	414
300	689	588	527	496	483	481
400	776	681	620	580	559	549
600	904	822	760	719	688	670
800	1007	930	870	827	796	774
1000	1092	1020	961	917	886	863
1200	1167	1100	1040	996	963	941
1500	1265	1202	1146	1101	1068	1044
2000	1408	1347	1295	1250	1218	1197
2500	1531	1473	1423	1381	1348	1329
3000	1636	1587	1535	1495	1462	1448

* Values are from Lunbeck, Michels and Wolkers

(Continued on following page)

VELOCITY of SOUND in GASEOUS NITROGEN (Cont.)

Comments: (cont.)

Velocity of Sound in Gaseous Nitrogen as a Function of Pressure

Temp. °K	Press. atm.	Velocity m/sec	Temp. °K	Press. atm.	Velocity m/sec
Keesom and Van Lammeren			77.95	0.9026*	176.0
				0.7122	176.9
90.37	0.9299*	191.0		0.5789	177.5
	0.7293	191.7		0.4380	178.0
	0.5541	192.2		0.3029	178.7
	0.4380	192.6		0.2025	179.2
	0.3207	192.9		0.1183	179.7
	0.1973	193.3	71.92	0.3879	170.9
	0.1176	193.3		0.3382	171.1
82.95	1.0146*	181.8		0.2627	171.6
	0.7957	182.8		0.1931	172.0
	0.5953	183.4		0.1188	172.6
	0.4179	184.0	Hilsenrath, et al.		
	0.2923	184.6			
	0.1921	185.0	100.0	0.01	203.86
	0.1022	185.5		0.1	203.52
				1.0	201.50

* These values also appear on the velocity of sound as a function of temperature plot.

Velocity of Sound in Gaseous Nitrogen as a Function of Temperature*

Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
Pressure = 1 atm.		Pressure = 1 atm.	
100	201.50	200	288.10
110	212.28	210	295.18
120	222.06	220	302.25
130	231.15	230	308.99
140	240.25	240	315.73
150	249.01	250	322.13
160	257.10	260	328.54
170	265.19	270	334.94
180	273.27	280	341.34
190	280.69		

* Values are from Hilsenrath, et al.

(Continued on following page)

VELOCITY of SOUND in GASEOUS NITROGEN (Cont.)

Comments: (cont.)

Work done by other investigators is also of interest. Foley made a critical review of all work on the velocity of sound in nitrogen prior to 1928 for inclusion in the section on sound in the International Critical Tables and reported 337.7 m/sec at 0°K and 1 atm. pressure. Dixon and co-workers gave a value 337.6 at 0°C and 720.6 m/sec at 1000°C. Shilling and Partington worked with nitrogen from which the rare gases had not been removed but which had been freed from moisture by passage over sodium hydroxide and phosphorus pentoxide. Measurements were carried out from 16.7 to 1000°C yielding values from 347.6 to 720.6 m/sec at these limiting temperatures.

Hodge made measurements on impure nitrogen at 27°C at pressures from 1 to 100 atmospheres. Since water vapor and other impurities of unknown amounts had not been removed, no importance can be attached to his results. Colwell and Gibson used a rapid succession of sound pulses and an oscilloscope and found no variation in velocity at 0°C for pressures from 26 to 176 cm Hg. The average of 2100 measurements gave a value of 337.12 m/sec at 0°C.

The above authors also give values for the velocity as a function of pressure ranging from 183.1 m/sec at zero pressure and 80°K to about 180 m/sec at 0.8 atmospheres.

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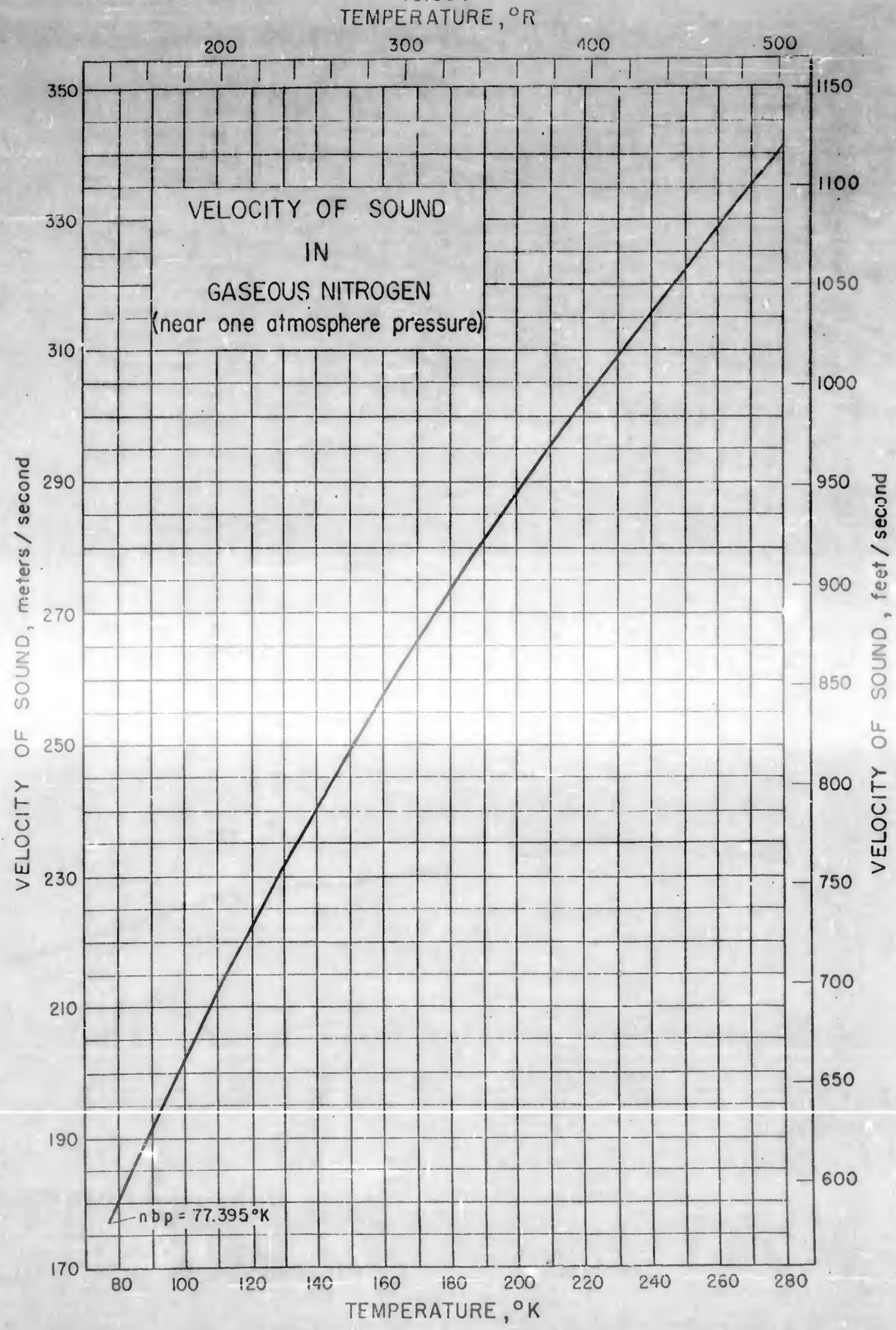
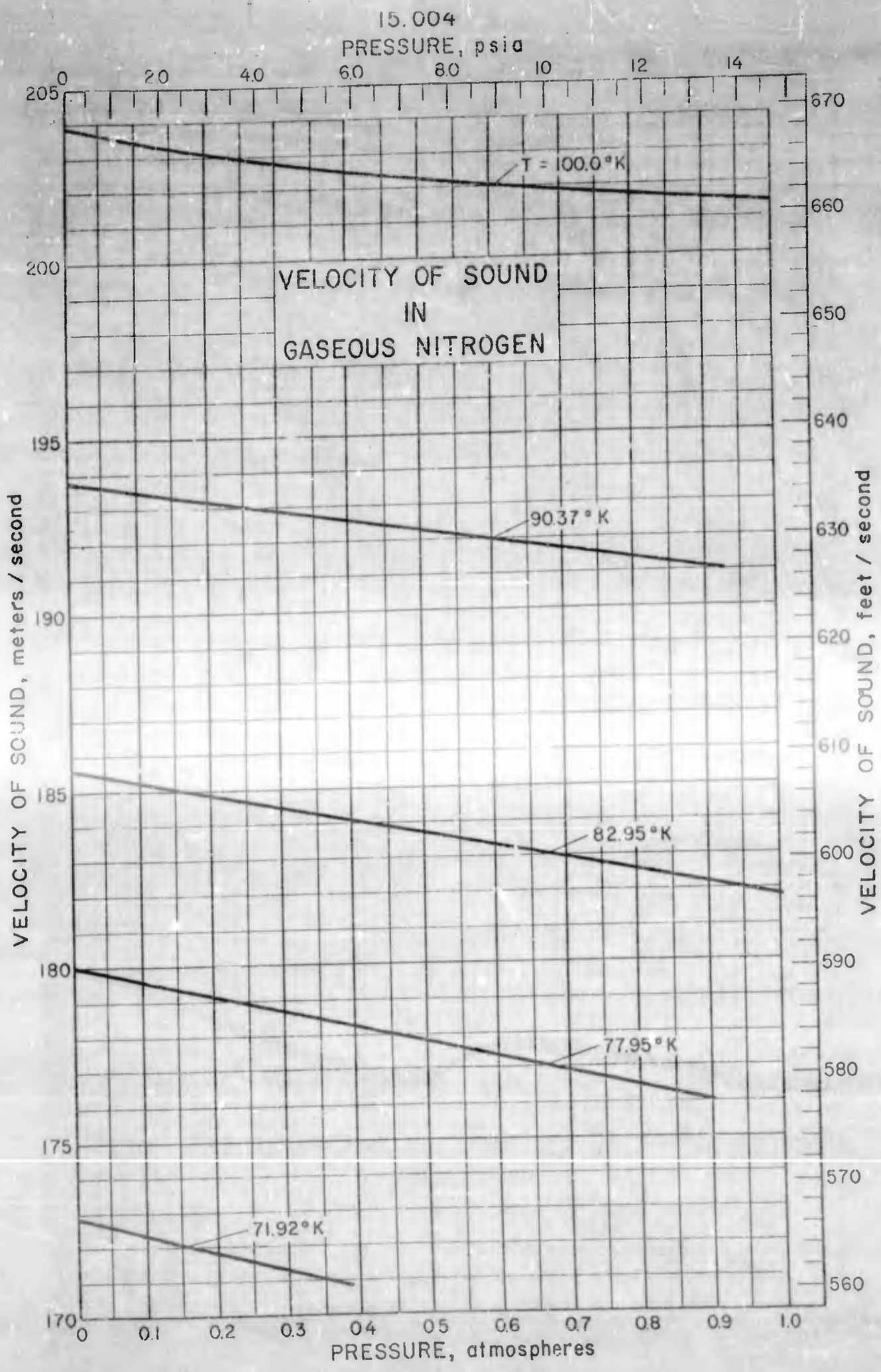
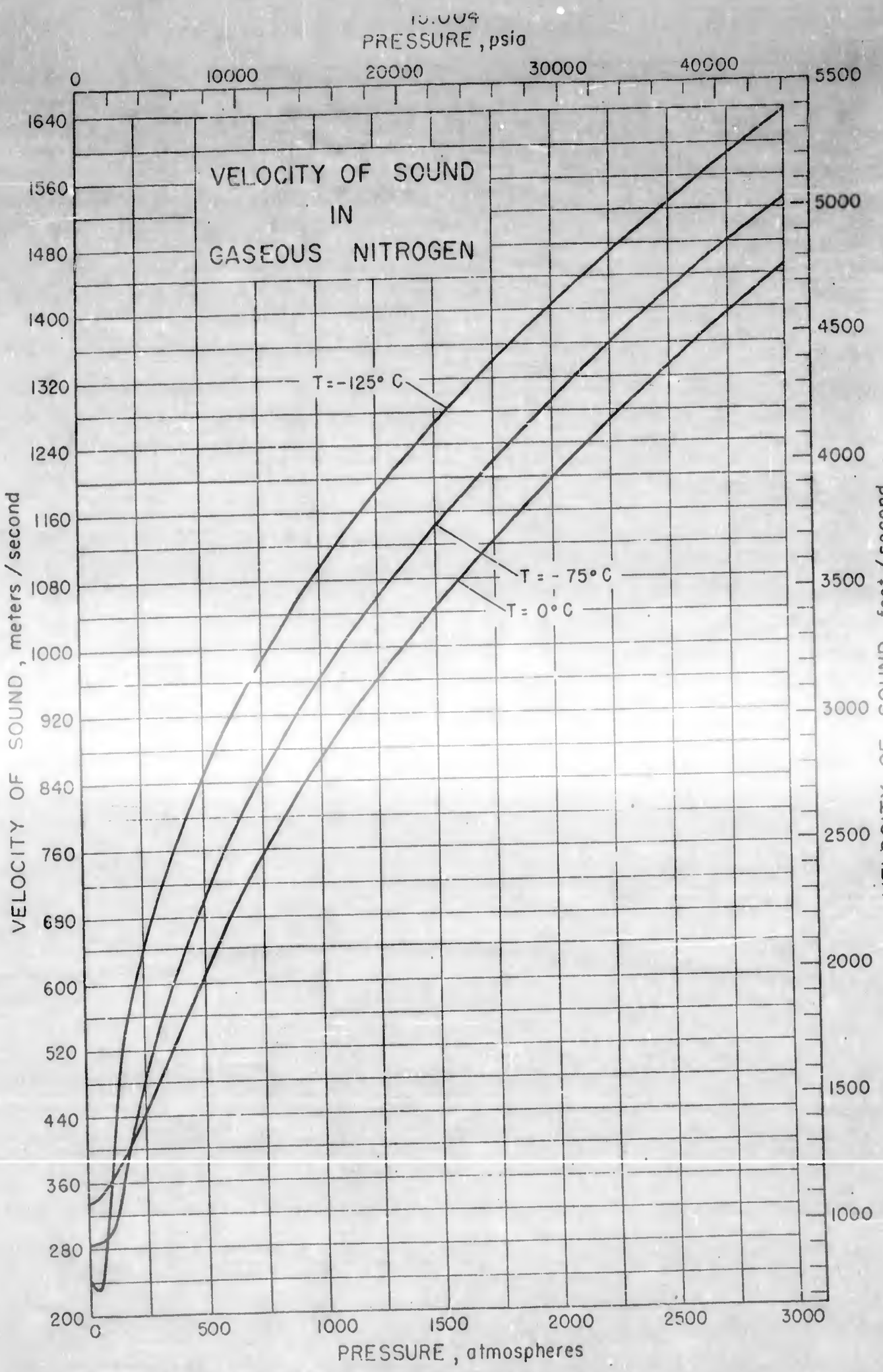
15.004


TEMPERATURE, °R
200
300
400
500
VELOCITY OF SOUND
IN
GASEOUS NITROGEN
(near one atmosphere pressure)
VELOCITY OF SOUND, meters / second
350
330
310
290
270
250
230
210
190
170
VELOCITY OF SOUND, feet / second
1150
1100
1050
1000
950
900
850
800
750
700
650
600
nbp = 77.395°K
80
100
120
140
160
180
200
220
240
260
280
TEMPERATURE, °K


15.004
PRESSURE, psia
0
2.0
4.0
6.0
8.0
10
12
14
205
200
195
190
185
180
175
170
670
660
650
640
630
620
610
600
590
580
570
560
T = 100.0°K
90.37°K
82.95°K
77.95°K
71.92°K
VELOCITY OF SOUND
IN
GASEOUS NITROGEN
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PRESSURE, atmospheres


PRESSURE, psia
0
10000
20000
30000
40000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
VELOCITY OF SOUND
IN
GASEOUS NITROGEN
T=-125° C
T=-75° C
T=0° C
1640
1560
1480
1400
1320
1240
1160
1080
1000
920
840
760
680
600
520
440
360
280
200
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
0
500
1000
1500
2000
2500
3000
PRESSURE, atmospheres

VELOCITY of SOUND in LIQUID OXYGEN

Sources of Data:

Liepmann, H. W.; Helv. Phys. Acta 11, 381 (1938)

Galt, J. K.; J. Chem. Phys. 16, 505 (1948)

Van Itterbeek, A. and de Bock, A.; Physica 14, 542 (1948)

de Bock, A.; Verhandel. Koninkl. Akad. Wetenschap. 11, No. 31 (1949) 48 pp.

Van Itterbeek, A. and Van Dael, W.; Bull. inst. intern. froid. Annexe 1958-1, 295 (1958)

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564, (1955) 488 pp.

Other References:

Pitt, A. and Jackson, W. J.; Can. J. Research 12, 686 (1935)

Bär, R.; Nature 135, 153 (1935)

Liepmann, H. W.; Helv. Phys. Acta 9, 507 (1936)

Comments:

Values of the velocity of sound in liquid oxygen are presented here as functions of temperature and pressure between the temperatures of 60°K and 90°K at pressures ranging from the pressures of the saturated liquid to 70 atmospheres. The data illustrated on the graphs and tabulated below are from the references listed above under "Sources of Data".

The data by Galt; Van Itterbeek and de Bock; Van Itterbeek, de Bock and Verhaegen; Liepmann (1938); and de Bock are tabulated below and illustrated in the graph showing the velocity of sound in liquid oxygen versus temperature. Galt reports sound of frequency 44.4 megacycles per second used in his determinations, and estimated his experimental sample as being 99.5% oxygen. Van Itterbeek and de Bock used an acoustical interferometer with an x-cut quartz crystal of frequency 539.6 kilocycles per second in making measurements in which they estimate a maximum error of 0.2%. Van Itterbeek, de Bock and Verhaegen used a frequency of 535 kc/sec to propagate the sound in their observations. Liepmann (1938) reports velocities of sound in liquid oxygen as a function of the boiling temperature at various pressures, using frequencies of 7,500 and 1,500 kc/sec. de Bock reports data obtained with the same apparatus used by Van Itterbeek and de Bock. No further information on the purity of the samples or the accuracy of the measurements is given by any of the authors from any of the sources of data.

The data by Van Itterbeek and Van Dael are tabulated below and illustrated on the graph of the velocity of sound in liquid oxygen at constant temperature as a function of pressure. The authors report a frequency of 539.6 kc/sec used in the observations made at 77.35°K and two frequencies of 527 and 534 kc/sec used in the observations made at 90.31°K. No mention is made as to the accuracy of the measurements or

(Continued on following page)

VELOCITY of SOUND in LIQUID OXYGEN (Cont.)

Comments: (cont.)

the purity of the sample used. These two isotherms were extrapolated to saturation pressures as derived from data reported by Hilsenrath, et al.

Using the vibrations of a piezoelectric quartz plate driven at a high frequency of 427 kc/sec, Pitt and Jackson found the velocity of sound in liquid oxygen at -182.9°C to be 912 m/sec. By means of the scattering of light by ultrasonic waves in liquids, Bär found the velocity at -183.6°C to be 903 m/sec. He used a frequency of 7,500 kc/sec.

The units of the velocity of sound in liquid oxygen used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmosphere (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Liquid Oxygen

as a Function of Temperature

Temperature °K	Velocity m/sec
Galt	
60 ± 5	1119
70 ± 1	1094
87.0 ± 0.2	952
de Bock	
73.00	1036.3
76.55	1014.4
76.75	1011.2
80.45	987.1
80.65	988.0
83.45	967.0
83.45	968.6
85.30	955.6
85.30	955.1
87.50	935.1
87.50	936.2
90.30	904.9

Temperature °K	Velocity m/sec.
Van Itterbeek & de Bock	
73.0	1034
75.0	1022
77.5	1007
80.0	991
82.5	974
85.0	956
87.5	935
90.0	909
Van Itterbeek, de Bock & Verhaegen	
60.5	1128.9
62.0	1137.4
64.5	1111.1
67.9	1083.0
78.6	1007.3
82.5	966.8
86.1	938.5
90.5	902.3

(Continued on following page)

VELOCITY of SOUND in LIQUID OXYGEN (Cont.)

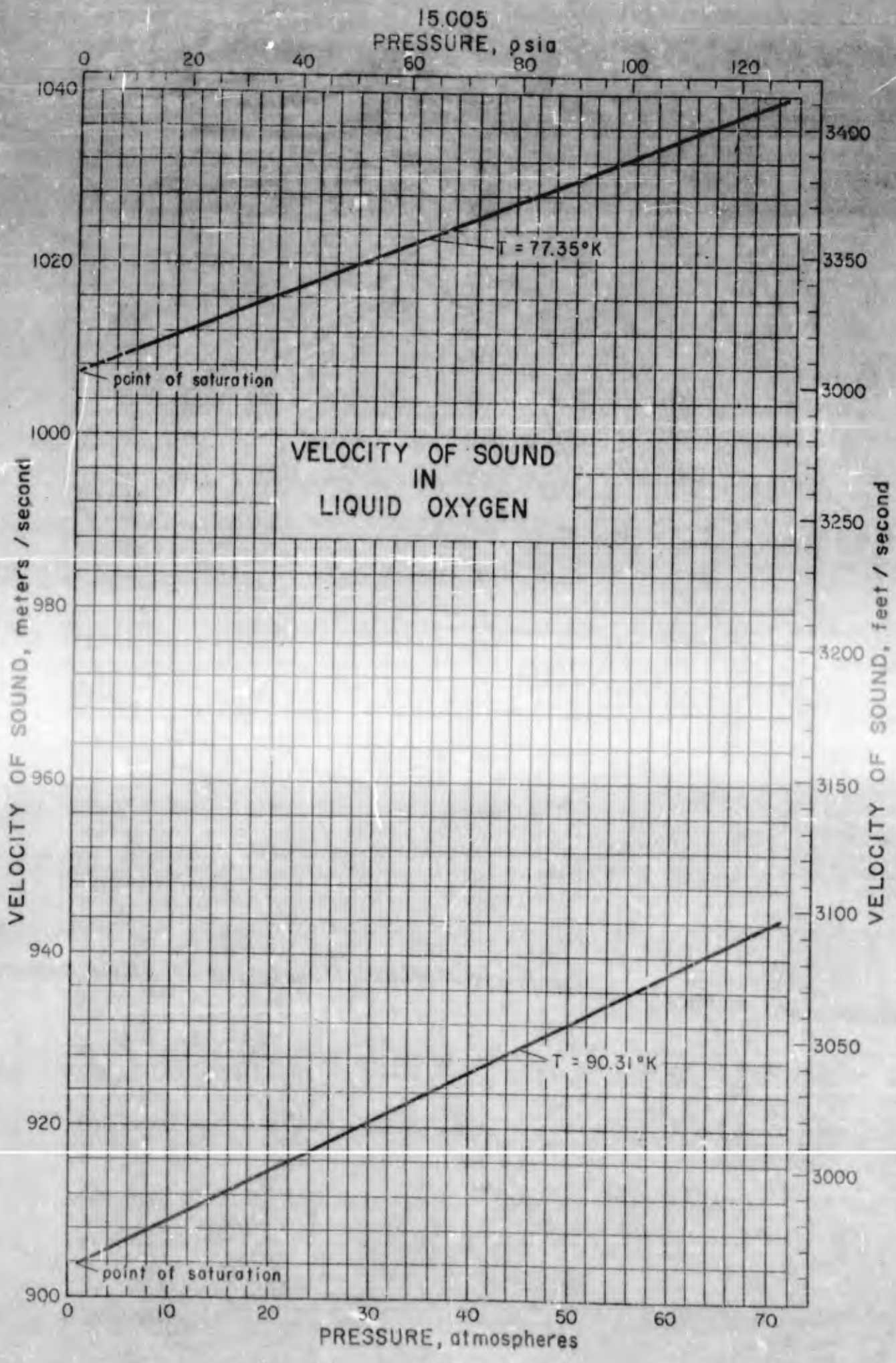
Comments: (cont.)

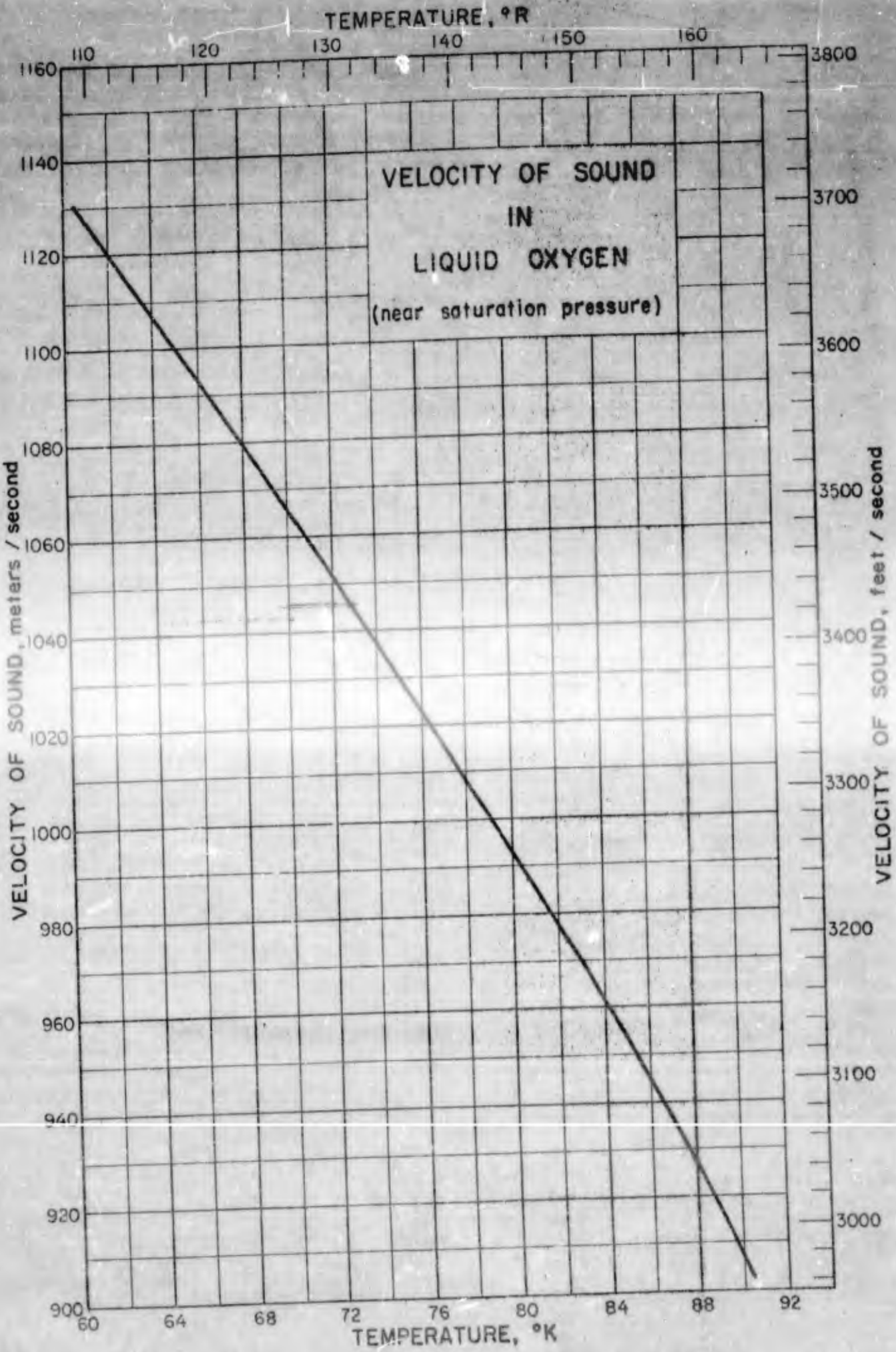
Velocity of Sound in Saturated Liquid Oxygen as a Function of Temperature

Liepmann (1938)					
Temp. °C ± 0.1	Velocity, m/sec*		Temp. °C ± 0.1	Velocity, m/sec*	
	7500 kc/sec	1537 kc/sec		7500 kc/sec	1537 kc/sec
-183.6	911	---	-197.3	1028	
-183.7	---	915	-198.4	---	1042
-185.8	932	928	-198.5	---	1044
-187.2	945	---	-199.2	1043	---
-187.7	---	948	-200.7	---	1072
-189.2	954	---	-201.4	1061	---
-189.4	---	962	-203.3	---	1091
-190.5	975	---	-203.6	1079	---
-191.7	982	---	-204.8	1090	---
-193.5	1000	---	-204.9	---	1100
-195.6	1021	---	-209.9*	1121	---
* Values have a maximum error of about 1%.					

Velocity of Sound in Liquid Oxygen as a Function of Pressure

Van Itterbeek and Van Dael			
Pressure atm.	Velocity m/sec	Pressure atm.	Velocity m/sec
77.35°K		90.31°K	
6.3	1009.9	3.8	905.1
12.5	1012.6	10.2	908.4
15.8	1014.0	16.6	912.1
19.7	1017.7	18.8	913.3
23.9	1019.3	23.6	917.0
27.9	1021.7	29.4	920.2
31.5	1021.9	36.5	922.7
34.7	1023.2	38.3	925.6
45.4	1027.9	45.5	928.6
53.2	1031.8	49.5	930.3
55.1	1032.0	55.2	934.8
59.8	1034.8	58.3	937.6
62.2	1036.2	61.8	939.4
64.0	1036.5	66.2	939.5
70.1	1039.2	68.3	942.3
71.1	1039.7	71.2	944.5


15.005
PRESSURE, psia
0
20
40
60
80
100
120
1040
1020
1000
980
960
940
920
900
3400
3350
3000
3250
3200
3150
3100
3050
3000
T = 77.35°K
point of saturation
VELOCITY OF SOUND
IN
LIQUID OXYGEN
T = 90.31°K
point of saturation
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
0
10
20
30
40
50
60
70
PRESSURE, atmospheres


TEMPERATURE, °R
110
120
130
140
150
160
1160
1140
1120
1100
1080
1060
1040
1020
1000
980
960
940
920
900
3800
3700
3600
3500
3400
3300
3200
3100
3000
VELOCITY OF SOUND
IN
LIQUID OXYGEN
(near saturation pressure)
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
60
64
68
72
76
80
84
88
92
TEMPERATURE, °K

VELOCITY of SOUND in GASEOUS OXYGEN

Sources of Data:

Van Itterbeek, A. and Van Paemel, O.; Physica 5, 593 (1938)

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564, (1955) 488 pp.

Other References:

Dulong, P. L.; Ann. de chimie et de phys. 41, 113 (1829)

Dulong, P. L.; Pogg. Ann. 16, 438 (1829)

Cook, S. R.; Phys. Rev. 23, 212 (1906)

Schweikert, G.; Ann. Physik. 48, 593 (1915)

Keesom, W. H., Van Itterbeek, A. and Van Lammeren, J. A.; Proc. Acad. Sci. Amsterdam 34, 996 (1930); Communs. Phys. Lab. Univ. Leiden No. 216d (1931)

Pitt, A. and Jackson, W. J.; Can. J. Research 12, 686 (1935)

Van Itterbeek, A. and Mariens, P.; Physica 4, 207 (1937)

Van Itterbeek, A. and Mariens, P.; Physica 4, 609 (1937)

Van Itterbeek, A. and Van Doninck, W.; Proc. Phys. Soc. (London) 62B, 62 (1949)

Bancroft, D.; Am. J. Phys. 24, 355 (1956)

Van Itterbeek, A. and Zink, J.; Appl. Sci. Research A7, 375 (1958)

Pielemeier, W. H., Phys. Rev. 36, 1005 (1930)

Comments:

The velocity of sound in gaseous oxygen is presented here as a function of temperature and pressure. Data for temperatures from 74.12°K to 280°K are given at various pressures from 0.01139 atmospheres to 100 atmospheres. The data tabulated below and illustrated on the graphs are from the references listed above under "Sources of Data".

The data illustrated in the graph of the velocity of sound as a function of pressure at pressures below 1 atmosphere are from Van Itterbeek and Van Paemel. The isotherms of velocity of sound versus pressure were extrapolated to the vapor pressures as derived from data reported by Hilsenrath, et al. Van Itterbeek and Van Paemel report an average error of 0.1% in their measurements made with ultrasonic sound. No mention is made of purity of the sample used.

The data illustrated in the graph of the velocity of sound as a function of pressure for pressures from 1 to 100 atmospheres are from Hilsenrath, et al. The values of the velocity of sound for 0 pressure have been calculated for the ideal gas, i.e., $c = \sqrt{RT\gamma}$, where c is the velocity of sound, R is the gas constant, T is the temperature and γ is the ratio of specific heats. Hilsenrath, et al., calculated the velocity of low frequency sound in gaseous oxygen with an equation of state for oxygen. At temperatures below 0°C they claim a maximum error of .5% in their values. Hilsenrath, et al., present their data as ratios

(Continued on following page)

VELOCITY of SOUND in GASEOUS OXYGEN (Cont.)

Comments: (cont.)

in the form of a/a_o, where a is the value of the velocity of sound at low frequency at a given temperature and pressure, and a_o is a datum value (a_o = 314.82 m/sec) at 0°C and 1 atmosphere of pressure. All values from Hilsenrath, et al., tabulated here have been converted to specific values of velocity of sound.

The plot of the velocity of sound versus temperature for pressures near 1 atmosphere is an illustration of data from both Van Itterbeek and Van Paemel and Hilsenrath, et al.

The units of the velocity of sound in gaseous oxygen in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Oxygen as a Function of Pressure

Van Itterbeek and Van Paemel

Press. atm.	Vel. m/sec	Press. atm.	Vel. m/sec	Press. atm.	Vel. m/sec	Press. atm.	Vel. m/sec
92.03°K		88.72°K		83.05°K		78.15°K	
0.9815*	179.6	0.7242	176.6	0.4226	171.3	0.2061	167.2
0.8355	179.9	0.5974	177.3	0.3111	172.0	0.1470	167.7
0.6770	180.5	0.4723	177.6	0.1889	173.3	0.0968	167.9
0.5145	180.9	0.3408	178.0	0.0842	173.3	0.0451	168.5
0.3500	181.5	0.2024	178.6				
0.2606	181.9			80.60°K		76.00°K	
		84.95°K		0.2624	169.5	0.1329	165.3
86.92°K				0.2526	169.8	0.0892	165.8
0.6250	174.9	0.4776	173.5	0.1803	169.9	0.0517	166.1
0.3007	176.2	0.3454	173.9			0.01139	165.3
0.1108	177.1	0.2276	174.5	0.1091	170.4	74.12°K	
0.5164	175.5	0.1203	175.1	0.0566	170.9	0.1032	163.3
0.4115	175.9					0.0703	163.6
0.2007	176.6					0.0358	164.3

* Values also appear on the graph of the velocity of sound as a function of temperature.

(Continued on following page)

VELOCITY of SOUND in GASEOUS OXYGEN (Cont.)

Comments: (cont.)

Hilsenrath, et al.					
Velocity of Sound, m/sec					
Temp. °K	Pressure, atmospheres				
	1*	10	40	70	100
120	207.47				
140	224.47				
160	240.52	233.91			
180	255.32	250.91	235.80		
200	269.49	266.34	257.84	255.63	
220	282.71	280.82	275.78	275.78	286.80
240	295.30	294.04	291.84	293.10	300.97
260	307.26	306.63	306.32	308.52	314.82
280	318.60	318.91	319.54	322.69	328.04

* Values in this column also appear on the velocity of sound as a function of temperature graph.

As early as 1829, P. L. Dulong arrived at a value of 317.17 m/sec for the velocity of sound in oxygen gas at 0°C and one atmosphere pressure with reference to air under the same conditions assumed to be 333 m/sec. Cook made measurements between liquid air and room temperatures, which are in good agreement with the data presented here.

Schweikert's article contains an excellent list of 47 original references with titles of papers dating back to 1829. His own final value obtained with Kundt's dust figures in tubes was 315.7 m/sec at 0°C and one atmosphere. His value for air under like conditions was 331.9 m/sec.

Pielemeier employed ultrasonic frequencies ranging from 316 to 1219 kc/sec and found the velocity of sound relatively independent of frequency within this frequency range.

Keesom, Van Itterbeek and Van Lammeren obtained a value of 315.4 m/sec at 0°C. Measurements were also made by these authors at lower temperatures and various pressures below 1 atmosphere. These values are in good agreement with the data presented here.

Pitt and Jackson found a velocity of 315.4 m/sec at 0°C and 177.6 m/sec at -182.9°C, at one atmosphere pressure. Van Itterbeek and Mariens give 315.5 m/sec at 0°C and 1 atmosphere and also at 90.19°K, which agree quite well with those of Keesom, Van Itterbeek and Van Lammeren.

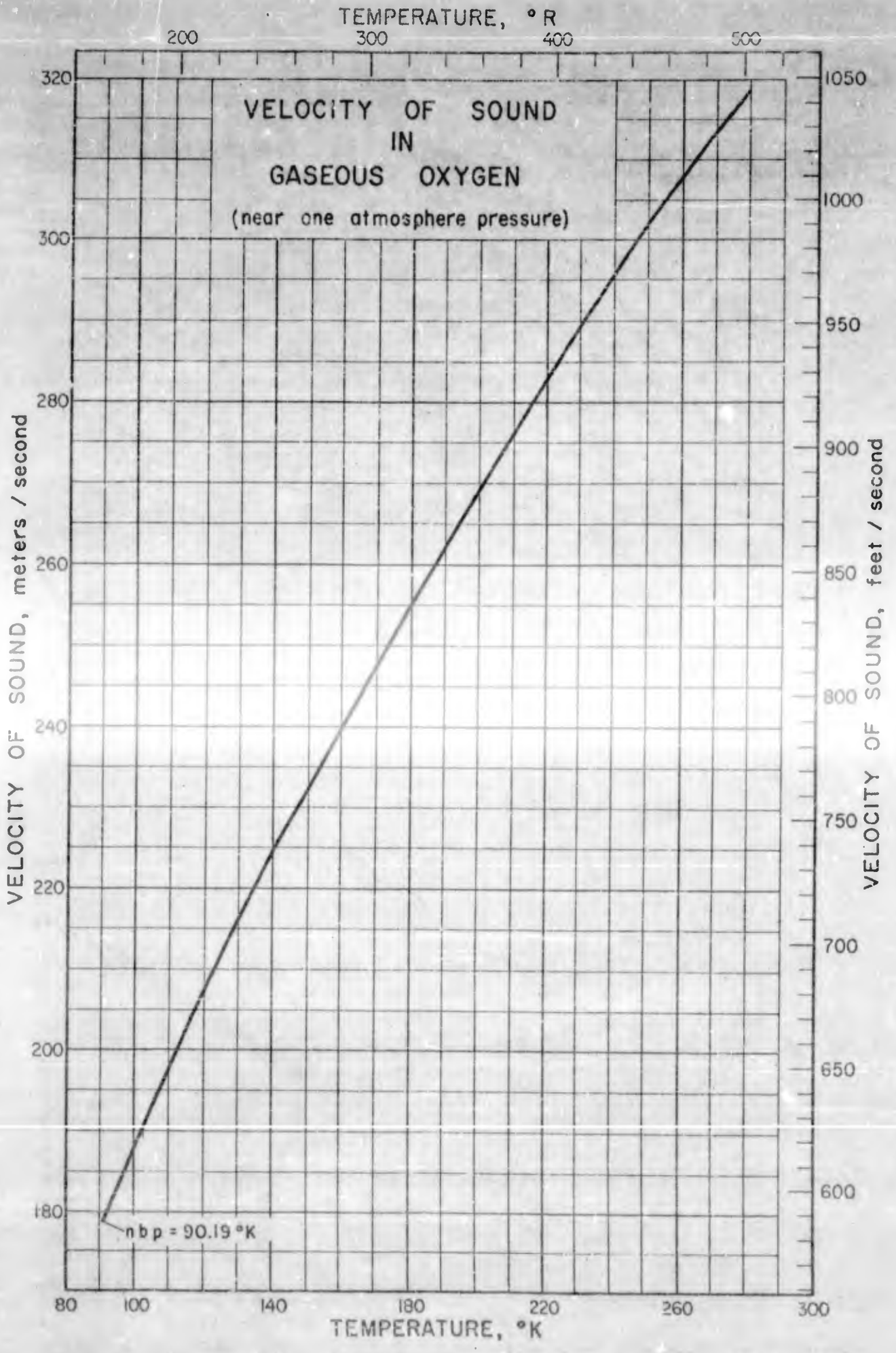
(Continued on following page)

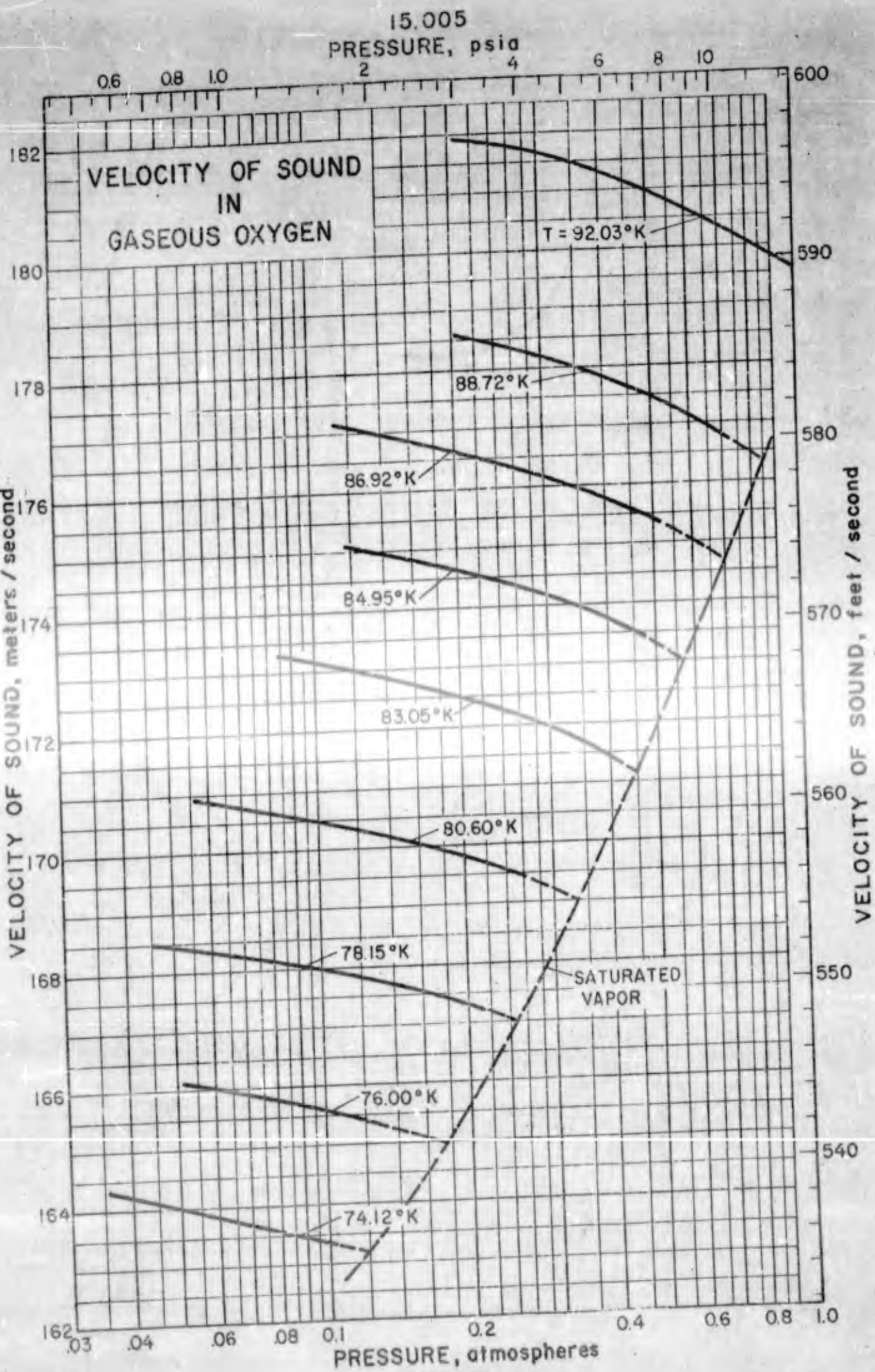
VELOCITY of SOUND in GASEOUS OXYGEN (Cont.)

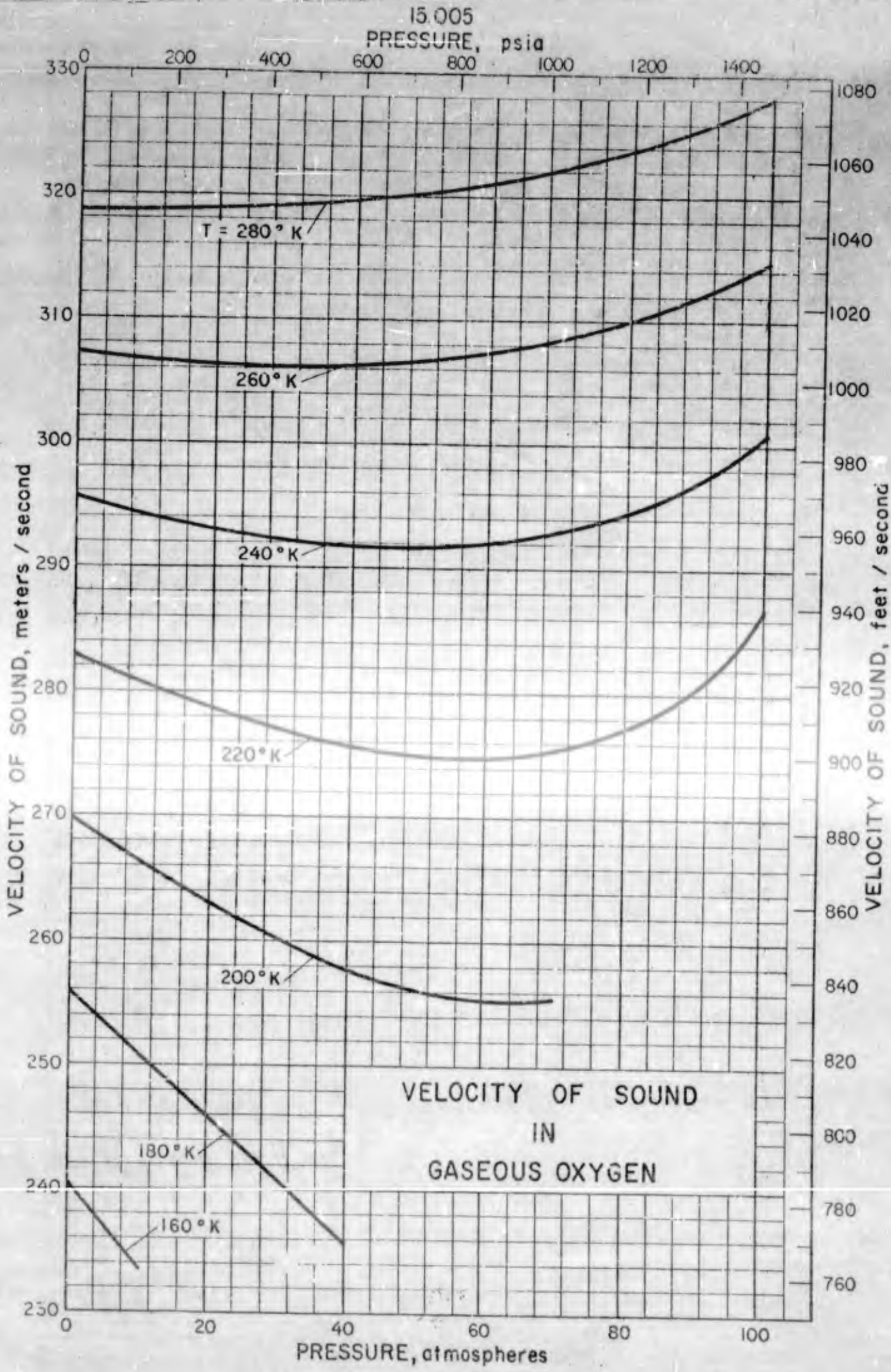
Comments: (cont.)

The article by Van Itterbeek and Van Doninck deals principally with mixtures of gases, but also contains a few measurements on pure oxygen. Bancroft described a method of determining the velocity of sound by observing the frequencies of radial oscillation of a gas confined in a spherical cavity, by which method he found a velocity of 315.12 m/sec for oxygen at one atmosphere and 0°C.

Van Itterbeek and Zink studied the effect of pressures of up to 69 atmospheres on the velocity of sound in oxygen over a limited temperature range. The measurements of Van Itterbeek and Zink are in agreement with the data given here.


TEMPERATURE, °R
200
300
400
500
VELOCITY OF SOUND
IN
GASEOUS OXYGEN
(near one atmosphere pressure)
320
300
280
260
240
220
200
180
VELOCITY OF SOUND, meters / second
1050
1000
950
900
850
800
750
700
650
600
VELOCITY OF SOUND, feet / second
nbp = 90.19 °K
80
100
140
180
220
260
300
TEMPERATURE, °K


15.005
PRESSURE, psia
0.6
0.8
1.0
2
4
6
8
10
600
590
580
570
560
550
540
182
180
178
176
174
172
170
168
166
164
162
VELOCITY OF SOUND
IN
GASEOUS OXYGEN
T = 92.03°K
88.72°K
86.92°K
84.95°K
83.05°K
80.60°K
78.15°K
76.00°K
74.12°K
SATURATED
VAPOR
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
.03
.04
.06
.08
0.1
0.2
0.4
0.6
0.8
1.0
PRESSURE, atmospheres


15.005
PRESSURE, psia
0
200
400
600
800
1000
1200
1400
330
320
310
300
290
280
270
260
250
240
230
1080
1060
1040
1020
1000
980
960
940
920
900
880
860
840
820
800
780
760
T = 280° K
260° K
240° K
220° K
200° K
180° K
160° K
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
VELOCITY OF SOUND
IN
GASEOUS OXYGEN
0
20
40
60
80
100
PRESSURE, atmospheres

VELOCITY of SOUND in GASEOUS AIR

Sources of Data:

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564 (1955) 488 pp.

Michels, A., Wassenaar, T. and Wolkers, G. J.; J. Appl. Sci. Research A5, 121 (1955)

Other References:

Foley, A. L.; Proc. Indiana Acad. Sci. 37, 205 (1927)

Partington, J. R. and Shilling, W. G.; Specific Heats of Gases, D. Van Nostrand Company, New York, (1924) p. 77

Cornish, R. E. and Eastman, E. D.; J. Am. Chem. Soc. 50, (1) 627 (1928)

Keesom, W. H. and Van Itterbeek, A.; Proc. Acad. Sci. Amsterdam 34, 204 (1931)

Van Itterbeek, A. and Keesom, W. H.; Koninkl. Ned. Akad. Wetenschap Amsterdam, Proc. 34, 988 (1931); Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 216c (1931)

Hodge, H. O.; Ann. Physik. 34, 665 (1939)

Colwell, R. C. and Gibson, L. H.; Acoust. Soc. Am. 12, 436 (1941)

Van Itterbeek, A. and Van Doninck, W.; Ann. Phys. 19, 88 (1944)

Kneser, H. O., Ann. Physik. 34, 665 (1939)

Quigley, T. H.; Phys. Rev. 67, 298 (1945)

Comments:

The velocity of sound in gaseous air is presented here as a function of temperature and pressure. Data for temperatures from 50°K to 280°K at various pressures between 0.01 and 1000 atmospheres are given. The data illustrated on the graphs and tabulated below are from the references listed above under "Sources of Data".

The compilation of thermal properties of gases by Hilsenrath, et al., contains calculated values of the velocity of low frequency sound in air. The data illustrated below in the graph of velocity of sound as a function of temperature, and the graph of the velocity of sound as a function of pressure for low pressures, are from this compilation. The authors report these values of the velocity of sound as being based on air composed of 0.7809 nitrogen, 0.2095 oxygen, 0.0093 argon and 0.0003 carbon dioxide moles per mole of air, yielding an average molecular weight of 28.966. Hilsenrath, et al., present their data as ratios in the form of a/a_o, where a is the value of the velocity of sound at low frequency at a given temperature and pressure, and a_o is a datum value (a_o = 331.45 m/sec) at 0°C and 1 atmosphere of pressure. All values from Hilsenrath, et al., tabulated here have been converted to specific values of velocity of sound. A maximum error of 3% for the velocities of sound at low pressures for temperatures below 270°K is reported.

(Continued on following page)

VELOCITY of SOUND in GASEOUS AIR (Cont.)

Comments: (cont.)

Data from Michels, Wassenaar and Wolkers are tabulated below and illustrated in part, on the graph of the velocity of sound as a function of pressure for pressures from 0 to 1000 atmospheres. These values of velocity of sound were calculated by Michels, et al., from an equation of state based on a correlation of their own P-V-T experimental data. A maximum error of 10% is possible in the values of the velocity of sound; however, at temperatures given here the accuracy is probably much better. Michels, et al., report the air used in their experimental determinations as beingfree of water vapor and carbon dioxide.

The units of the velocity of sound in gaseous air in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Air as a Function of Pressure*

Velocity, m/sec								
Temp.	Pressure, atm.							
°K	.01	.1	.4	.7	1**	4	7	10
50	141.69							
60	155.28							
70	167.75							
80	179.38	179.05						
90	190.25	189.95	189.16	188.33				
100	200.56	200.36	199.73	199.07	198.44			
110	210.34	210.17	209.71	209.21	208.68	203.38	197.54	190.98
120	219.72	219.59	219.19	218.79	218.39	214.25	209.91	205.20
130	228.70	228.57	228.27	227.94	227.64	224.39	221.01	217.53
140	237.32	237.22	236.99	236.72	236.46	233.87	231.25	228.60

* Values are from Hilsenrath, et al.

** Values also appear on the graph of the velocity of sound as a function of temperature.

(Continued on following page)

Velocity of Sound in Gaseous Air as a Function of Pressure

Michels, Wassenaar and Wolkers

Press. atm.	Velocity, m/sec								
	-135°C	-125°C	-115°C	-100°C	-85°C	-70°C	-50°C	-25°C	0°C
0	235.8	244.2	252.3	264.0	275.2	285.9	299.6	316.0	331.46
10	226.4	236.8	246.4	259.9	272.2	284.2	298.8	316.1	332.3
20	215.8	229.0	240.8	256.5	270.3	282.9	298.3	316.6	333.4
30	203.7	221.5	235.4	253.0	268.2	282.3	298.7	317.4	334.7
40	191.3	214.5	231.0	250.7	267.3	281.9	299.3	318.8	336.4
50	225.6	211.2	228.8	250.3	267.4	282.5	300.4	320.5	338.3
60	303.5	221.3	230.3	250.7	268.5	283.9	302.3	322.5	340.5
70	354.5	253.7	239.4	253.8	270.9	286.2	304.6	325.0	343.0
80	393.0	294.1	256.5	260.2	274.8	289.5	307.6	327.8	345.8
90	424.4	330.3	280.1	270.2	280.6	293.5	311.1	331.1	349.1
100	451.2	361.6	306.5	283.4	288.4	299.3	315.5	334.8	352.4
150	551.9	475.3	420.3	368.9	346.9	341.7	347.5	359.8	374.3
200	625.2	553.7	503.5	448.3	414.4	397.3	389.9	393.1	401.7
250	(684.6)	615.5	568.6	514.5	476.6	452.6	436.5	430.5	433.1
300		(665.8)	622.3	570.6	531.6	504.2	481.9	469.0	466.4
350		(710.0)	(668.5)	619.2	580.3	551.2	525.3	507.1	499.8
400			(709.7)	662.1	623.9	594.0	565.8	543.9	532.8
450				700.9	663.1	633.2	603.5	579.1	565.0
500				(736.5)	699.6	669.3	638.8	612.6	596.0
550				(769.4)	732.5	702.4	672.0	644.3	625.7
600					(763.5)	733.5	703.1	674.3	654.4
650					(792.5)	763.5	732.3	702.8	681.8
700						(790.5)	759.8	730.5	708.3
750						(817.8)	786.0	755.8	733.3
800							(811.2)	780.5	757.3
850							(835.2)	804.1	780.3
900								826.6	802.5
950								848.4	823.8
1000	parenthesis indicate extrapolated values							(868.9)	844.4

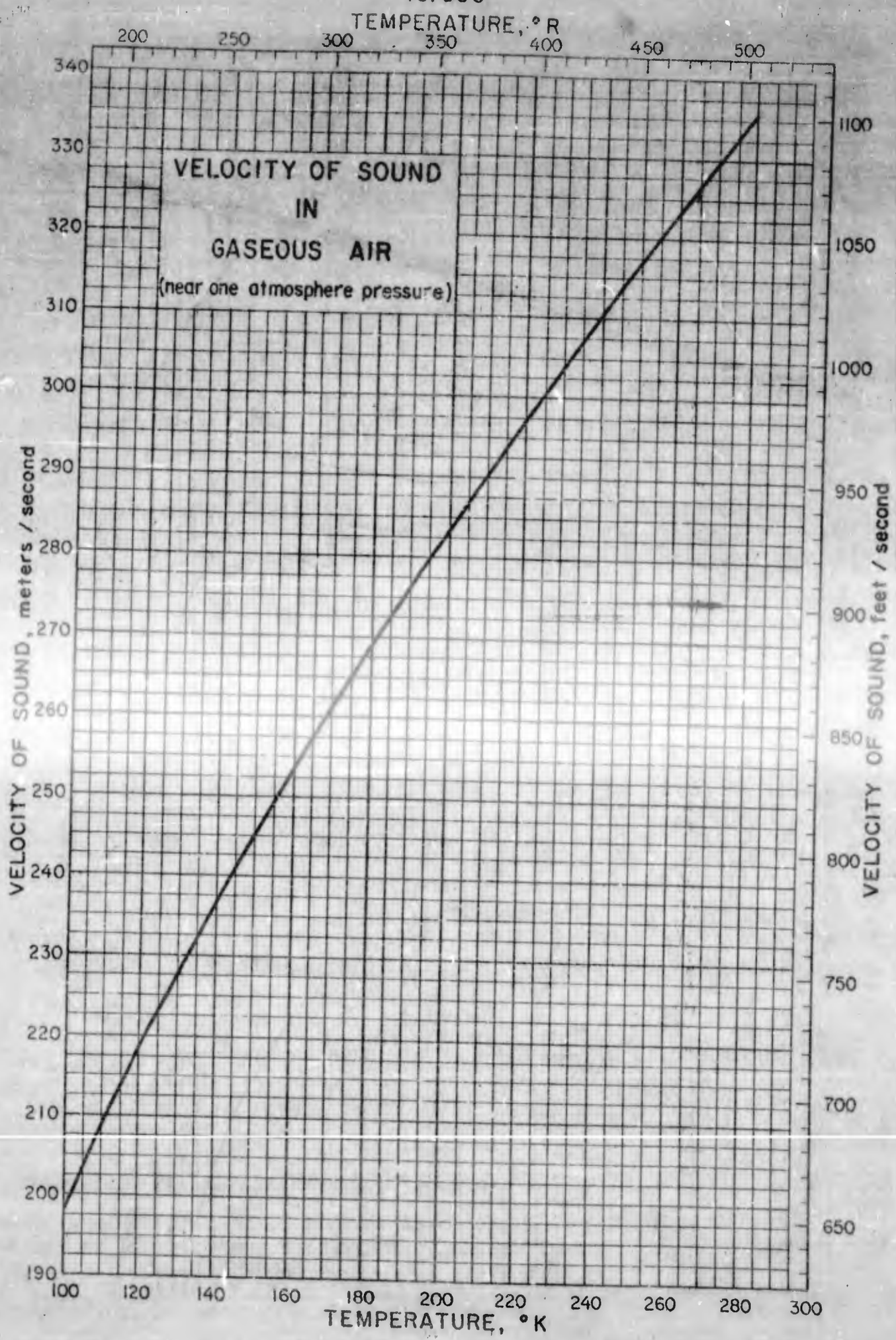
VELOCITY of SOUND in GASEOUS AIR (Cont.)

Comments: (cont.)

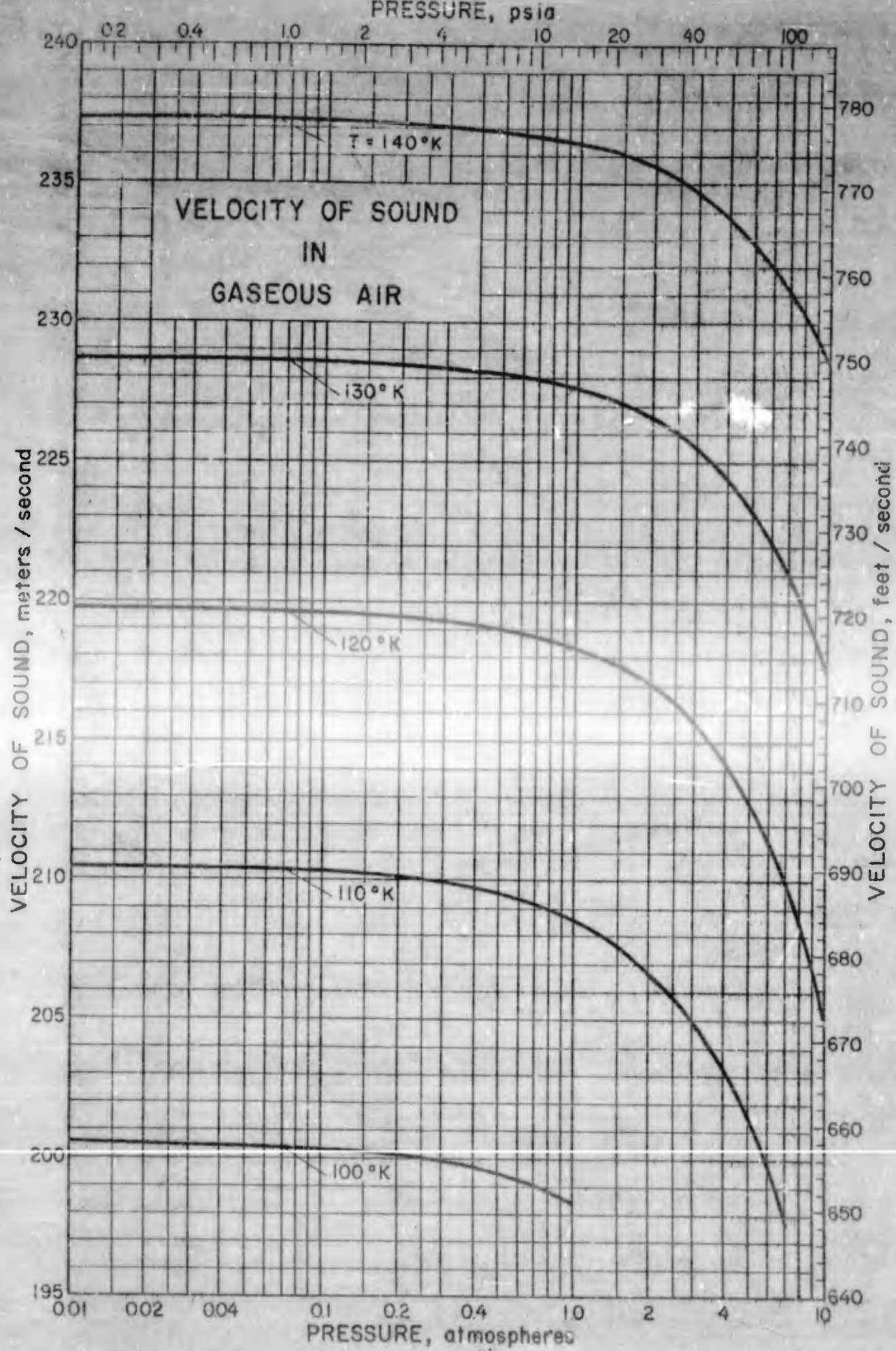
Velocity of Sound in Gaseous Air
as a Function of Temperature*

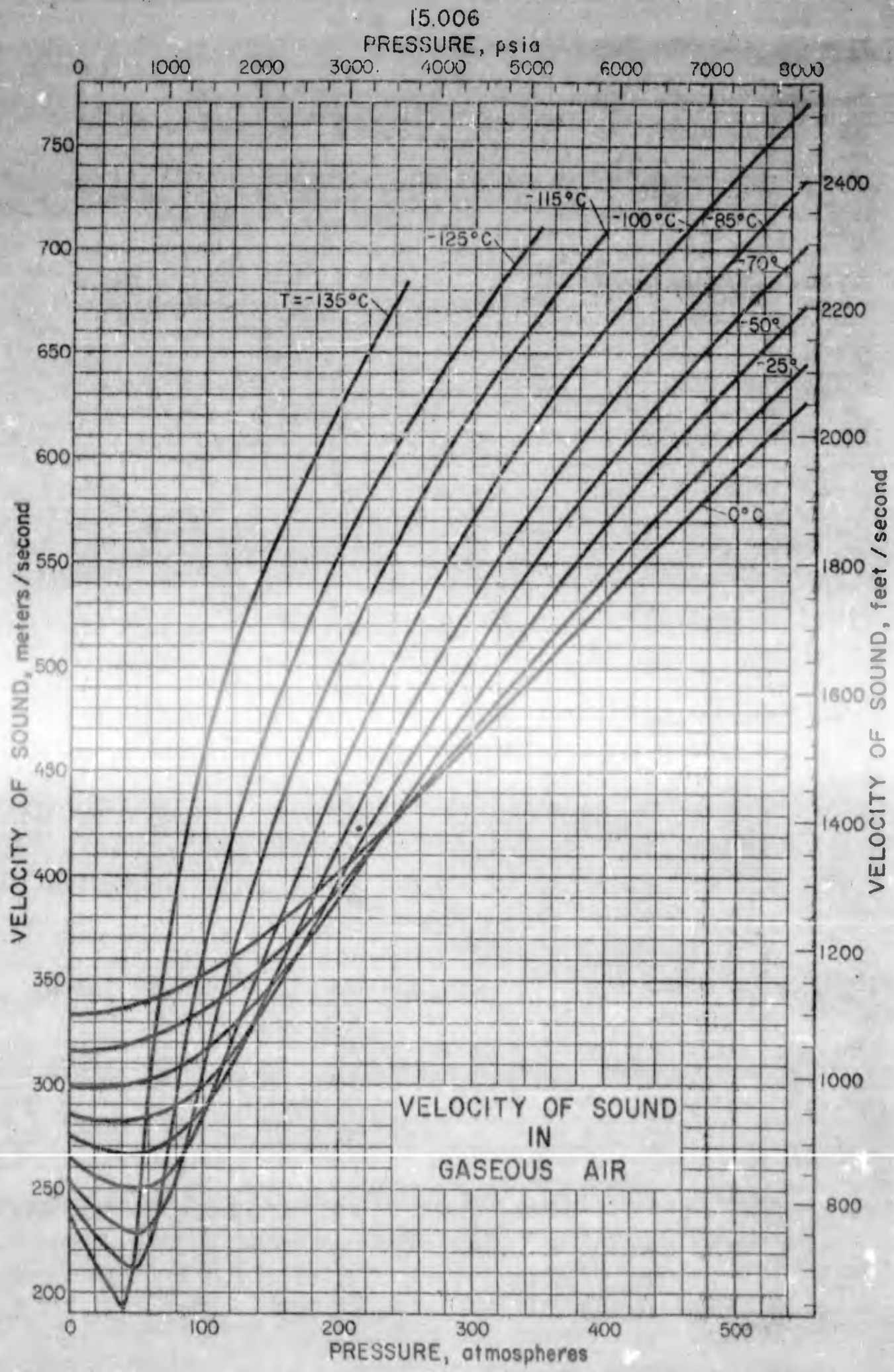
Velocity, m/sec			
Temp. °K	Press. 1 atm.	Temp. °K	Press. 1 atm.
150	244.97	220	297.38
160	253.16	230	304.11
170	261.02	240	310.60
180	268.74	250	317.10
190	276.16	260	323.40
200	283.39	270	329.56
210	290.48	280	335.56

* Values are from Hilsenrath, et al.


TEMPERATURE, °R
200
250
300
350
400
450
500
VELOCITY OF SOUND
IN
GASEOUS AIR
(near one atmosphere pressure)
VELOCITY OF SOUND, meters / second
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
190
VELOCITY OF SOUND, feet / second
1100
1050
1000
950
900
850
800
750
700
650
100
120
140
160
180
200
220
240
260
280
300
TEMPERATURE, °K

15.006


PRESSURE, psia
0.2
0.4
1.0
2
4
10
20
40
100
T = 140°K
VELOCITY OF SOUND
IN
GASEOUS AIR
130°K
120°K
110°K
100°K
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
240
235
230
225
220
215
210
205
200
195
780
770
760
750
740
730
720
710
700
690
680
670
660
650
640
0.01
0.02
0.04
0.1
0.2
0.4
1.0
2
4
10
PRESSURE, atmospheres


15.006
PRESSURE, psia
0
1000
2000
3000
4000
5000
6000
7000
8000
750
700
650
600
550
500
450
400
350
300
250
200
2400
2200
2000
1800
1600
1400
1200
1000
800
T=-135°C
-125°C
-115°C
-100°C
-85°C
-70°
-50°
-25°
0°C
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
VELOCITY OF SOUND
IN
GASEOUS AIR
0
100
200
300
400
500
PRESSURE, atmospheres

VELOCITY of SOUND in GASEOUS CARBON MONOXIDE

Sources of Data:

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564 (1954) 488 pp.

Van Itterbeek, A. and Van Doninck, W.; Physica 10, 481 (1943)

Other References:

Dulong, P. L.; Ann. de chimie et de phys. 41, 113 (1829)

Wullner, A.; Ann. Physik. 4, 321 (1878)

Schweikert, G.; Ann. Physik. 48, 593 (1915)

Van Itterbeek, A. and Mariens, P.; Physica 4, 609 (1937)

Van Itterbeek, A. and Van Doninck, W.; Proc. Phys. Soc. (London) 62B, 62 (1949)

Comments:

The velocity of sound in gaseous carbon monoxide is presented here as a function of temperature and pressure, for temperatures between 70°K and 280°K at various pressures between 0 and 1 atmosphere.

The data illustrated in the graph of velocity of sound versus temperature and tabulated below are from the references given above under "Sources of Data"; while the data illustrated in the graph of velocity of sound versus pressure are from Van Itterbeek and Van Doninck. Hilsenrath, et al., calculated values of the velocity of low frequency sound with the aid of an equation of state for carbon monoxide. These values are given in the source of data in the form of a/a_o, where a is the value of the velocity of low frequency sound at a given temperature and pressure, and a_o (a_o - 336.93 m/sec) is the velocity of sound at 0°C and 1 atmosphere of pressure. The value of a_o was computed by Hilsenrath, et al., on the basis of the Lennard-Jones intermolecular potential. The values tabulated are for 1 atmosphere of pressure at various temperatures and have been converted to specific values of velocity of sound. The data from Hilsenrath, et al., tabulated here are reported by the authors as accurate to 1%. Van Itterbeek and Van Doninck, using sound with a frequency of 522.4 kc/sec in a sample of chemically prepared carbon monoxide, report values of the velocity of sound at low temperatures and pressures.

The values of the velocity of sound at 0 pressure were calculated for the ideal gas, i.e., $c = \sqrt{RT\gamma}$, where c is the velocity of sound, R is the gas constant, T is the temperature and γ is the specific heat ratio. The 80.9°K isotherm on the plot of velocity of sound versus pressure has been extrapolated to the saturated vapor pressure as derived from the data reported by Hilsenrath, et al. The experimental data by Van Itterbeek and Van Doninck at 75.0°K and 70.8°K contains values of the velocity of sound near saturated pressures, making possible the extrapolation of the saturation curve which appears on this plot. No estimate is made by the authors as to the accuracy of their measurements or the purity of their sample.

(Continued on following page)

VELOCITY of SOUND in GASEOUS CARBON MONOXIDE (Cont.)

Comments: (cont.)

The units of the velocity of sound in carbon monoxide gas used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Carbon Monoxide
as a Function of Temperature (at One Atmosphere Pressure)

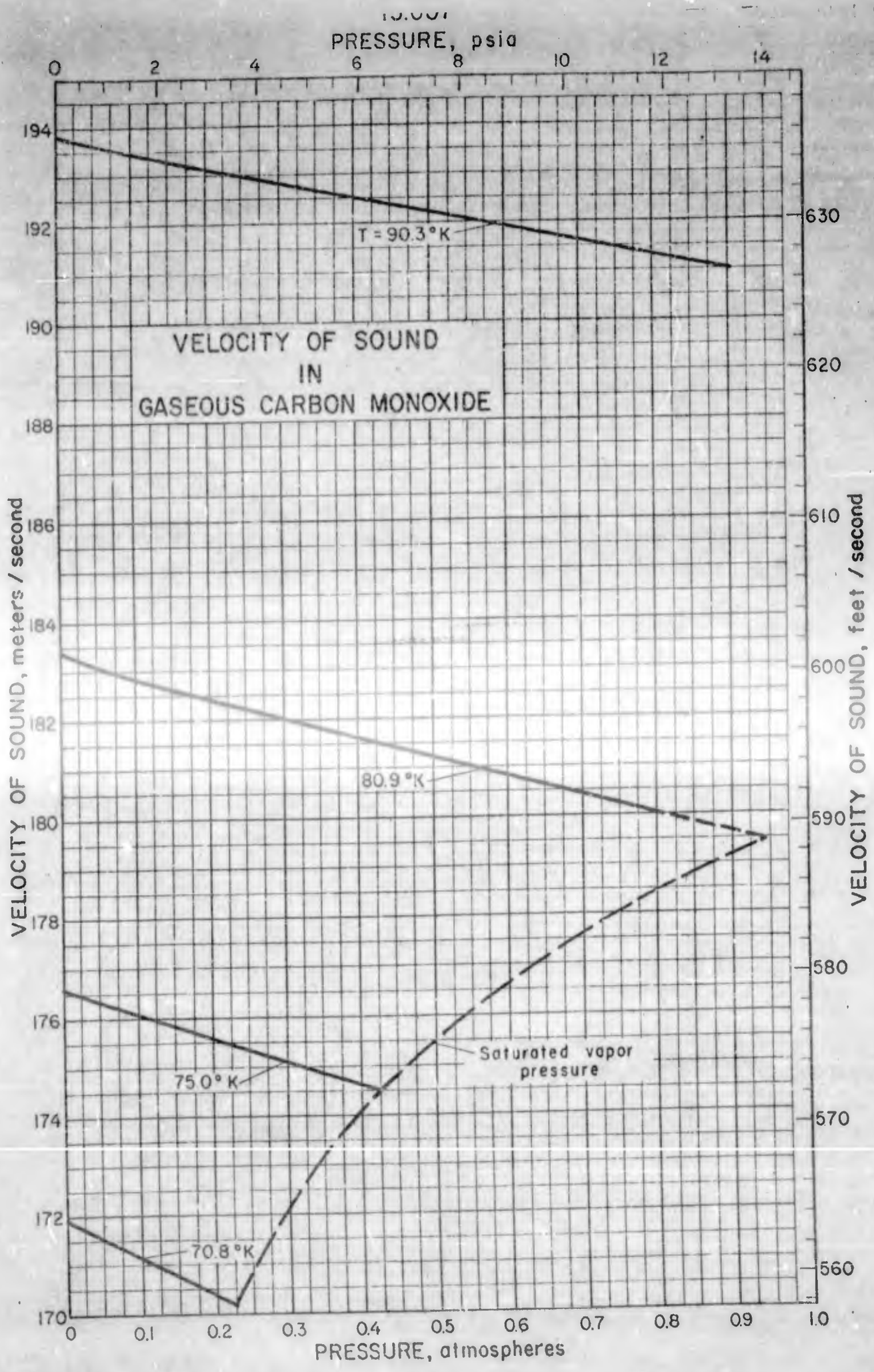
Hilsenrath, et al.			
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
200	288.08	250	322.44
210	295.15	260	328.84
220	302.23	270	334.91
230	308.96	280	341.31
240	315.70		

Velocity of Sound in Gaseous Carbon Monoxide
as a Function of Pressure

Van Itterbeek and Van Doninck			
Press. atm.	Velocity m/sec	Press. atm.	Velocity m/sec
70.8°K		75°K	
0.100	170.8	0.100	176.1
0.120	171.0	0.170	175.6
0.160	170.5	0.210	175.5
0.200	170.4	0.300	175.0
0.220	170.2	0.427	174.5
0.225	170.2	90.3°K	
80.9°K		0.175	193.2
0.147	182.6	0.236	192.9
0.225	182.3	0.375	192.7
0.358	181.8	0.400	192.5
0.425	181.5	0.500	192.2
0.526	181.1	0.595	192.0
0.600	180.8	0.697	191.6
0.810	180.0	0.903	191.0*

* Data included in graph of velocity of sound versus temperature.

(Continued on following page)

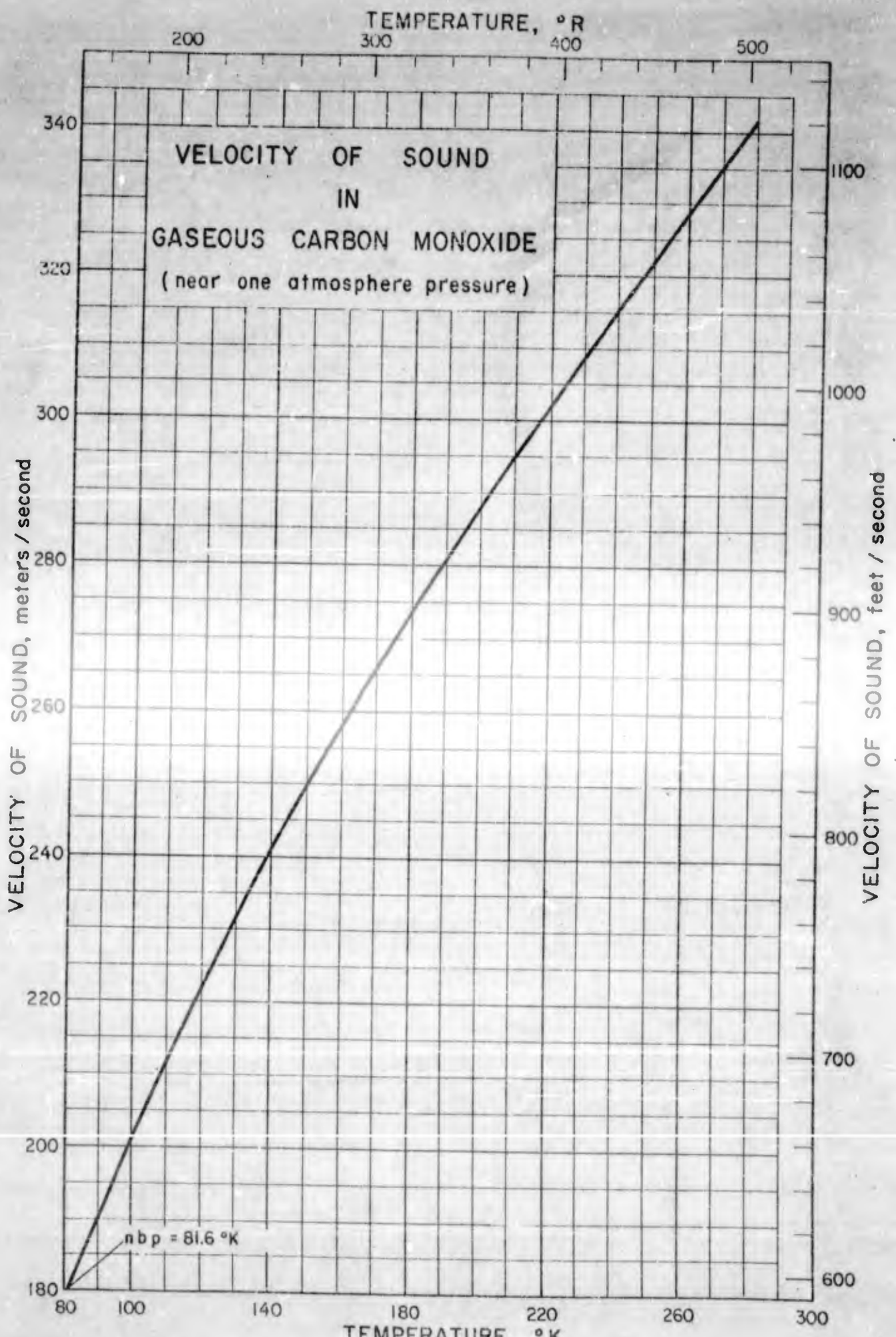

PRESSURE, psia
0
2
4
6
8
10
12
14
194
192
190
188
186
184
182
180
178
176
174
172
170
630
620
610
600
590
580
570
560
T = 90.3°K
VELOCITY OF SOUND
IN
GASEOUS CARBON MONOXIDE
80.9°K
75.0°K
Saturated vapor pressure
70.8°K
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PRESSURE, atmospheres

VELOCITY of SOUND in GASEOUS CARBON MONOXIDE (Cont.)

Comments: (cont.)

In 1829 Dulong arrived at a value of 337.4 m/sec as the velocity of sound in carbon monoxide at one atmosphere pressure and 0°C. In this work he made use of resonance in tubes of known length. Wüllner, working on the specific heats of gases, arrived at a value of 337.129 m/sec at 1 atm. and 0°C. Schweikert, using Kundt's dust figures arrived at the somewhat higher value of 337.7 m/sec.

Van Itterbeek and Mariens employed a frequency of 304.4 kc/sec and found 337.6 m/sec at 0°C and 1 atmosphere. Hilsenrath, et al., report a value of 336.93 m/sec at 0°C and 1 atmosphere for the velocity of low frequency sound in gaseous carbon monoxide.


TEMPERATURE, °R
200
300
400
500
VELOCITY OF SOUND
IN
GASEOUS CARBON MONOXIDE
(near one atmosphere pressure)
VELOCITY OF SOUND, meters / second
340
320
300
280
260
240
220
200
180
VELOCITY OF SOUND, feet / second
1100
1000
900
800
700
600
nbp = 81.6 °K
80
100
140
180
220
260
300
TEMPERATURE, °K

VELOCITY of SOUND in LIQUID ARGON

Source of Data:

Van Itterbeek, A. and Verhaegen, L.; Proc. Phys. Soc. (London) B62, 800 (1949)

Other References:

Galt, J. K.; J. Chem. Phys. 16, 505 (1948)

Liepmann, H. W.; Helv. Phys. Acta 12, 421 (1939)

Venkatasubramanian, V. S.; J. Indian Inst. Sci. A37, 227 (1955)

Comments:

Velocity of sound in liquid argon is given here as a function of temperature under saturation pressures.

The data illustrated in the graph and tabulated below are from Van Itterbeek and Verhaegen, cited above under "Source of Data." The sample used in these observations had 0.1% impurities of unreported composition. No estimate of the accuracy of their data was made but the authors do report the frequency of the sound used as 523.00 kc/sec ±0.01 kc/sec.

The units of the velocity of sound in liquid argon used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Saturated Liquid Argon

Van Itterbeek and Verhaegen		
Temp. °K	Press. atm.	Velocity m/sec
87.35	1.01	849
85.80	.849	857
83.95	.691	875
87.15	.992	845
85.85	.859	860
85.30	.803	868

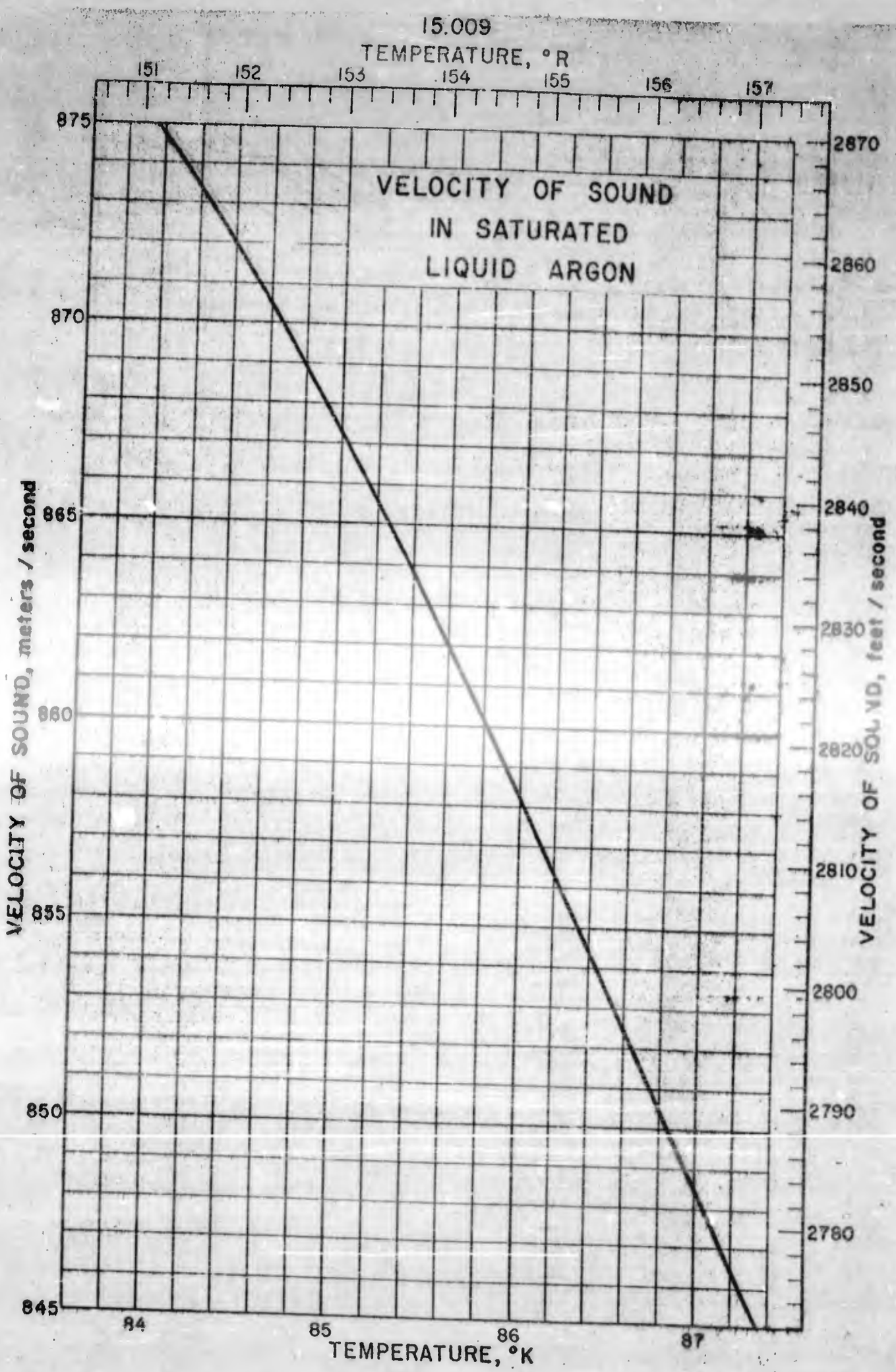
The earliest reference to the velocity of sound in liquid argon appears to be that of Liepmann, who measured the angle of diffraction of light in a sound wave. His results, obtained by reference to measurements made on liquid oxygen are, in general, 1% lower than those by Van Itterbeek and Verhaegen. This could be explained by the impurities (2% nitrogen) present in the Liepmann experimental sample.

(Continued on following page)

VELOCITY of SOUND in LIQUID ARGON (Cont.)

Comments: (cont.)

Galt used ultrasonic waves and found a velocity of 853 m/sec at 87.2°K. Venkatasubramanian derived a formula based on a Lennard-Jones liquid model for calculations of the sonic velocity in liquid argon. His calculations give a value of 830 m/sec which he compares with observed values of Liepmann and Galt; however, no statement is made as to the temperature used in his calculation.


15.009
TEMPERATURE, °R
151
152
153
154
155
156
157
VELOCITY OF SOUND
IN SATURATED
LIQUID ARGON
875
870
865
860
855
850
845
2870
2860
2850
2840
2830
2820
2810
2800
2790
2780
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
84
85
86
87
TEMPERATURE, °K

VELOCITY of SOUND in GASEOUS ARGON

Sources of Data:

Hilsenrath, J., et al.; Natl. Bur. Standards Circ. 564 (1955) 488 pp.

Van Itterbeek, A. and Van Paemel, O.; Physica 5, 845 (1938)

Other References:

Strieder, F.; Verhandl. deut. physik. Ges. 16, 615 (1914)

Dixon, H. B., Campbell, C. and Parker, A.; Proc. Roy. Soc. (London) A100, 1 (1921)

Greenspan, M.; J. Acoust. Soc. Am. 28, 644 (1956)

Bancroft, D.; Am. J. Phys. 24, 355 (1956)

Comments:

The velocity of sound in argon gas is given here as a function of temperature and pressure for pressures from 0 to 1 atmosphere, and temperatures between 78.93°K and 280°K.

Velocity of sound in gaseous argon as a function of temperature is illustrated by the first graph. The data for this graph are from both of the citations listed above under "Sources of Data". Hilsenrath, et al., calculated values of velocity of sound with an equation of state which was based on a correlation of experimental data. The authors reported on extensive comparisons of their calculated values with experimental data and report an average deviation for their entire tables on argon of 1%. These values from Hilsenrath, et al., are reported as ratios of velocity of sound (a/a_o), where a is the value of the velocity of sound at a given pressure and temperature, and a_o is the velocity of sound at 0°C and 1 atmosphere pressure. The datum value (a_o = 307.88 m/sec) was calculated by Hilsenrath, et al., on the basis of the Lennard-Jones intermolecular potential. The values from Hilsenrath, et al., tabulated here have been converted to specific values of velocity of sound.

The graph of the velocity of sound as a function of pressure illustrates part of the data from Van Itterbeek and Van Paemel. A cross plot of this data indicates that part of the data is not consistent with the remainder. The values of the velocity of sound at zero pressure which have been calculated for the ideal gas, i.e., $c = \sqrt{RT\gamma}$, where c is the velocity of sound, R is the gas constant, T is the temperature and γ is the ratio of specific heats, are again not consistent with part of this data, but are in excellent agreement with the rest of the data. The data by Van Itterbeek and Van Paemel which does not agree with the calculated zero pressure data have been omitted on the graph. Van Itterbeek and Van Paemel used supersonics in their measurements of velocity of sound. The authors make no estimate of the accuracy of their measurements, but do report a very small amount of oxygen in their experimental sample.

(Continued on following page)

VELOCITY of SOUND in GASEOUS ARGON (Cont.)

Comments: (cont.)

The units of the velocity of sound in gaseous agron in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Argon

as a Function of Pressure

Van Itterbeek and Van Paemel								
Temp. °K	Press. atm.	Vel. m/sec	Temp. °K	Press. atm.	Vel. m/sec	Temp. °K	Press. atm.	Vel. m/sec
90.29*	0.691	176.1	80.88	0.439	166.7	85.73	0.262	171.1
	0.574	176.3		0.326	166.9		0.180	171.3
	0.453	176.7		0.242	167.3		0.124	171.6
	0.338	177.1		0.143	167.9		0.0730	172.1
	0.214	177.3	90.25	0.671	174.6	80.85	0.389	165.6
	0.110	177.9		0.567	174.9		0.320	165.8
	0.0574	178.3		0.455	175.3		0.244	166.1
90.18	0.698	175.9		0.337	175.6		0.173	166.4
	0.568	176.2		0.228	176.0		0.107	166.8
	0.334	176.9		0.143	176.3	78.93	0.314	163.8
	0.205	177.3		0.0842	176.4		0.245	164.0
90.20	0.428	176.5	85.73	0.592	170.1		0.170	164.3
	0.282	177.1		0.493	170.3		0.115	164.5
				0.386	170.7		0.0545	164.8

* Values also appear on graph of velocity of sound versus temperature.

(Continued on following page)

VELOCITY of SOUND in GASEOUS ARGON (Cont.)

Comments: (cont.)

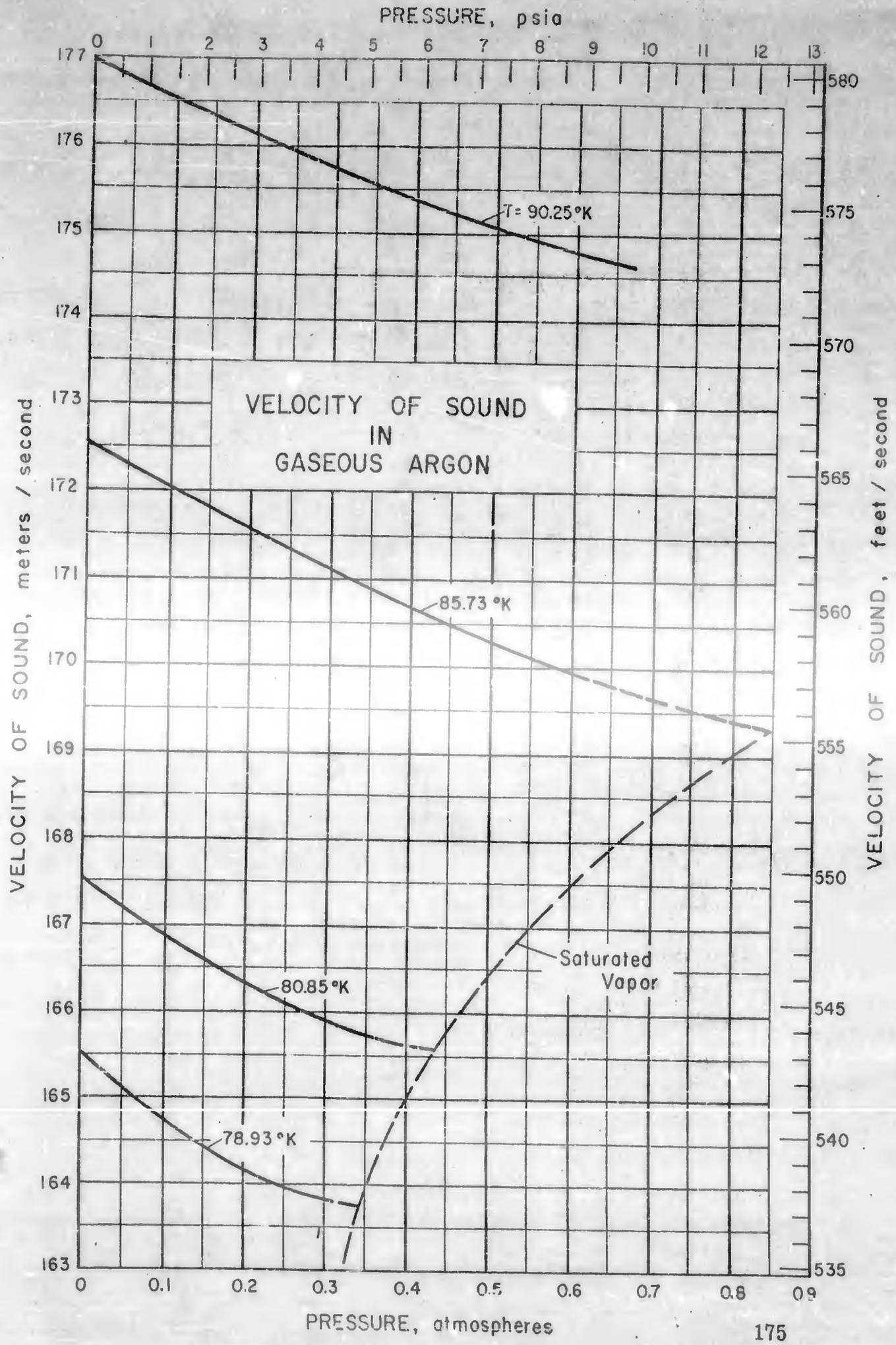
Velocity of Sound in Gaseous Argon
as a Function of Temperature

Hilsenrath, et al.	
Pressure, 1 atm.	
Temp. °K	Velocity m/sec
100	184.42
120	202.89
140	219.52
160	235.22
180	249.69
200	263.24
220	276.17
240	288.48
260	300.49
280	311.57

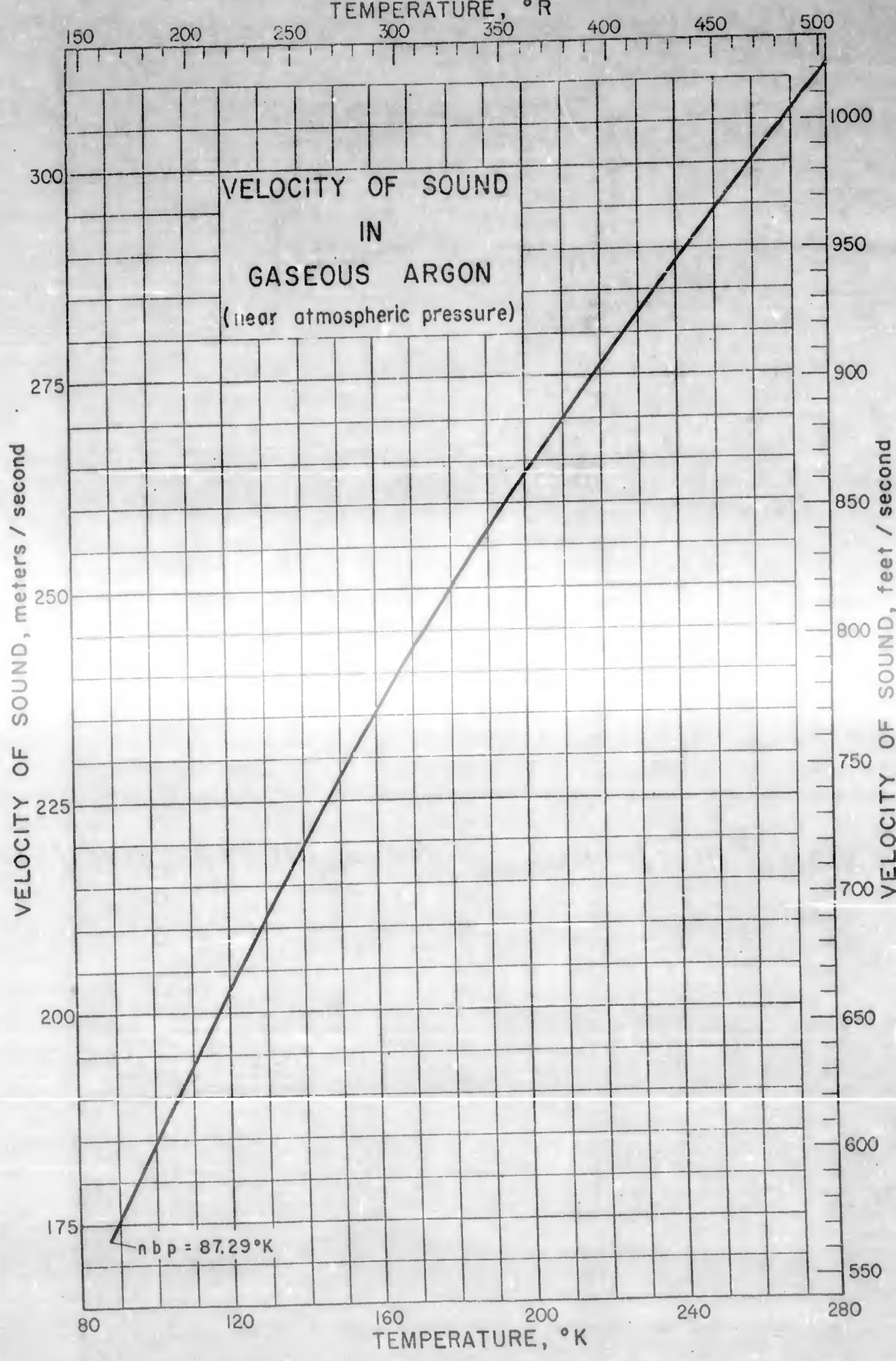
Strieder determined the velocity of sound in argon by means of dust figures in Kundt's tubes to be 316.56 m/sec at 18.3°C. This value was based on the assumption that the velocity in air was 341.94 m/sec. No effect was observed from x-rays acting on argon. Dixon, Campbell and Parker found a value of 308.5 m/sec at 0°C for the velocity of sound.

Greenspan determined the attenuation of sound at 11 mc in helium, neon, argon, krypton and xenon at various pressures between atmospheric and a few mm Hg, and compared the results with existing theories.

Using the method of observing the frequencies in a radial oscillating gas confined in a spherical cavity, Bancroft found a value of 307.83 m/sec for the velocity of sound in argon gas at 0°C and approximately atmospheric pressure.


PRESSURE, psia
0 1 2 3 4 5 6 7 8 9 10 11 12 13
VELOCITY OF SOUND
IN
GASEOUS ARGON
T = 90.25°K
85.73 °K
80.85 °K
78.93 °K
Saturated Vapor
VELOCITY OF SOUND, meters / second
177 176 175 174 173 172 171 170 169 168 167 166 165 164 163
VELOCITY OF SOUND, feet / second
580 575 570 565 560 555 550 545 540 535
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
PRESSURE, atmospheres

15.009


TEMPERATURE, °R
150
200
250
300
350
400
450
500
VELOCITY OF SOUND
IN
GASEOUS ARGON
(near atmospheric pressure)
VELOCITY OF SOUND, meters / second
300
275
250
225
200
175
VELOCITY OF SOUND, feet / second
1000
950
900
850
800
750
700
650
600
550
n b p = 87.29°K
80
120
160
200
240
280
TEMPERATURE, °K

VELOCITY of SOUND in LIQUID METHANE

Source of Data:

Van Itterbeek, A. and Verhaegen, L.; Proc. Phys. Soc. (London) 62B, 800 (1949)

Other Reference:

Van Itterbeek, A., de Bock, A. and Verhaegen, L.; Physica 15, 624 (1949)

Comments:

Velocity of sound in liquid methane is given here as a function of temperature under saturation pressures.

The data illustrated in the graph and tabulated below are from Van Itterbeek and Verhaegen, cited above under "Source of Data". The frequency of sound used by Van Itterbeek and Verhaegen was 523 kc/sec. No mention is made of the purity of the sample used but a maximum error of 1% in their data is claimed.

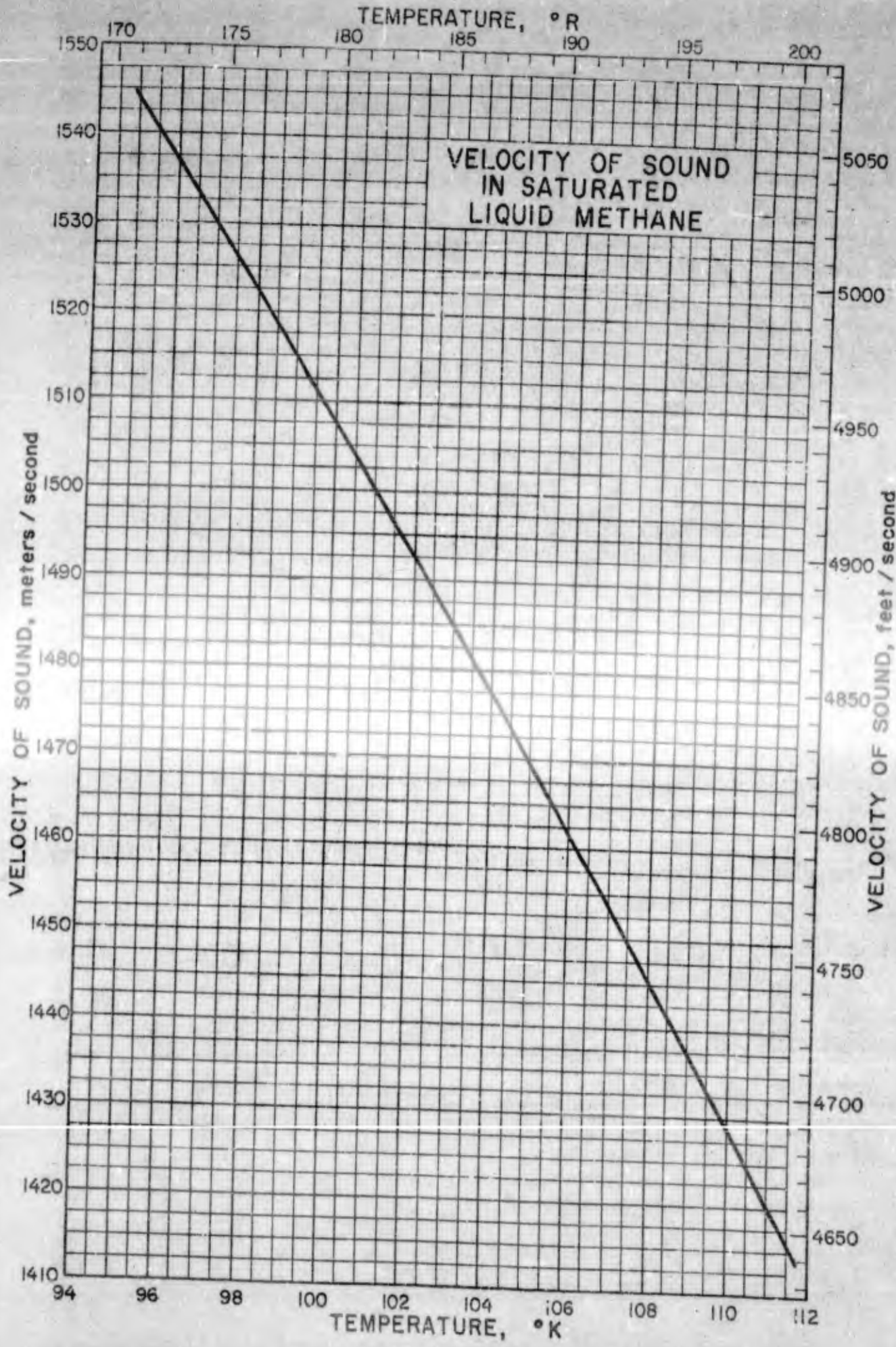
The units of the velocity of sound in liquid methane used in the tabulations below and on the graph are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Saturated Liquid Methane

Van Itterbeek and Verhaegen		
Temp. °K	Press. atm.	Velocity m/sec
94.9	.195	1545
102.6	.437	1485
105.6	.603	1462
108.8	.792	1461
111.4	.982	1418
111.7	1.01	1414

FEEG/RDM/RS Issued: 4/20/61

15.010


TEMPERATURE, °R
170
175
180
185
190
195
200
VELOCITY OF SOUND IN SATURATED LIQUID METHANE
VELOCITY OF SOUND, meters / second
1550
1540
1530
1520
1510
1500
1490
1480
1470
1460
1450
1440
1430
1420
1410
VELOCITY OF SOUND, feet / second
5050
5000
4950
4900
4850
4800
4750
4700
4650
94
96
98
100
102
104
106
108
110
112
TEMPERATURE, °K

VELOCITY of SOUND in GASEOUS METHANE

Source of Data:

Quigley, T. H.; Phys. Rev. 67, 298 (1945)

Other References:

Masson, A.; Compt. rend. 44, 464 (1857)

Masson, A.; Ann. chimie. et phys. 53, 257 (1858)

Lacam, A.; J. phys. radium 14, 426 (1953)

Lacam, A.; J. phys. radium 15, 381 (1954)

Noury, J. and Lacam, A.; J. phys. radium 15, 301 (1954)

Comments:

Velocity of sound in gaseous methane is presented here as a function of temperature between the normal boiling point and 252°K. The experimental data has been extrapolated from 115°K to the normal boiling temperature of 111.67°K.

The data illustrated on the graph and tabulated below are from Quigley, cited above under "Source of Data". Quigley used frequencies of approximately 588 kc/sec at one atmosphere pressure in his observations of the velocity of sound. He gives a detailed discussion of the errors resulting from the experimental apparatus, but makes no estimate of the purity of the sample or the accuracy of the data reported.

The units of the velocity of sound in gaseous methane are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665), and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Methane

as a Function of Temperature

Quigley (P = 1 atmosphere)					
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
115.58	274.40	168.62	336.55	226.47	389.35
124.21	284.91	170.34	336.59	225.74	389.35
133.55	296.29	184.80	352.49	226.09	389.45
144.26	308.56	186.30	352.55	253.10	410.76
144.18	308.61	186.62	352.53	252.85	410.83
154.77	321.97	203.53	370.02	252.54	410.83
		226.05	389.37		

(Continued on following page)

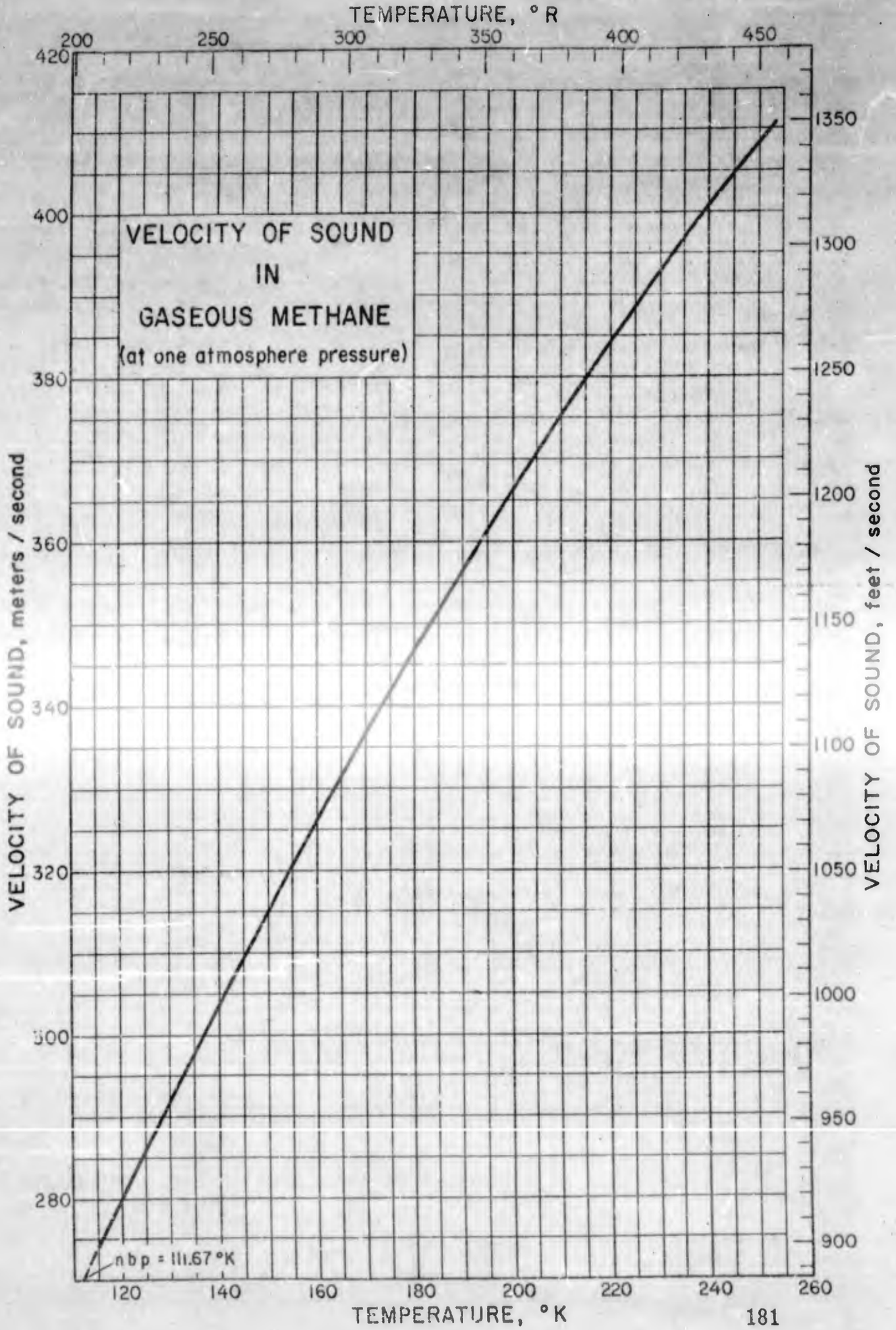
VELOCITY of SOUND in GASEOUS METHANE (Cont.)

Comments: (cont.)

In the course of his work on the correlation of the physical properties of materials, Masson determined the velocity of sound in many solids and fluids. For the work on gases he followed the lead of Dulong, using copper and tin organ pipes filled with gases which he caused to resonate. For methane he arrived at the value of 431.82 m/sec at 0°C, which is in good agreement with later determinations.

Lacam worked at temperatures of 25 and 50°C, and at pressures between 100 and 900 atmospheres and observed that below 220 atmospheres the velocity increases as the temperature increases, at a given pressure. Above 220 atmospheres the velocity decreases as the temperature increases at a fixed pressure. These measurements were made at about 900 kc/sec. Noury and Lacam found a minimum sonic velocity occurs at about 70 atmospheres in observations ranging from 1 to 150 atmospheres, using frequencies of 720, 890, and 1030 kc/sec. In general, he reports that the velocities were greater at higher frequencies.

In the pressure range from 100 to 1000 atmospheres, at high temperatures, Lacam showed that above 200 atmospheres the velocity decreases, at given values of the pressure, with both an increase in temperature and an increase in frequency.


TEMPERATURE, °R
200
250
300
350
400
450
VELOCITY OF SOUND
IN
GASEOUS METHANE
(at one atmosphere pressure)
VELOCITY OF SOUND, meters / second
420
400
380
360
340
320
300
280
VELOCITY OF SOUND, feet / second
1350
1300
1250
1200
1150
1100
1050
1000
950
900
n b p = 111.67 °K
120
140
160
180
200
220
240
260
TEMPERATURE, °K

16.000

EQUILIBRIUM CONCENTRATIONS of BINARY MIXTURES of CRYOGENIC FLUIDS

CONTENTS

Equilibrium Concentrations of Helium-Hydrogen Mixtures..... 16.001/2

Equilibrium Concentrations of Helium-Nitrogen Mixtures..... 16.001/4

Solubility of Helium in Liquid Methane 16.001/10

Equilibrium Concentration of Hydrogen-Nitrogen Mixtures 16.002/4

Equilibrium Concentrations of Hydrogen-Carbon Monoxide Mixtures .. 16.002/7

Equilibrium Concentrations of Hydrogen-Methane Mixtures 16.002/10

Equilibrium Concentrations of Nitrogen-Oxygen Mixtures 16.004/5

Equilibrium Concentrations of Nitrogen-Carbon Monoxide Mixtures .. 16.004/7

Equilibrium Concentrations of Nitrogen-Argon Mixtures 16.004/9

Equilibrium Concentrations of Nitrogen-Methane Mixtures 16.004/10

EQUILIBRIUM CONCENTRATIONS of HELIUM-HYDROGEN MIXTURES

Source of Data:

Smith, S. R., Dissertation for Degree of Doctor of Philosophy, Ohio State University (1952)

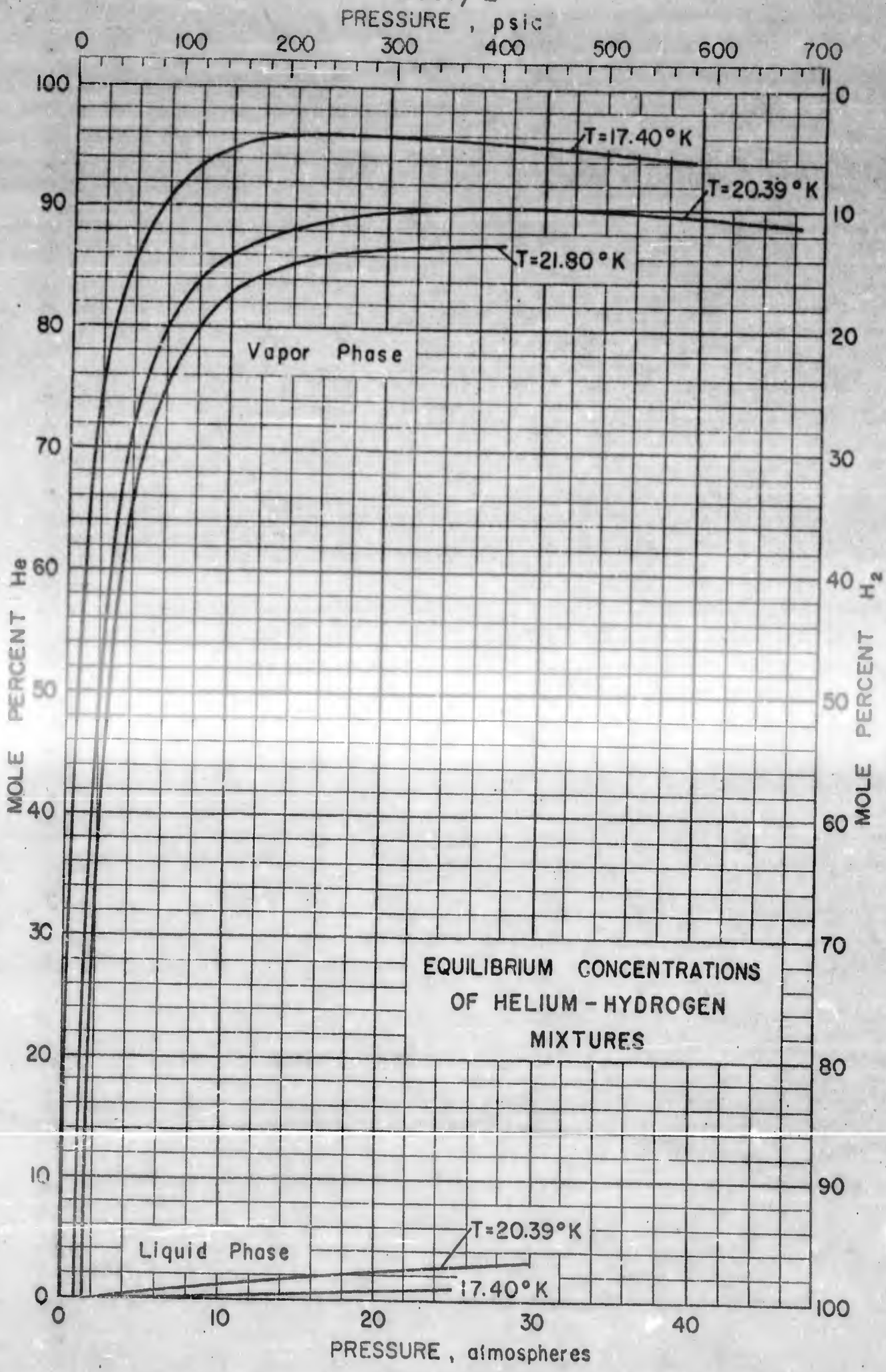
Comments:

The following tabular data from the dissertation by S. R. Smith, describe the liquid-vapor equilibrium for hydrogen-helium mixtures. These measurements were made at 17.40°, 20.39° and 21.80°K for pressures to about 500 psia where an inversion in the densities of the phases prevented an extension of the data to higher pressures with the experimental apparatus employed. Smith reported the absolute accuracy of the analysis of the samples as approximately two percent of the ratio of the mole fractions of the components.

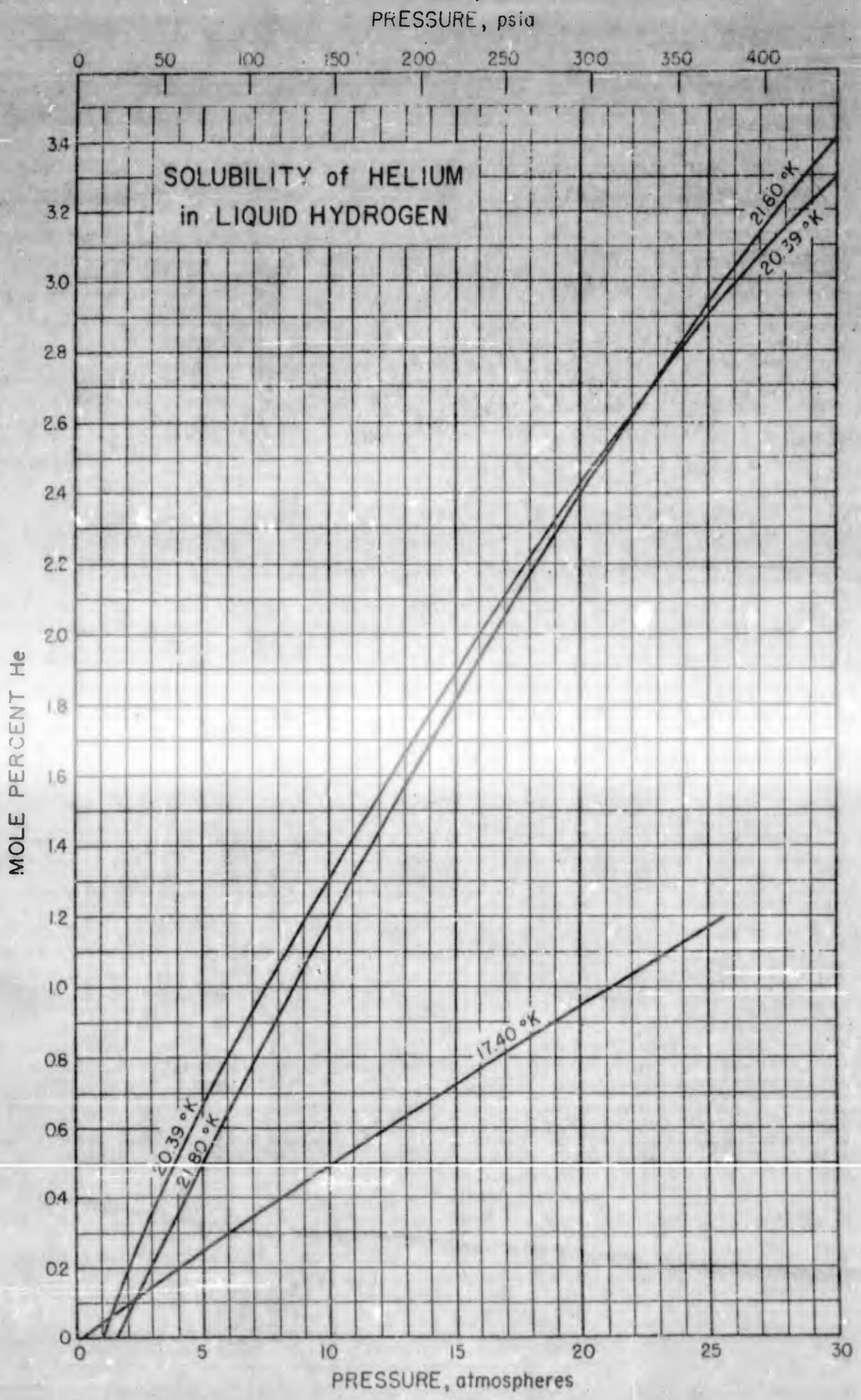
These data are illustrated on two graphs. The first presents the data for both the liquid and the vapor phases, with the exception of the 21.80°K isotherm for the liquid phase which was omitted since it nearly coincides with the 20.39°K isotherm. The liquid phase data are then presented on the second graph on an expanded scale.

FEEG/RS Issued: 3-30 61

16.001/2


PRESSURE , psia
0
100
200
300
400
500
600
700
T=17.40°K
T=20.39°K
T=21.80°K
Vapor Phase
Liquid Phase
T=20.39°K
17.40°K
EQUILIBRIUM CONCENTRATIONS
OF HELIUM - HYDROGEN
MIXTURES
MOLE PERCENT He
MOLE PERCENT H2
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
PRESSURE , atmospheres

16.001 / 2


PRESSURE, psia
0
50
100
150
200
250
300
350
400
SOLUBILITY of HELIUM
in LIQUID HYDROGEN
21.60 °K
20.39 °K
17.40 °K
20.39 °K
21.80 °K
MOLE PERCENT He
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
PRESSURE, atmospheres

EQUILIBRIUM CONCENTRATIONS of HELIUM-HYDROGEN MIXTURES

(Liquid and Vapor Phases)

Press. psia	mole % He	
	Liquid	Vapor
17.40°K		
48	0.19	83.4
48	0.20	83.5
83	0.22	90.1
83	0.28	90.8
96	0.27	91.8
96	0.31	91.8
141	0.45	93.5
141	0.51	93.4
157	--	95.5
157	--	95.3
196	--	96.1
196	--	96.2
207	0.67	94.3
207	0.74	94.4
236	--	96.3
236	--	96.2
267	--	96.3
267	--	96.3
316	1.05	95.0
316	1.08	95.0
358	1.11	95.2
358	1.15	95.2
473	--	93.6
473	--	93.6
525	--	94.4
525	--	94.3
579	--	94.2
579	--	94.2
20.39°K		
28	--	61.0
28	--	61.0
63	--	72.9
63	0.59	72.6

Press. psia	mole % He	
	Liquid	Vapor
69	--	74.4
69	--	74.0
102	--	82.5
102	0.87	82.6
177	1.53	87.2
177	--	87.3
197	1.63	--
197	1.70	--
222	2.04	--
222	1.98	--
256	2.16	89.0
256	2.17	89.3
256	2.25	--
257	2.16	--
257	2.18	--
291	2.47	90.2
291	--	90.1
306	2.53	--
306	2.48	--
311	2.55	--
317	2.66	--
317	2.56	--
344	2.82	--
350	2.78	--
350	2.77	--
350	2.58	--
351	--	89.5
358	2.77	--
358	2.64	--
365	2.95	90.2
365	2.97	90.2
375	2.94	--
375	2.89	--
376	--	90.0
395	--	89.7
395	--	89.8
396	3.01	--

Press. psia	mole % He	
	Liquid	Vapor
396	2.95	--
405	--	90.2
406	3.06	--
467	--	88.6
475	3.44	--
564	--	89.7
564	--	89.7
629	--	88.3
682	--	88.7
682	--	88.9
852	--	90.9
852	--	90.7
21.80°K		
43	0.18	--
43	0.20	--
55	--	65.8
55	--	65.9
76	--	71.5
76	--	71.8
76	--	71.9
82	0.29	--
82	0.21	--
157	1.21	83.6
157	1.36	83.7
189	--	82.2
189	--	82.1
189	--	82.2
227	1.49	--
227	1.46	--
306	2.44	--
306	2.44	--
386	3.06	87.4
386	3.13	87.2
447	--	88.9
447	--	88.7
447	--	88.9

EQUILIBRIUM CONCENTRATIONS of HELIUM-NITROGEN MIXTURES

Source of Data:

Kharakhorin, F. F., Zhur. Tekh. Fiz. 10, 1533-40 (1940)

Other References:

Gonikberg, M. G. and Fastowsky, W. G., Acta Physicochim. U.R.S.S. 12, 67-72 (1940)

Ruhemann, M. and Fedoritenko, A., Zhur. Tekh. Fiz. 7, 335-42 (1937)

Comments:

The following tabular data from the reference by Kharakhorin, describe the liquid-vapor equilibrium for helium-nitrogen mixtures. Additional values for this mixture are also reported by Gonikberg and Fastowsky for temperatures of 78°, 90.1° and 109°K and are in fair agreement with the data presented here.

These data by Kharakhorin are illustrated on three graphs. The first presents the data for both the liquid and the vapor phases as isotherms (T = C), on coordinates of pressure and mole concentration. The liquid data are then presented with the same coordinates on the second graph with an expanded scale. The third graph is a cross-plot from the first two graphs and represents the data as isobars (P = C) on coordinates of temperature and mole concentration.

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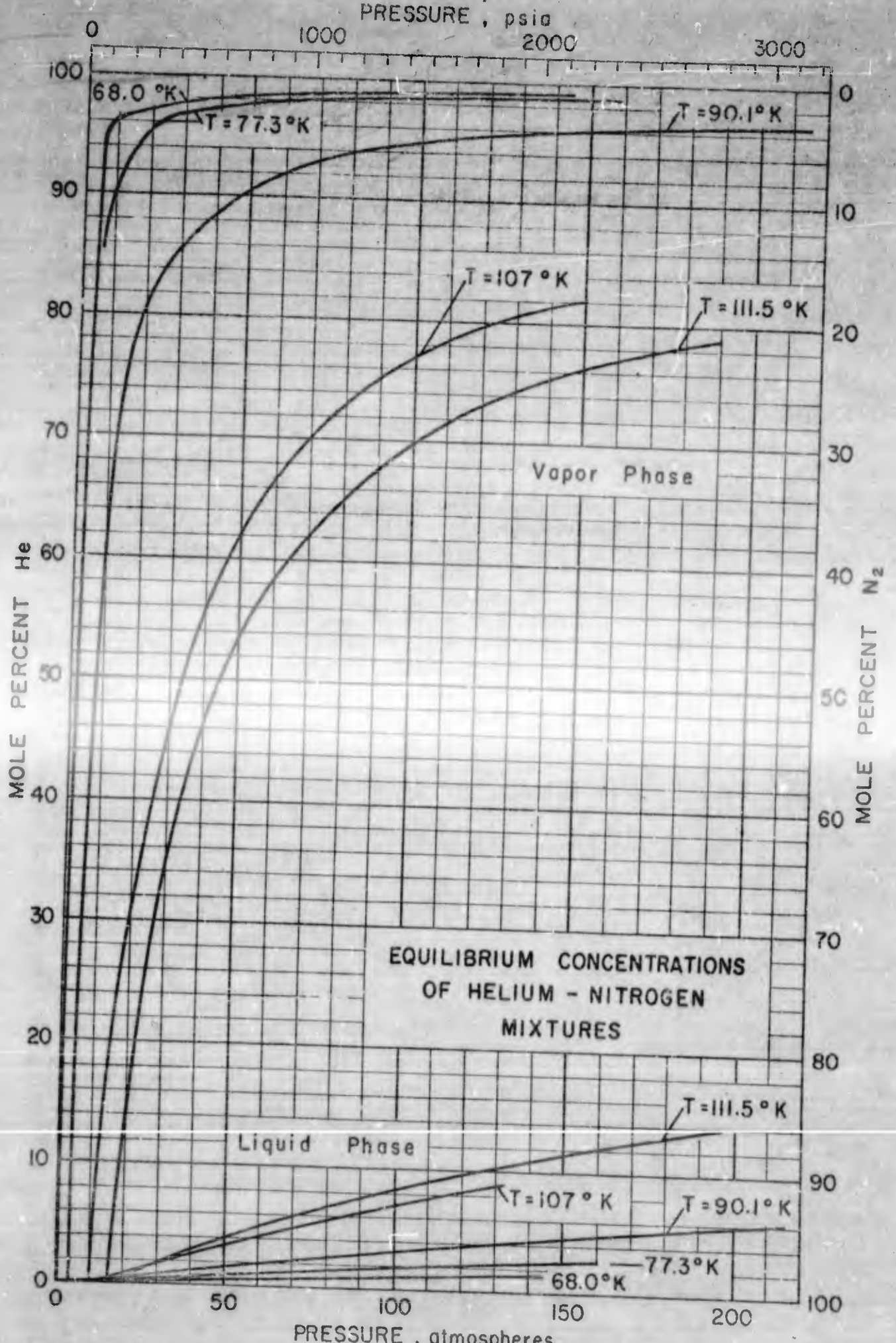
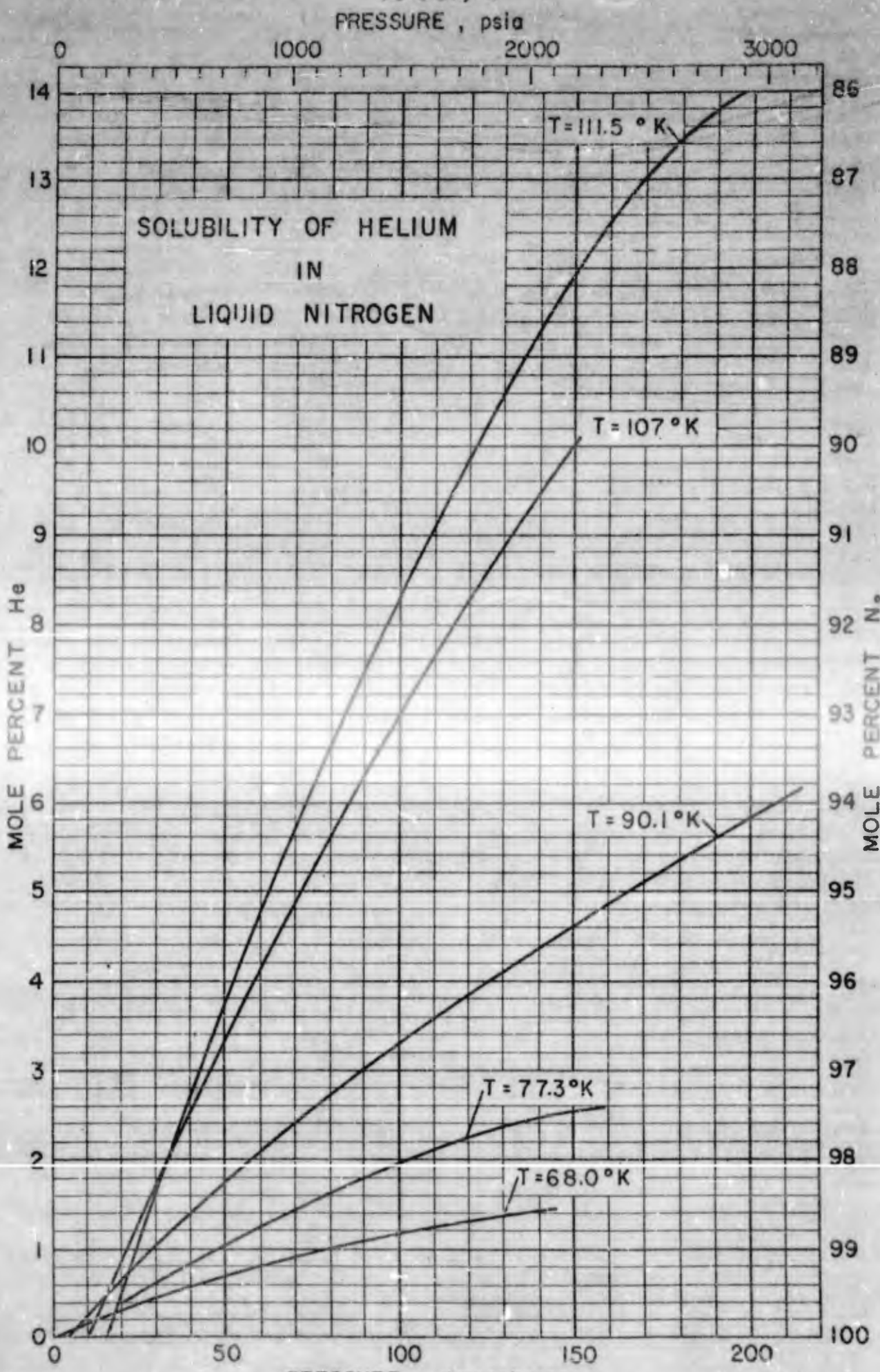
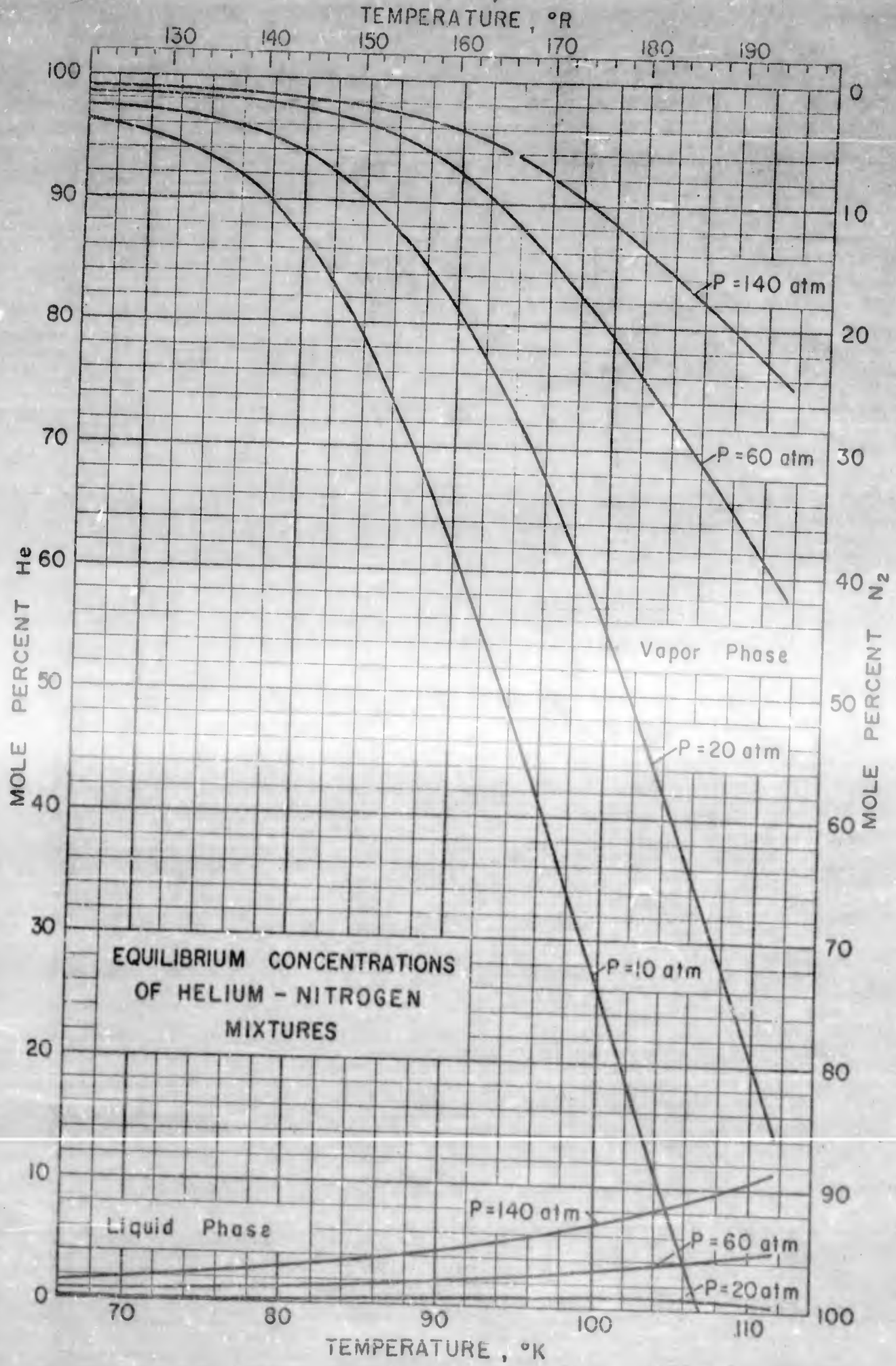
16.001/4


PRESSURE , psia
0
1000
2000
3000
68.0 °K
T = 77.3 °K
T = 90.1° K
T = 107 ° K
T = 111.5 °K
Vapor Phase
MOLE PERCENT He
MOLE PERCENT N2
EQUILIBRIUM CONCENTRATIONS
OF HELIUM - NITROGEN
MIXTURES
T = 111.5 ° K
Liquid Phase
T = 107 ° K
T = 90.1° K
77.3°K
68.0°K
0
50
100
150
200
PRESSURE , atmospheres

16.001/4


PRESSURE , psia
0
1000
2000
3000
SOLUBILITY OF HELIUM
IN
LIQUID NITROGEN
T = 111.5 °K
T = 107 °K
T = 90.1 °K
T = 77.3 °K
T = 68.0 °K
MOLE PERCENT He
MOLE PERCENT N2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
0
50
100
150
200
PRESSURE , atmospheres


TEMPERATURE , °R
130
140
150
160
170
180
190
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT He
MOLE PERCENT N2
P = 140 atm
P = 60 atm
P = 20 atm
P = 10 atm
Vapor Phase
Liquid Phase
EQUILIBRIUM CONCENTRATIONS
OF HELIUM - NITROGEN
MIXTURES
70
80
90
100
110
TEMPERATURE , °K

EQUILIBRIUM CONCENTRATIONS of HELIUM-NITROGEN MIXTURES

Table of Selected Values

(Liquid and Vapor Phases)

Press. atm.	Molc % He	
	liquid	vapor
T = 68.0°K		
0.326	0	0
4.480	0.107	83.25
11.620	0.195	96.48
22.300	0.370	97.45
48.500	0.885	98.22
92.750	1.145	98.60
95.700	1.160	98.65
108.000	1.240	98.80
144.500	1.480	98.96
T = 77.3°K		
1.00	0	0
4.85	0.098	80.69
11.60	0.300	91.90
22.30	0.460	96.00
33.90	0.730	96.59
48.50	0.960	97.75
58.60	1.125	98.00
71.25	1.520	98.15
78.00	1.585	98.20
97.30	2.030	98.22
111.40	2.100	-
121.00	2.325	98.30
145.00	2.545	98.47
146.50	2.550	98.53
158.20	2.715	98.60
158.50	2.740	98.74

Press. atm.	Mole % He	
	liquid	vapor
T = 90.1°K		
3.60	0	0
4.84	0.03	15.75
11.65	0.38	62.30
18.50	0.52	80.25
19.10	0.54	80.70
22.30	0.84	81.70
29.00	1.10	85.00
30.00	1.12	85.40
34.00	1.30	86.95
41.00	1.35	88.45
48.50	1.62	90.45
58.00	2.08	91.65
67.75	2.27	92.80
74.00	2.34	92.95
83.50	2.83	93.80
87.50	-	94.15
101.50	3.72	94.45
106.50	3.82	95.70
136.00	4.37	95.85
165.50	5.00	95.95
178.70	5.05	96.10
192.70	5.63	96.27
204.50	6.00	96.21
214.50	6.18	96.53
T = 107°K		
10.205	0	0

Press. atm.	Mole % He	
	liquid	vapor
23.100	0.85	-
35.000	2.20	52.25
49.800	3.30	61.65
73.800	5.35	71.60
97.000	6.82	76.85
114.000	7.96	79.00
151.000	10.12	82.35
T = 111.5°K		
15.37	0	0
19.40	0.33	13.90
20.20	0.37	15.10
22.20	0.65	19.25
24.30	0.80	-
28.30	1.40	-
38.52	2.75	-
44.80	3.29	50.70
56.25	4.49	56.55
69.00	5.75	61.20
72.50	6.12	61.55
91.00	7.65	68.00
116.50	9.45	71.95
120.50	9.98	73.15
125.50	10.40	73.95
134.00	10.80	73.75
140.50	11.45	76.40
174.70	13.10	78.05
195.00	13.95	79.00

16.001/10

SOLUBILITY of HELIUM in LIQUID METHANE

Sources of Data:

Gonikberg, M. and Fastowsky, W., Acta Physicochim. U.R.S.S. 13, 399-404 (1940)

Matthew, C. S. and Hurd, C. O.; Trans. Am. Inst. Chem. Engrs. 42, 55-78 (1946)

Comments:

The data for the solubility of helium in liquid methane are from the experimental results of Gonikberg and Fastowsky. The value of the vapor pressure of methane at 106°K (P = 0.61 atm. at 0% He), however, was determined from values listed by Matthew and Hurd.

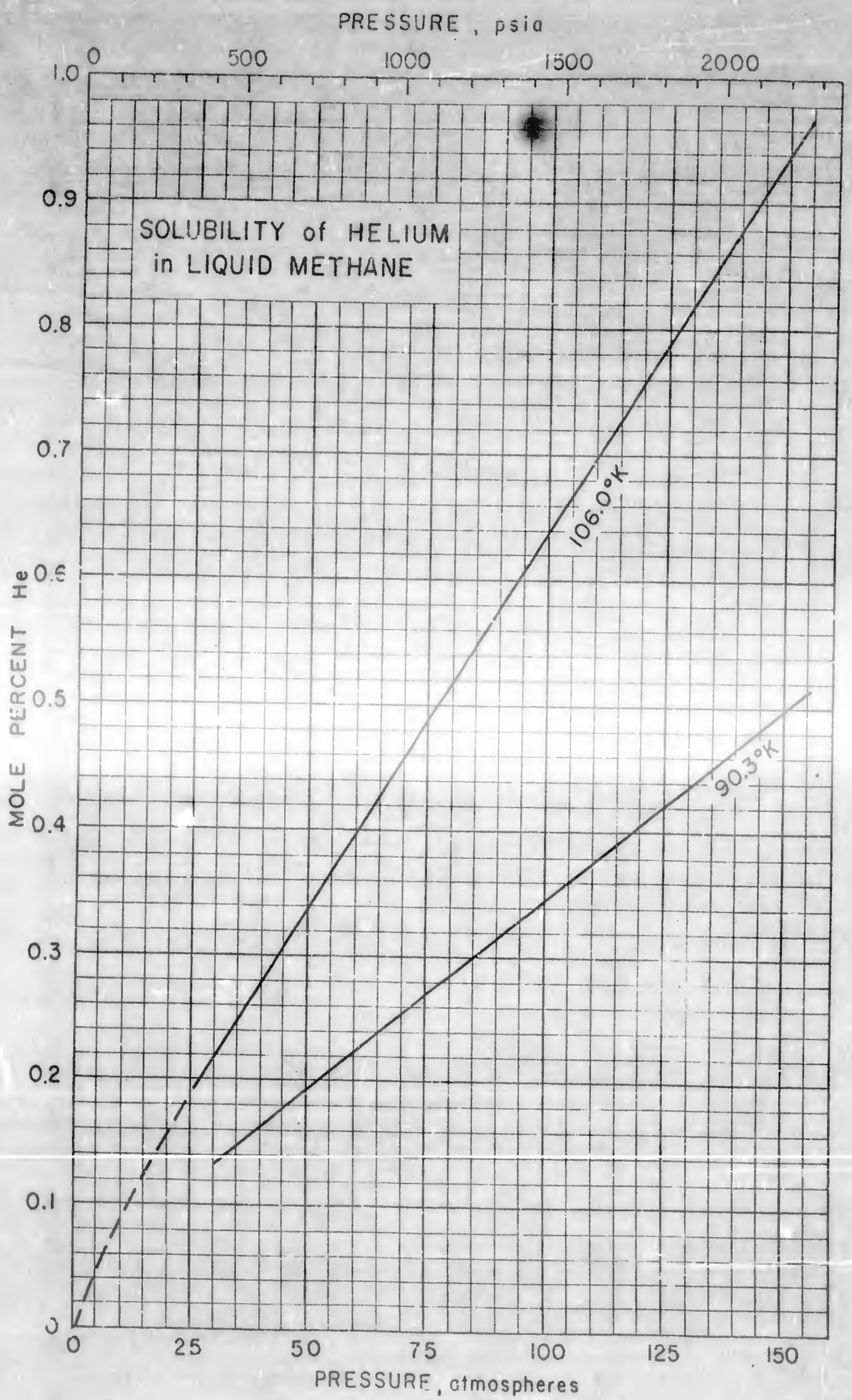
It should be noted that the curve for 90.3°K was not extrapolated to zero, mole percent helium, since the solid phase makes its appearance in this vicinity.

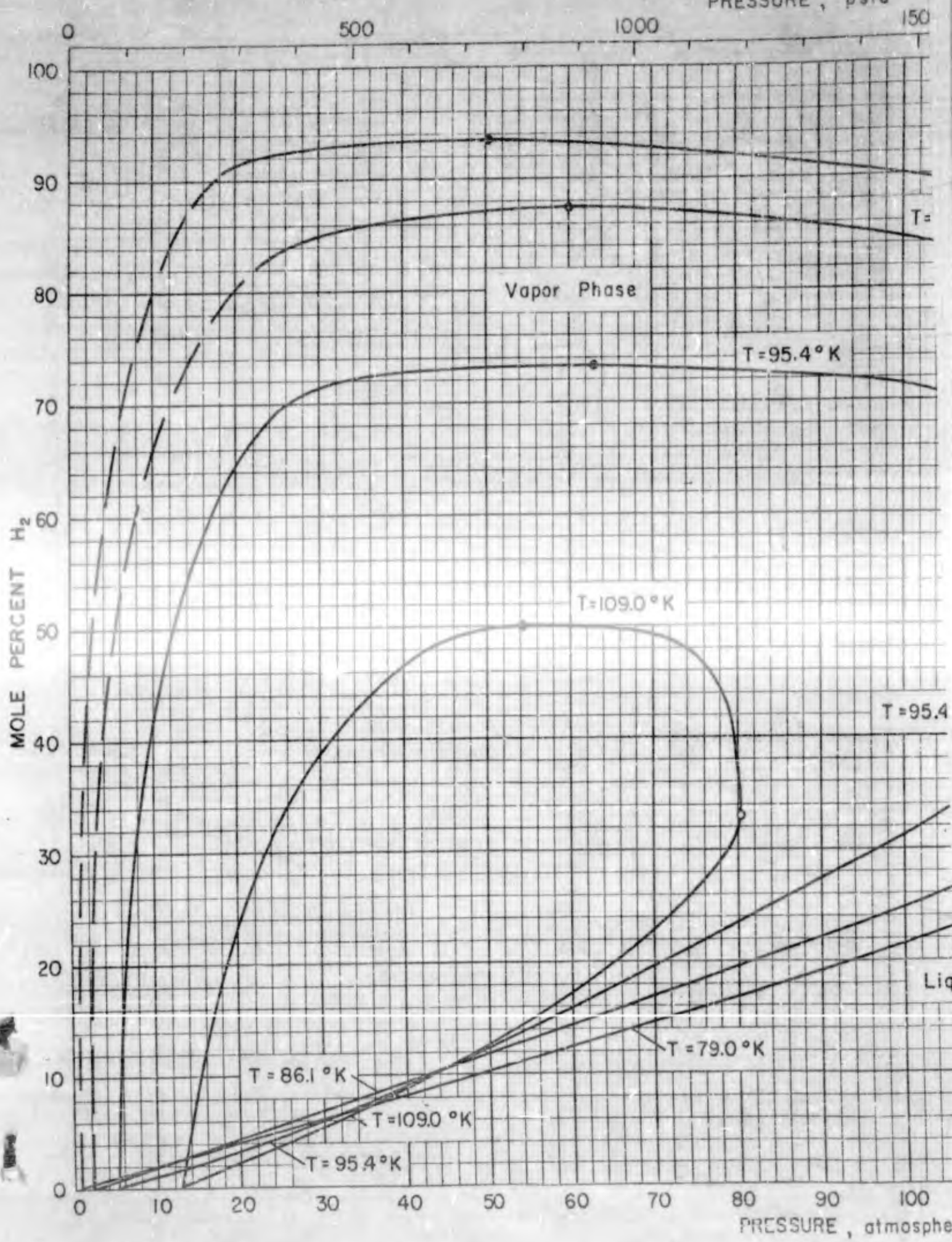
Table of Selected Values

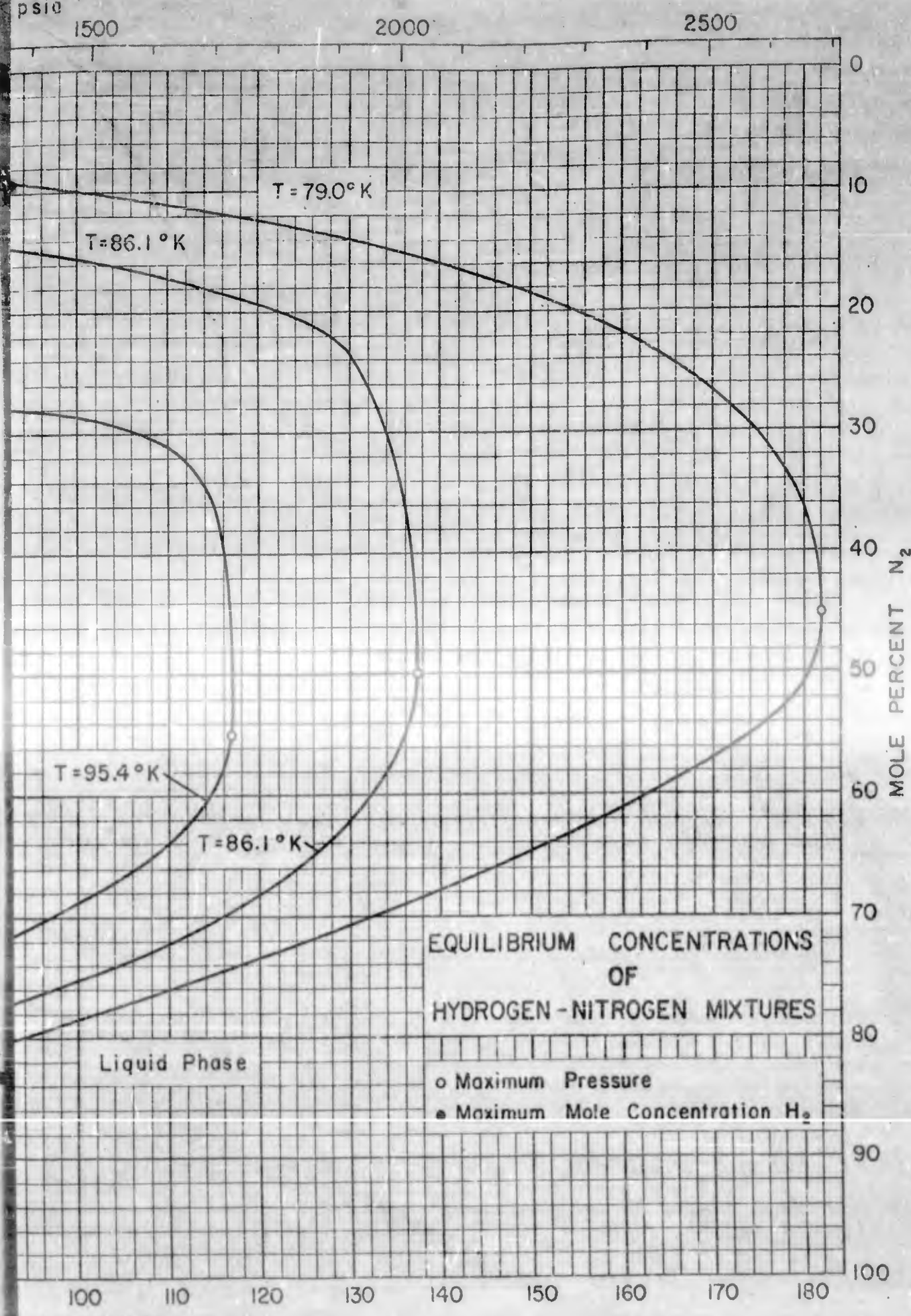
Pressure		Mole % He	Pressure		Mole % He
atm.	kg/cm^2	in liq. CH_4	atm.	kg/cm^2	in liq. CH_4
T = 90.3°K			T = 106.0°K		
29.0	30	0.13	25.2	26	0.19
75.5	78	0.27	59.0	61	0.39
94.8	98	0.32	96.8	100	0.63
112	116	0.37	144	149	0.90
135	139	0.46	155	160	0.97
157	162	0.52			

RS Issued: 3-10-61

16.001 / 10


PRESSURE , psia
0
500
1000
1500
2000
SOLUBILITY of HELIUM
in LIQUID METHANE
106.0°K
90.3°K
MOLE PERCENT He
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
25
50
75
100
125
150
PRESSURE, atmospheres


PRESSURE , psia
0
500
1000
150
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT H_2
Vapor Phase
T=
T=95.4° K
T=109.0° K
T=95.4
Liq
T=79.0 °K
T=86.1 °K
T=109.0 °K
T=95.4°K
0
10
20
30
40
50
60
70
80
90
100
PRESSURE , atmosphe


psia
1500
2000
2500
T = 79.0° K
T=86.1 °K
T=95.4 °K
T=86.1 °K
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT N_2
EQUILIBRIUM CONCENTRATIONS
OF
HYDROGEN - NITROGEN MIXTURES
Liquid Phase
o Maximum Pressure
• Maximum Mole Concentration H_2
100
110
120
130
140
150
160
170
180
atmospheres

EQUILIBRIUM CONCENTRATION of HYDROGEN-NITROGEN MIXTURES

Source of Data:

Gonikberg, M. G., Fastowsky, W. G. and Gurwitsch, J. G., Acta Physicochim. U.R.S.S. 11, 865-92 (1939)

Other References:

Eubanks, L. S., Dissertation for Degree of Doctor of Philosophy, Rice Institute (1957)

Maimoni-Biblarz, A., Dissertation for Degree of Doctor of Philosophy, Univ. California (1956)

Verschoyle, T. T. H., Trans. Roy. Soc. (London) A230, 189 (1932)

Ruhemann, M. and Zinn, N., Physik. Z. Sowjetunion 12, 389 (1937)

Dokoupil, Z., Van Soest, G. and Swenker, M. D. P., Appl. Sci. Research A5, 182-241 (1955)

Gonikberg, M. G., Acta Physicochim. U.R.S.S. 12, 921-30 (1940)

Shtekkel, F. A. and Tsin, N. M., Zhur. Khim. Prom. 16, 24-8 (1939)

Comments:

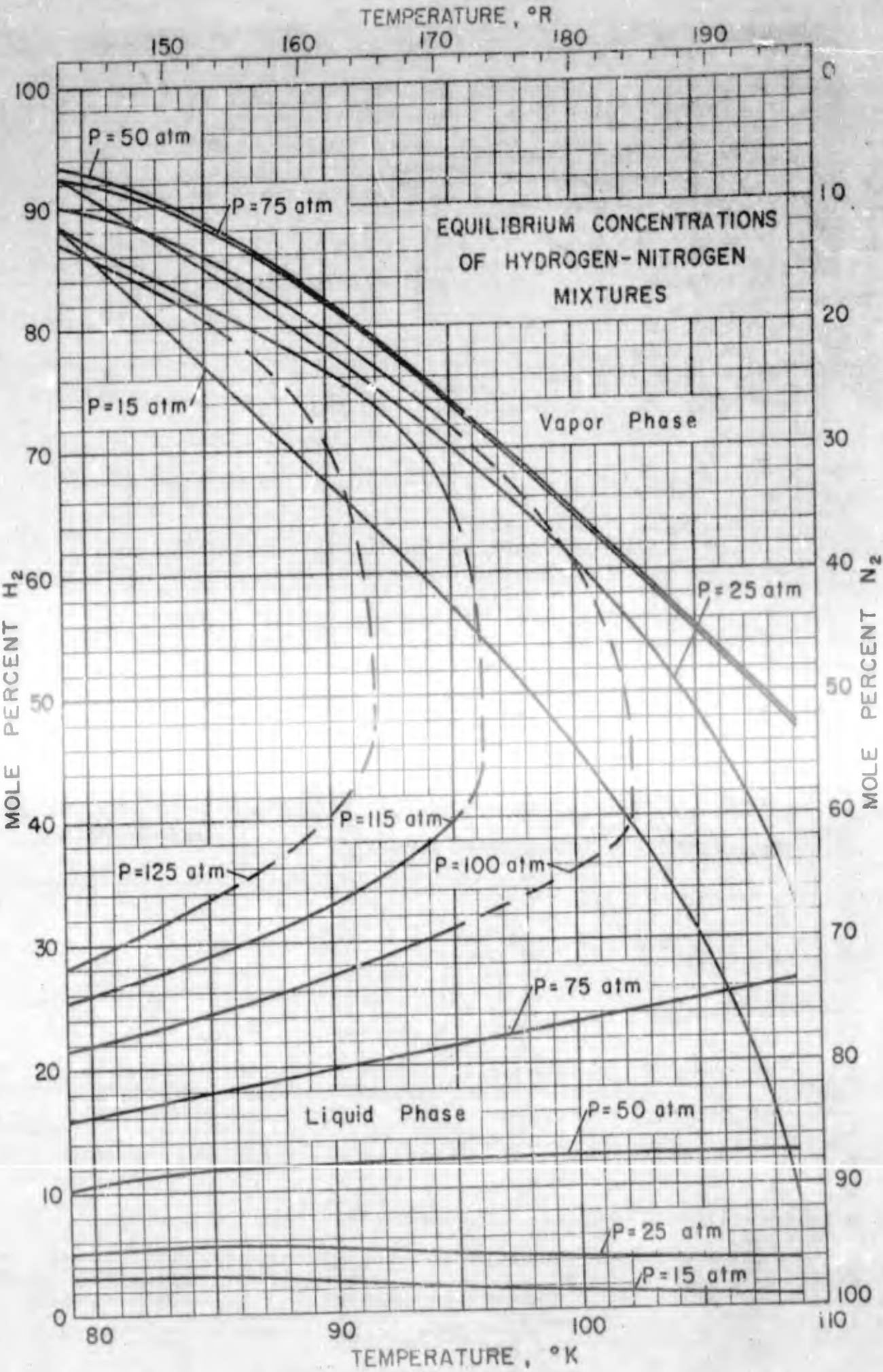
The following tables of data from the paper by Gonikberg, Fastowsky and Gurwitsch, describe the liquid-vapor equilibrium for hydrogen-nitrogen mixtures. The following graphs have been constructed from this data; the first presents the data for the liquid and vapor phases as isotherms (T = C) on coordinates of pressure and mole concentration. The second graph is a cross-plot from the first and presents the data as isobars (P = C) on coordinates of temperature and mole concentration.

The two dissertations by Maimoni-Biblarz and Eubanks present additional data for this binary system. Maimoni-Biblarz reports values at 90° and 95°K with pressures to 660 psia and Eubanks reports values at -310°, -280° and a few points at -240°F with pressures to 2300 psia. These data were compared with the data reported by Gonikberg, et al., on the X-T cross-plot and are in fair agreement as indicated below.

FEEG/RS Issued: 4-10-61

Comparison of Equilibrium Concentrations as reported by Gonikberg and Eubanks (X = mole percent hydrogen)					
Press. atm.	$X_{Gon.} - X_{Eub.}$		Press. atm.	$X_{Gon.} - X_{Eub.}$	
	liquid	vapor		liquid	vapor
T = 82.04°K			T = 99.82°K		
15	0	+2.4	15	-0.7	+6.0
25	0	+0.8	25	0	+2.0
50	+0.4	+2.3	50	+0.1	-7.0
75	-0.3	+1.0	75	+2.0	-6.8
100	-0.7	+2.2	100	+1.8	-1.4
115	-0.8	+1.3			
125	-0.2	+1.7			

Comparison of Equilibrium Concentrations as reported by Gonikberg and Maimoni-Biblarz (X = mole percent hydrogen)					
Press. atm.	$X_{Gon.} - X_{M.-B.}$		Press. atm.	$X_{Gon.} - X_{M.-B.}$	
	liquid	vapor		liquid	vapor
T = 90°K			T = 95°K		
15	--	-1.7	10.95	0	+0.5
25	--	-0.7	25.87	-1.0	-0.8
			44.74	-0.8	-4.0


TEMPERATURE, °R
150
160
170
180
190
EQUILIBRIUM CONCENTRATIONS OF HYDROGEN-NITROGEN MIXTURES
P = 50 atm
P = 75 atm
P = 15 atm
Vapor Phase
P = 25 atm
P = 115 atm
P = 125 atm
P = 100 atm
P = 75 atm
Liquid Phase
P = 50 atm
P = 25 atm
P = 15 atm
MOLE PERCENT H_2
MOLE PERCENT N_2
100
90
80
70
60
50
40
30
20
10
0
80
90
100
110
TEMPERATURE, °K

EQUILIBRIUM CONCENTRATION of HYDROGEN-NITROGEN MIXTURES

Table of Selected Values

Pressure		Mole % H_2	
atm.	kg/cm²	liquid	vapor
T = 79.0°K			
1.16	1.2	0	0
18.3	18.9	4.2	91.0
33.3	34.4	6.9	-
50.3	52	-	93.5*
51.3	53	10.7	93.6
66.8	69	15.8	92.2
78.5	81	17.3	91.3
94.9	98	19.9	91.5
99.8	103	21.3	90.2
107.5	111	22.4	88.9
120.2	124	26.6	-
122.1	126	27.1	-
143.4	148	33.7	82.0
153.1	158	36.4	80.5
175.3	181	45.7	69.7
182.0†	188†	55	55
T = 86.1°K			
2.42	2.5	0	0
23.34	24.1	5.2	83.0
43.6	45.0	9.8	86.5
60.0	62	-	87.5*
66.8	69	16.0	-
77.5	80	-	87.0
102.7	106	25.5	84.1
109.5	113	26.9	-
122.1	126	33.7	80.1
129.8	134	37.5	77.0
136.6	141	43.0	56.6
137.4†	142†	50	50
T = 95.4°K			
5.33	5.5	0	0
13.08	13.5	2.7	51.6
24.9	25.7	4.2	69.2
42.4	43.8	10.2	73.0
61.0	63	16.2	73.3
62.9	65	-	73.2*
76.5	79	22.1	72.7
91.1	94	27.7	72.2
109.5	113	39.4	69.1
115.3	119	41.7	63.5
116.2	120	43.2	47.3
117.1†	121†	45	45
T = 109°K			
12.9	13.3	0	0
19.0	19.6	1.8	20.7
33.9	35.0	-	42.3
44.9	46.4	10.3	48.9
54.2	56	-	50.2*
57.2	59	15.6	50.0
77.5	80	28.4	45.7
80.3†	83†	33	33

*maximum mole concentration
† maximum pressure

EQUILIBRIUM CONCENTRATIONS of HYDROGEN-CARBON MONOXIDE MIXTURES

Sources of Data:

Verschoyle, T. T. H.; Trans. Roy. Soc. (London) A230, 189 (1932)

Eubanks, L. S.; Dissertation for Degree of Doctor of Philosophy, Rice Institute (1957)

Other References:

Fischer, V.; Ann. Physik. 31, 531 (1938)

Ruhemann, M. and Zinn, N., Physik. Z. Sowjetunion 12, 389 (1937)

Steckel, F.; Physik. Z. Sowjetunion 8, 337 (1935)

Yushkevich, N. F. and Torocheshnikov, N. A.; Zhur. Khim. Prom. 13, 1273 (1936)

Comments:

The data for the equilibrium concentrations of the hydrogen-carbon monoxide system for the following tables and graphs, are from the references listed above by Verschoyle and by Eubanks. The data reported by Verschoyle are for solid-vapor equilibrium at temperatures of 58° and 63°K, and for liquid-vapor equilibrium at 68°, 73°, 83° and 88°K, to pressures of over 200 atmospheres. In addition, Verschoyle lists the points of maximum pressure and of maximum mole concentration, H_2, for each of these isotherms. The data from Eubanks is for liquid-vapor equilibrium at temperatures of 83°, 100°, 122°K and with a comparable pressure range.

The lack of agreement of the data from these two references is indicated by the values reported by both sources for 83.15°K which was the only temperature common to both. These data may be compared on the following P - X graph. It should also be noted that Verschoyle's data for the liquid and the vapor at 68° and 73°K have been extrapolated on this graph, to the point of maximum pressure, at which point properties of the liquid and vapor are identical.

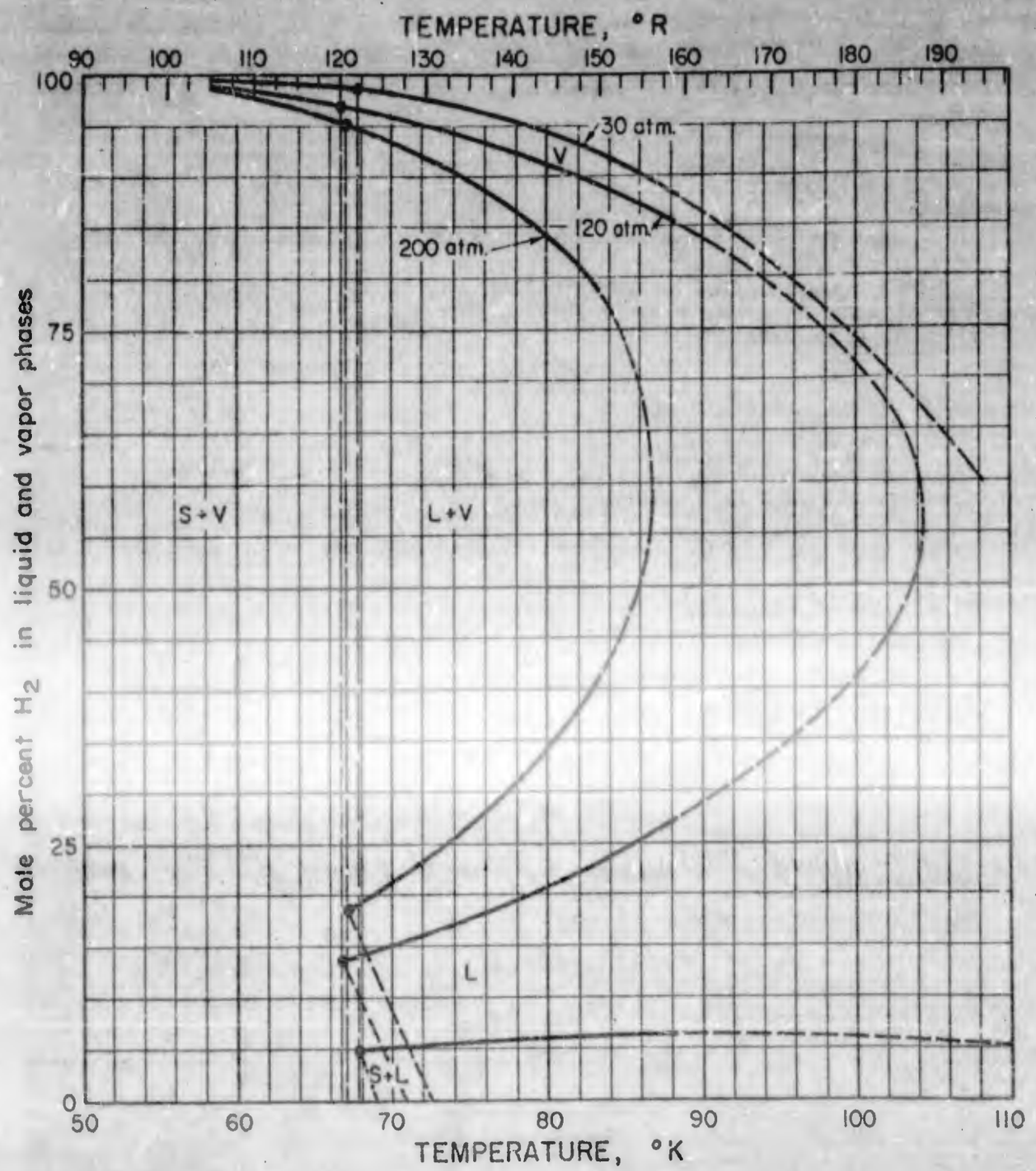
The curves in the graph below are taken from Verschoyle's paper, and give H_2-CO isobars (P = C) at 30, 120 and 200 atmospheres. These curves are from a cross-plot of the P-X graph together with the three-phase data tabulated below.

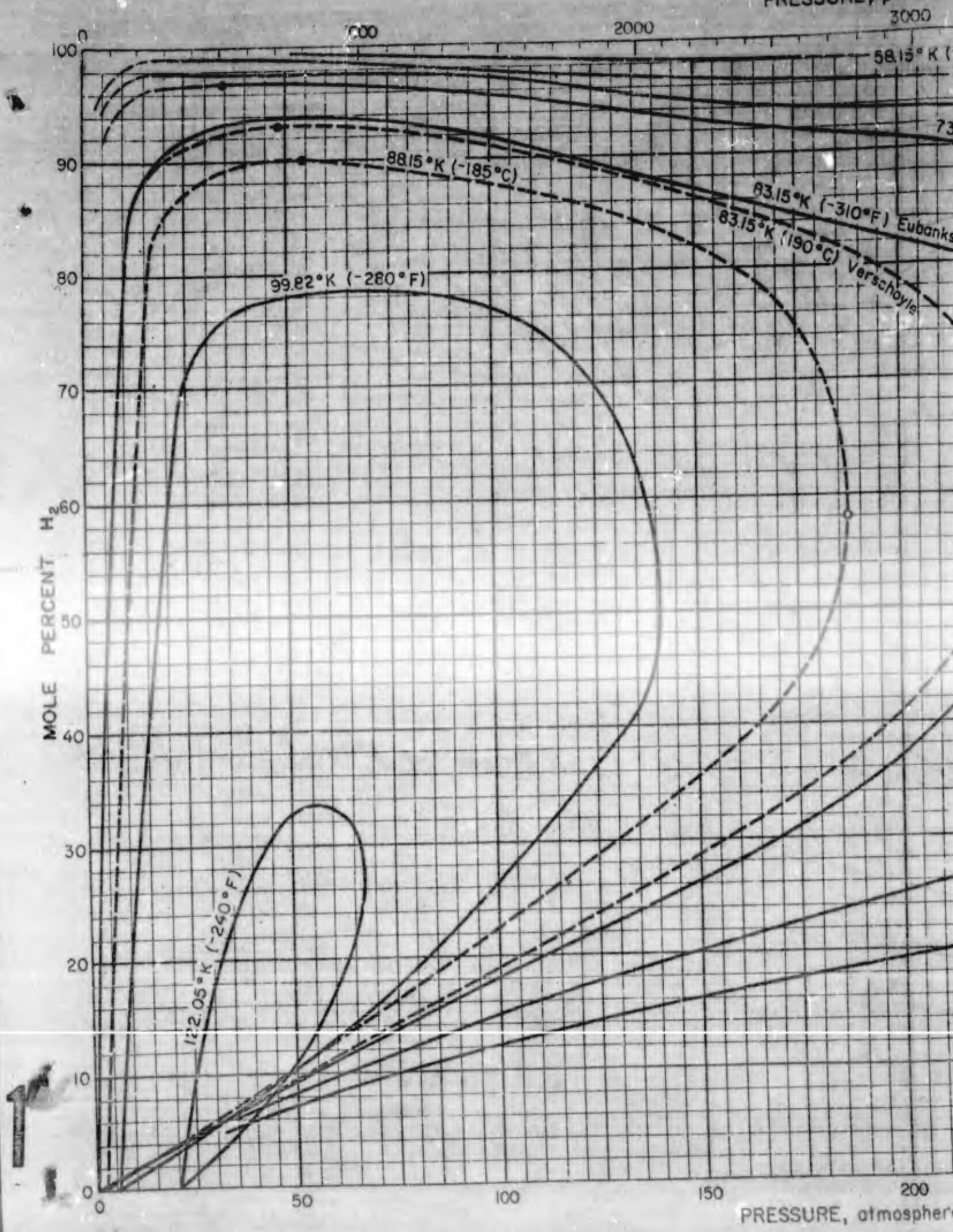
Selected Values of the H_2-CO, Three-Phase Curve

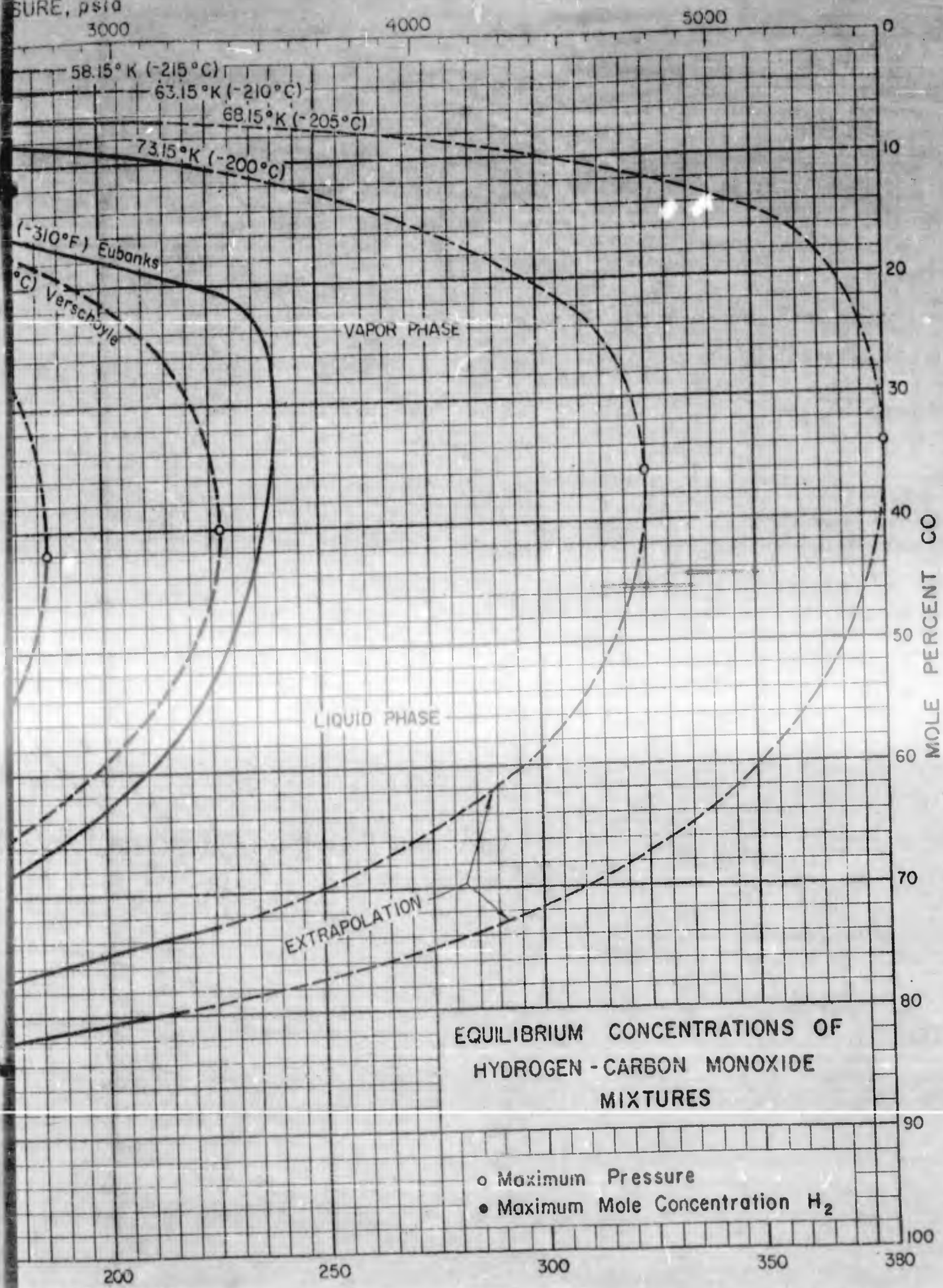
Pressure atm.	Temperature °C
55.2	-205.12
104.1	-206.59
147.4	-205.67
205.5	-206.39

FEEG/VJJ Issued: 9-30-60

EQUILIBRIUM CONCENTRATIONS of HYDROGEN-CARBON MONOXIDE MIXTURES




PRESSURE, psia
0
1000
2000
3000
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT H2
58.15°K (
73
88.15°K (-185°C)
83.15°K (-310°F) Eubanks
83.15°K (190°C) Verschoyle
99.82°K (-280°F)
122.05°K (-240°F)
0
50
100
150
200
PRESSURE, atmospher


SURE, psia
3000
4000
5000
58.15° K (-215° C)
63.15° K (-210° C)
68.15° K (-205° C)
73.15° K (-200° C)
(-310° F) Eubanks
°C) Verschoyle
VAPOR PHASE
LIQUID PHASE
EXTRAPOLATION
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT CO
EQUILIBRIUM CONCENTRATIONS OF
HYDROGEN - CARBON MONOXIDE
MIXTURES
o Maximum Pressure
• Maximum Mole Concentration H_2
200
250
300
350
380
RE, atmospheres

EQUILIBRIUM CONCENTRATIONS of HYDROGEN-CARBON MONOXIDE MIXTURES

Tables of Selected Values

Verschoyle

Press. atm.	Mole % H_2 in Vapor
-215°C (58.15°K) ±.06°	
(0.018)	(0.0)
51.37	99.47
89.52	98.90
128.05	98.50
157.03	98.08
176.37	98.18
-210°C (63.15°K) ±.03°	
(0.052)	(0.0)
16.81	99.22
21.85	99.12
32.03	99.18
65.74	98.76
79.80	97.42
104.01	97.80
137.76	97.03
147.39	96.88
176.41	96.53
195.75	96.31

Verschoyle (cont.)

Press. atm.	Mole % H_2 in Liq.	Mole % H_2 in Vapor
-205°C (68.15°K) ±.04°		
(0.15)	(0.0)	(0.0)
17.02	3.0	97.9
21.69	3.3	98.2
26.61	4.2	97.6
31.67	4.9	98.6
41.45	6.3	97.5
79.89	10.2	97.7
118.38	13.8	96.5
152.33	16.3	94.6
190.97	18.8	93.9
215.16	20.2	93.4
380*	66	66
-200°C (73.15°K) ±.04°		
0.33	0.0	0.0
17.3	3.3	96.7
22.2	---	95.4
31.5	---	96.4
31.8	5.6	97.5
‡34.	---	‡97.5
50.9	---	97.0
51.0	8.4	96.7
79.7	---	96.3
80.2	12.7	95.9
113.9	16.6	95.1
128.0	---	94.2
142.5	---	93.5
152.4	20.6	93.0
176.4	23.0	92.0
186.2	23.6	91.4
205.6	25.0	91.2
224.9	27.5	89.0
325*	64	64

Verschoyle (cont.)

Press. atm.	Mole % H_2 in Liq.	Mole % H_2 in Vapor
-190°C (83.15°K) ±.04°		
1.18	0.00	0.0
17.2	2.7	89.9
‡48.	---	‡93.
51.2	12.5	93.2
89.3	17.0	92.0
109.8	21.0	90.7
128.1	25.4	88.8
166.8	32.9	84.3
176.4	34.4	83.1
186.1	36.8	80.8
190.9	38.1	80.5
195.8	40.1	79.5
200.6	41.5	77.7
205.4	43.5	76.6
210.4	44.8	75.9
215.1	47.0	73.7
220.9	48.6	69.4
224.8	54.1	66.3
228*	60	60
-185°C (88.15°K) ±.03°		
2.18	0.0	0.0
17.2	3.6	84.0
22.1	5.2	86.6
31.4	7.1	88.3
‡54.	---	‡90.
55.9	13.4	90.2
89.6	21.7	88.7
128.2	30.3	84.8
166.7	41.0	77.1
181.3	45.4	79.4
187*	58	58

‡ Maximum mole % H_2

* Maximum pressure

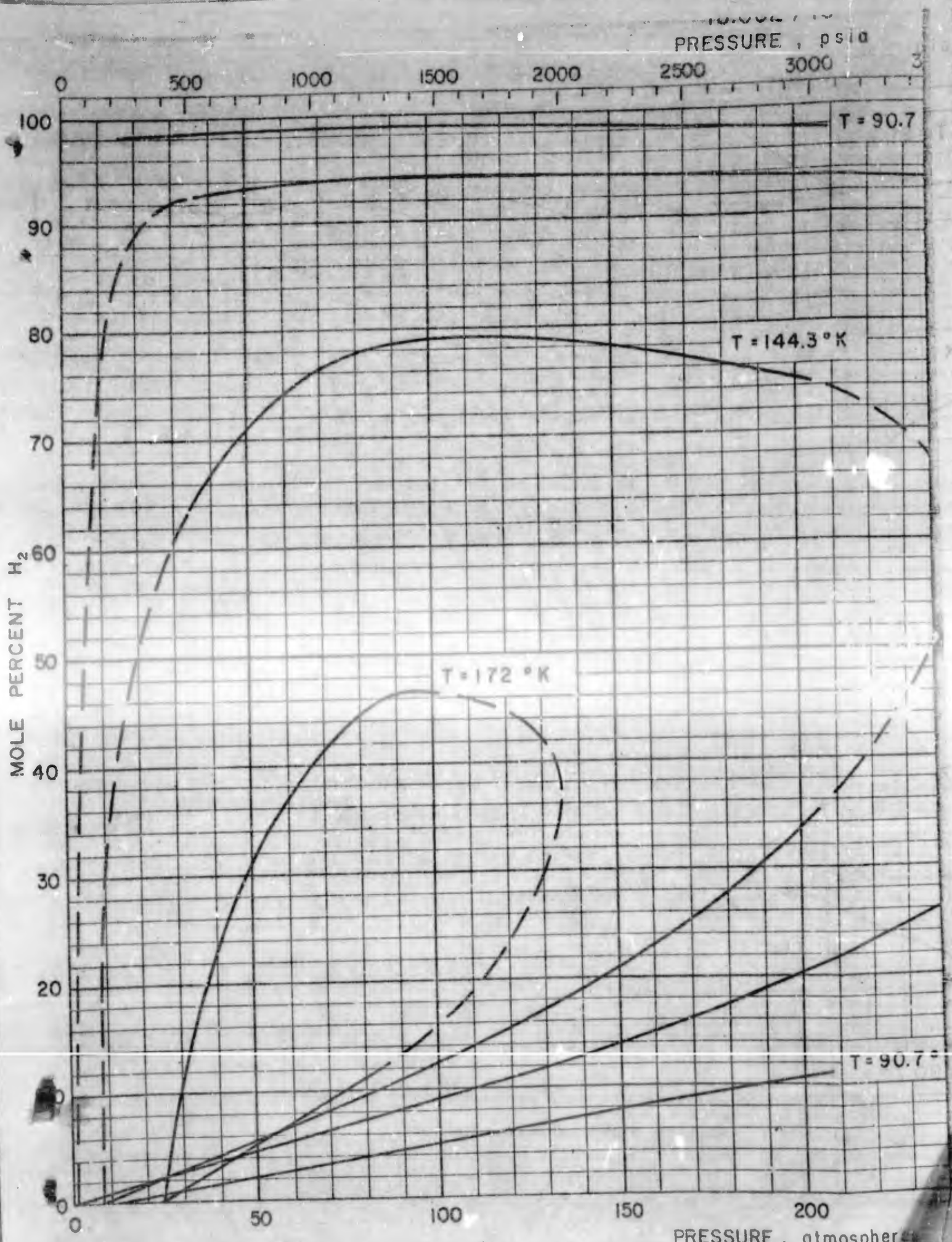
erschoyle (cont.)

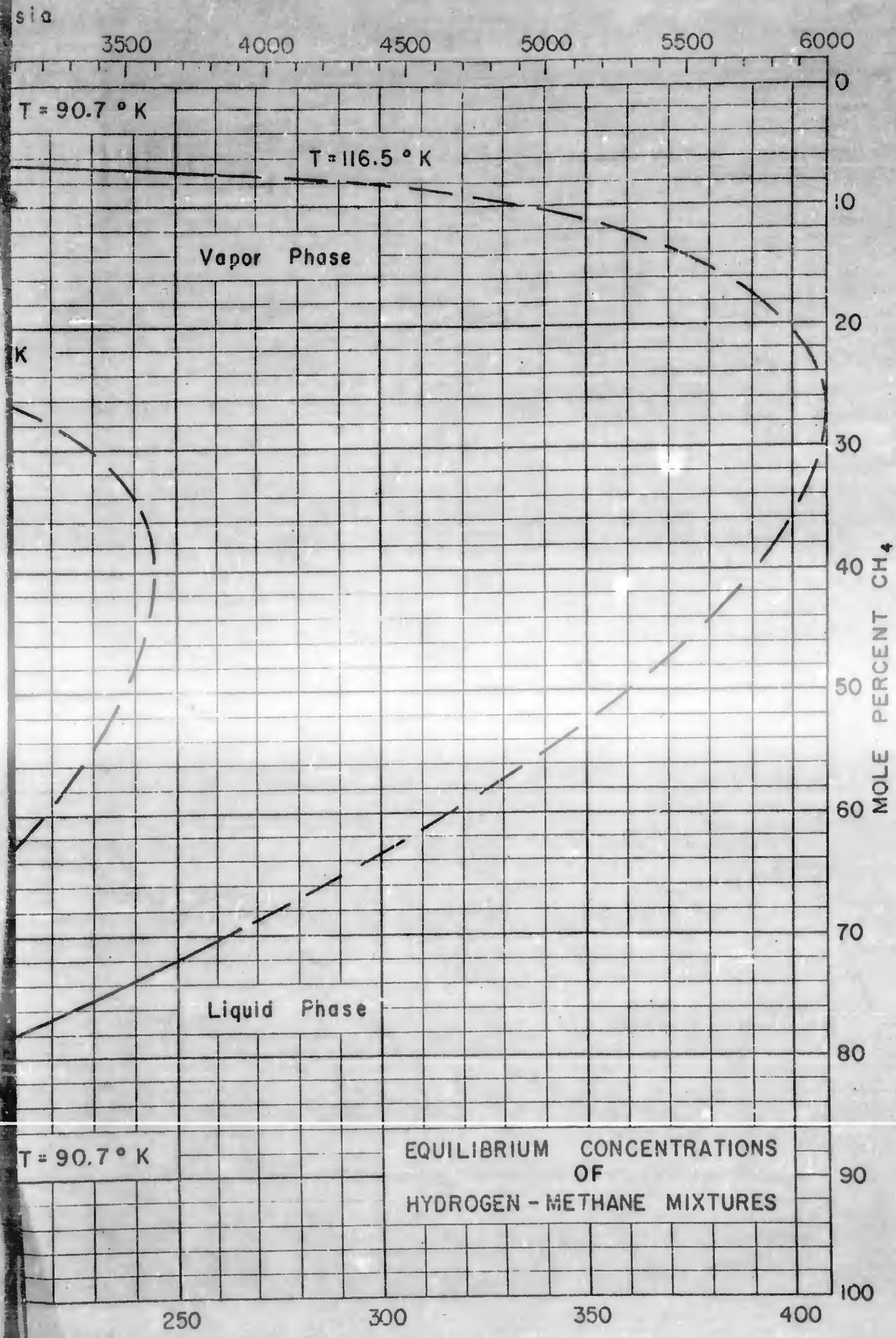
	Mole % H_2	
	in Liq.	in Vapor
°C (83.15°K) ±.04°		
8	0.00	0.0
	2.7	89.9
	---	‡93.
	12.5	93.2
	17.0	92.0
	21.0	90.7
	25.4	88.8
	32.9	84.3
	34.4	83.1
	36.8	80.8
	38.1	80.5
	40.1	79.5
	41.5	77.7
	43.5	76.6
	44.8	75.9
	47.0	73.7
	48.6	69.4
	54.1	66.3
	60	60
°C (88.15°K) ±.03°		
	0.0	0.0
	3.6	84.0
	5.2	86.6
	7.1	88.8
	---	‡90.
	13.4	90.2
	21.7	88.7
	30.3	84.8
	41.0	77.1
	45.4	70.4
	58	58

Eubanks

Pressure		Mole % H_2	
psia	atm.	in Liq.	in Vapor
-310°F (83.15°K)			
(17.3)	1.18	0.0	0.0
315	21.4	4.08	90.84
500	34.0	6.09	93.26
800	54.4	9.95	93.57
1100	74.9	13.55	93.07
1400	95.3	16.01	91.43
1700	115.7	21.09	89.98
2000	136.1	24.42	88.25
2300	156.5	27.74	85.89
2600	176.9	31.81	83.13
2900	197.3	30.25	84.81
3200	217.7	41.54	80.48
3500	238.2	66.39	75.76
-280°F (99.82°K)			
(80)	5.4	0.0	0.0
315	21.4	3.89	68.03
500	34.0	6.74	76.19
800	54.4	11.63	77.92
1100	74.9	16.33	78.48
1400	95.3	23.99	77.39
1700	115.7	32.57	73.37
2000	136.1	41.53	60.94
-240°F (122.04°K)			
(300)	20.4	0.0	0.0
500	34.0	4.49	22.60
800	54.4	13.82	33.49
960	65.3	31.45	

2


PRESSURE , psia
0
500
1000
1500
2000
2500
3000
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT H_2
T = 90.7
T = 144.3 °K
T = 172 °K
T = 90.7°
0
50
100
150
200
PRESSURE , atmospheres


sia
3500
4000
4500
5000
5500
6000
T = 90.7 ° K
T = 116.5 ° K
Vapor Phase
K
Liquid Phase
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT CH_4
T = 90.7 ° K
EQUILIBRIUM CONCENTRATIONS
OF
HYDROGEN - METHANE MIXTURES
250
300
350
400

EQUILIBRIUM CONCENTRATIONS of HYDROGEN-METHANE MIXTURES

Sources of Data:

Benham, A. L. and Katz, D. L.; A.I.Ch.E. Journal 3, 33 (1957)

Freeth, F. A. and Verschoyle, T. T. H.; Proc. Roy. Soc. (London) A130, 453-463 (1931)

Bloomer, O. T. and Parent, J. D.; Chem. Eng. Progr. Symposium 49 No. 6, 11-24 (1953)

Other References:

Fastovskii, V. G. and Gonikberg, M. G.; Zhur. Fiz. Khim. 14, 427-8 (1940)

Benham, A. L.; Dissertation for degree of Doctor of Philosophy, Univ. Michigan (1956)

Levitskaya, E. P.; Zhur. Tekh. Fiz. 11, 197-204 (1941)

Benham, A. L., Katz, D. L. and Williams, R. B.; A.I.Ch.E. Journal 3, No. 2, 235-241 (1957)

Comments:

The following tabular data from the references listed above as sources of data, are for the liquid-vapor equilibrium of hydrogen-methane mixtures. The data reported by Benham and Katz are pressure-concentration data for temperatures of 116.5°, 144.3°, 172°K. The data for 90.7°K are from the paper by Freeth and Verschoyle. Additional data at 90.3°, 103.1°, 110.0°, 122°, and 127°K are also available from the paper by Fastovskii and Gonikberg and are in fair agreement with the data presented here. The vapor pressure and temperature values for methane, i.e., for the 0% hydrogen concentration were derived from the data reported by Bloomer and Parent. The vapor and liquid data for the 116.5°, 144.3°, and 172°K isotherms have been extrapolated to the point of maximum pressure, (at this point the liquid and vapor phases are identical). This extrapolation was represented graphically by Benham and Katz and was reproduced on the following graph.

Equilibrium Concentration of Hydrogen-Methane Mixtures

Benham and Katz					
Press. atm.	Mole % H_2		Press. atm.	Mole % H_2	
	liquid	vapor		liquid	vapor
T = 172°K			101.-	13.10	79.31
34.0	1.70	15.83	135.4	18.05	78.23
68.0	3.77	40.60	204.1	3-.99	74.57
87.1	12.35	46.31	T = 116.5°K		
102.1	16.22	46.78			
T = 144.3°K			33.3	3.15	92.79
			101.-	9.50	9-.66
34.0	3.43	63.92	156.5	18.9-	93.83
68.0	7.81	76.16	272.2	31.70	92.89

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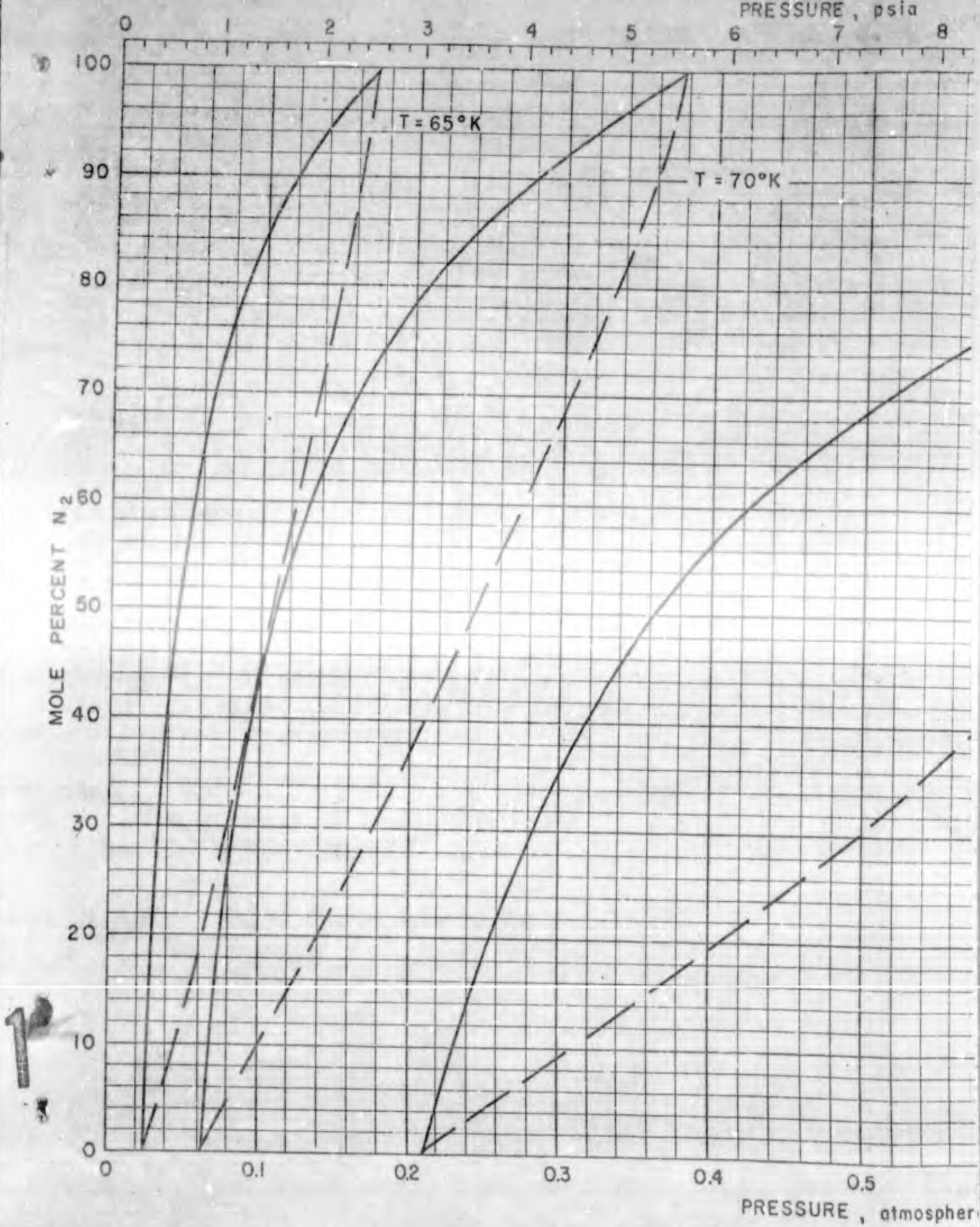
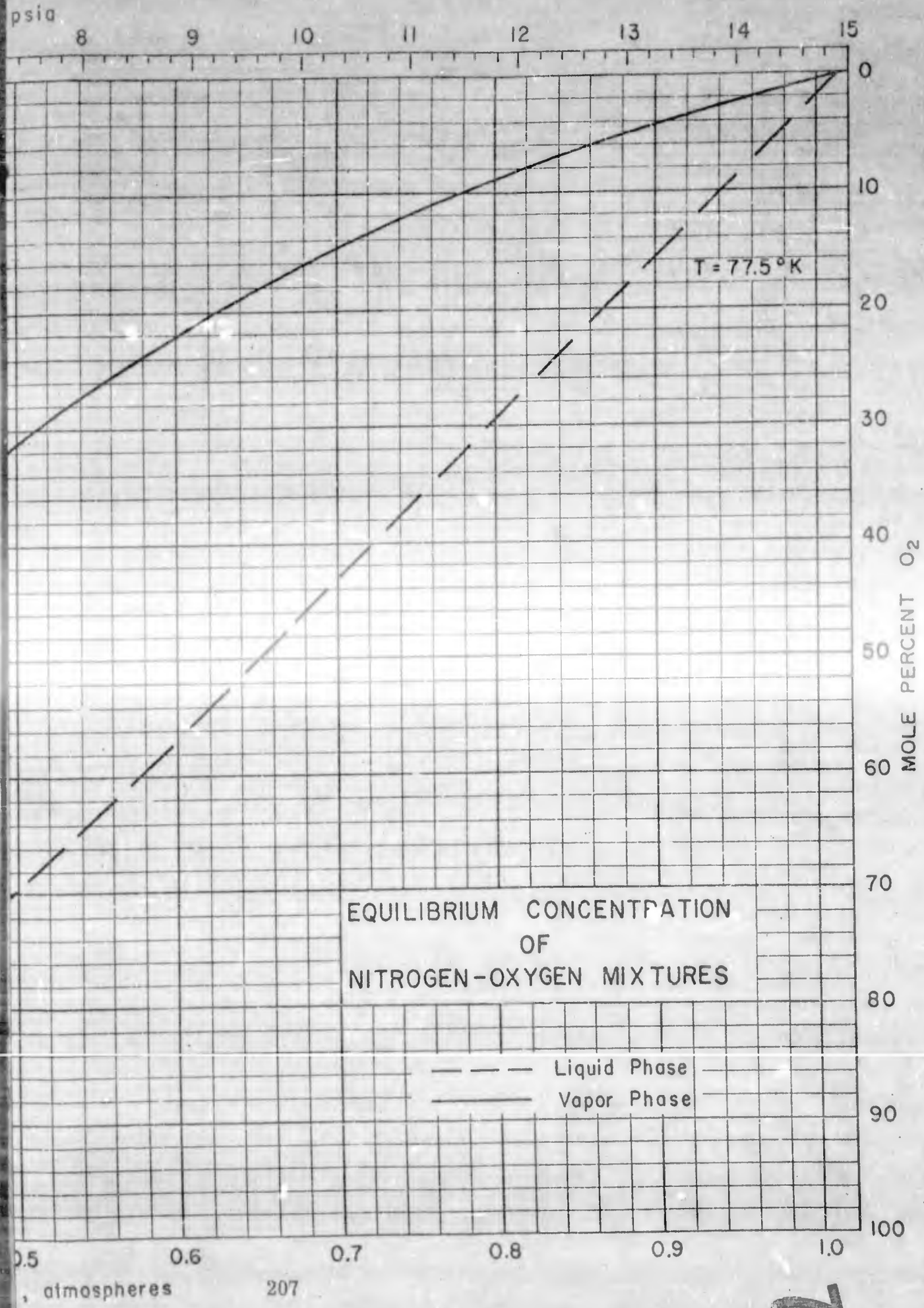
Equilibrium Concentration of Hydrogen-Methane Mixtures

Freeth and Verschoyle			
Temperature °C	Pressure atm.	Mole % H_2	
		liquid	vapor
-182.49	16.89	0.38	98.35
-182.47	16.96	-	97.90
-182.51	21.61	0.70	98.54
-182.48	26.62	-	98.73
-182.52	29.74	-	98.57
-182.50	36.41	0.56	97.99
-182.52	43.89	-	98.95
-182.50	46.10	0.64	98.63
-182.52	46.20	-	98.95
-182.49	55.61	1.70	98.75
-182.49	55.82	1.07	98.85
-182.47	79.56	3.83	99.05
-182.52	99.32	5.59	98.82
-182.48	128.19	8.19	98.46
-182.53	128.22	7.60	96.83
-182.54	166.76	7.84	97.89
-182.50	166.78	8.90	97.83
-182.51	186.08	10.16	-
-182.48	195.75	10.20	97.89
-182.52	205.42	-	97.69
-182.53	205.43	9.58	97.87

16.004 / 5


PRESSURE , psia
0
1
2
3
4
5
6
7
8
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT N_2
T = 65°K
T = 70°K
0
0.1
0.2
0.3
0.4
0.5
PRESSURE , atmospher


75
psia
8
9
10
11
12
13
14
15
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT O_2
T = 77.5°K
EQUILIBRIUM CONCENTRATION
OF
NITROGEN-OXYGEN MIXTURES
Liquid Phase
Vapor Phase
0.5
0.6
0.7
0.8
0.9
1.0
, atmospheres

EQUILIBRIUM CONCENTRATIONS of NITROGEN - OXYGEN MIXTURES

Sources of Data:

Armstrong, G. T., Goldstein, J. M. and Roberts, D. E., J. Research Natl. Bur. Standards 55, 265-277 (1955)

Cockett, A. H., Proc. Roy. Soc. (London) A239, 76 (1957)

Dodge, B. F. and Dunbar, A. K., J. Am. Chem. Soc. 49, 591-610 (1927)

Hilsenrath, J., et al., Natl. Bur. Standards Circ. 564 (1955)

Sagenkahn, M. L. and Fink, H. L., Penssylvania State College, O.S.R.D. Report 4493 (1944)

Other References:

Inglis, J. K. H., Phil. Mag. 11, 640-658 (1906)

Komarov, P., Likhter, A. and Ruhemann, M., Zhur. Tekh. Fiz. 5, 1723-8 (1935)

Kritschewsky, I. R. and Torotscheschnikow, N. S., Z. physik. Chem. (Leipzig) A176, 338-46 (1936)

Kuenen, J. P., Verschoyle, T. and Van Urk, A. Th., Koninkl. Ned. Akad. Wetenschap. Proc. 26, 49-64 (1923)

Prikhot'ko, A., Zhur. Eksptl. i Teoret. Fiz. 8, 671-681 (1938); Acta Physicochim. U.R.S.S. 10, 913-934 (1939)

Ruhemann, M., Physik. Z. Sowjetunion 16, 67-82 (1936)

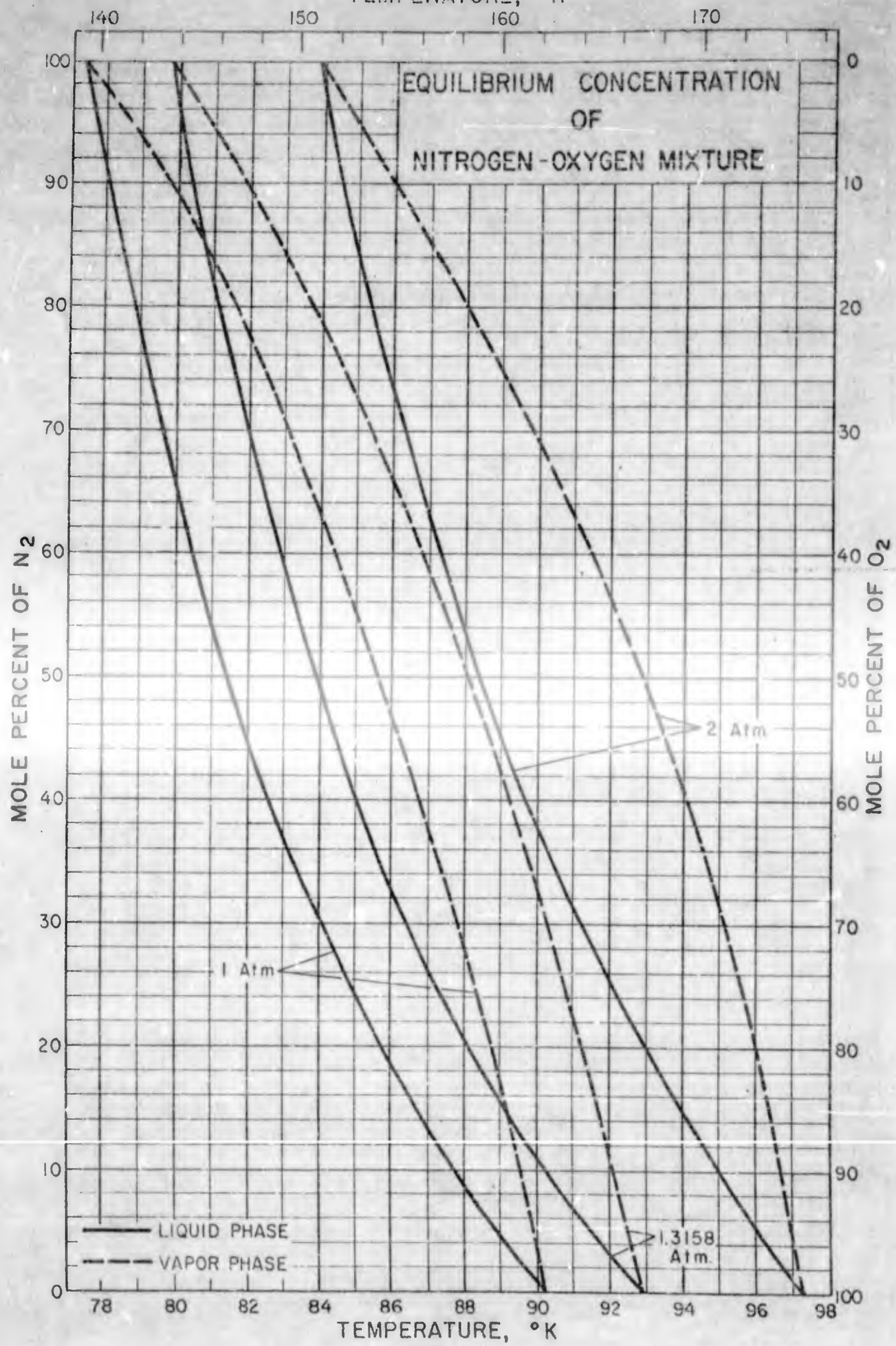
Ruhemann, M., Likhter, A. and Komarov, P., Physik. Z. Sowjetunion 8, 326-336 (1935)

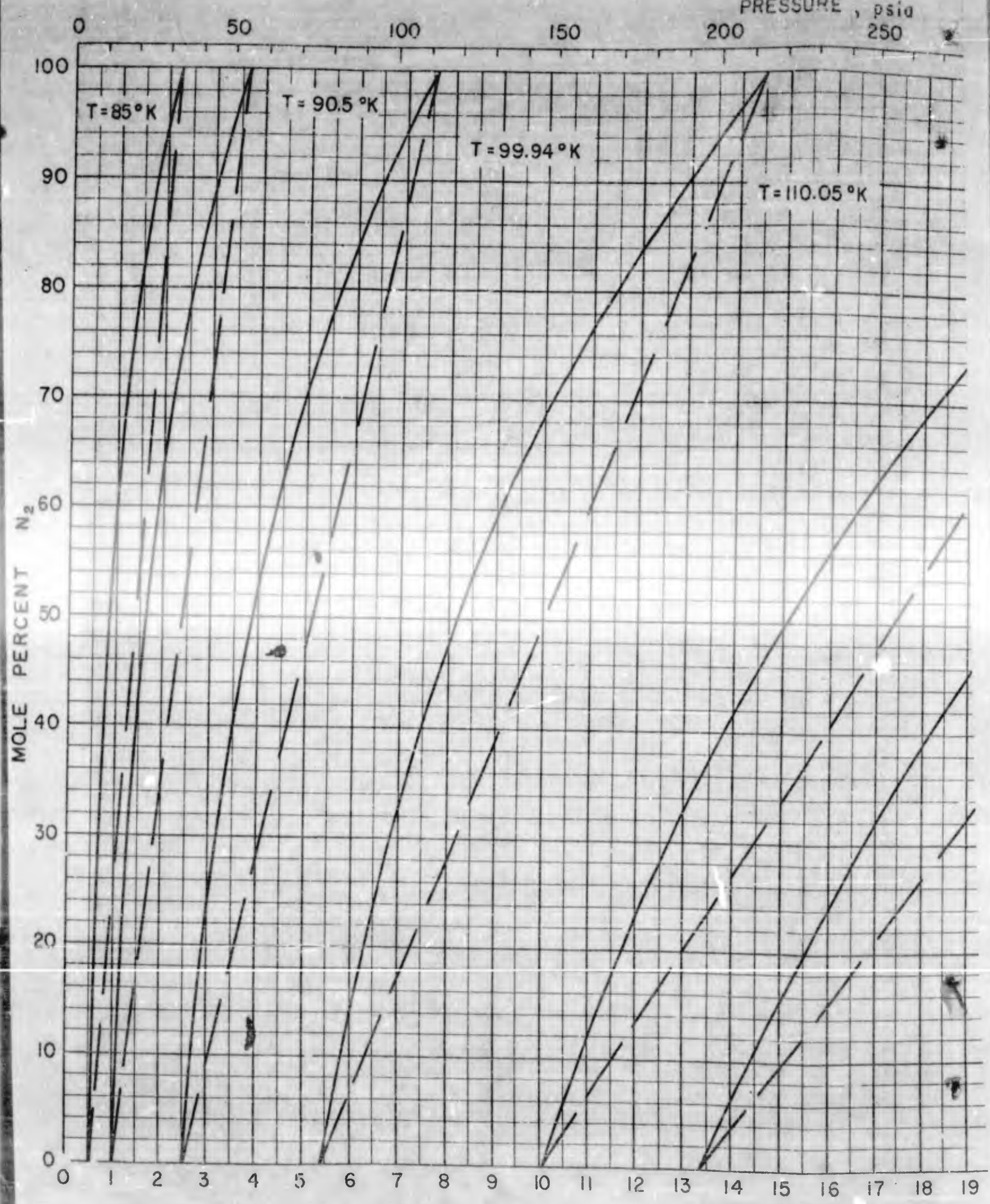
Weishaupt, J., Angew. Chem. B20, 321-326 (1948)

Comments:

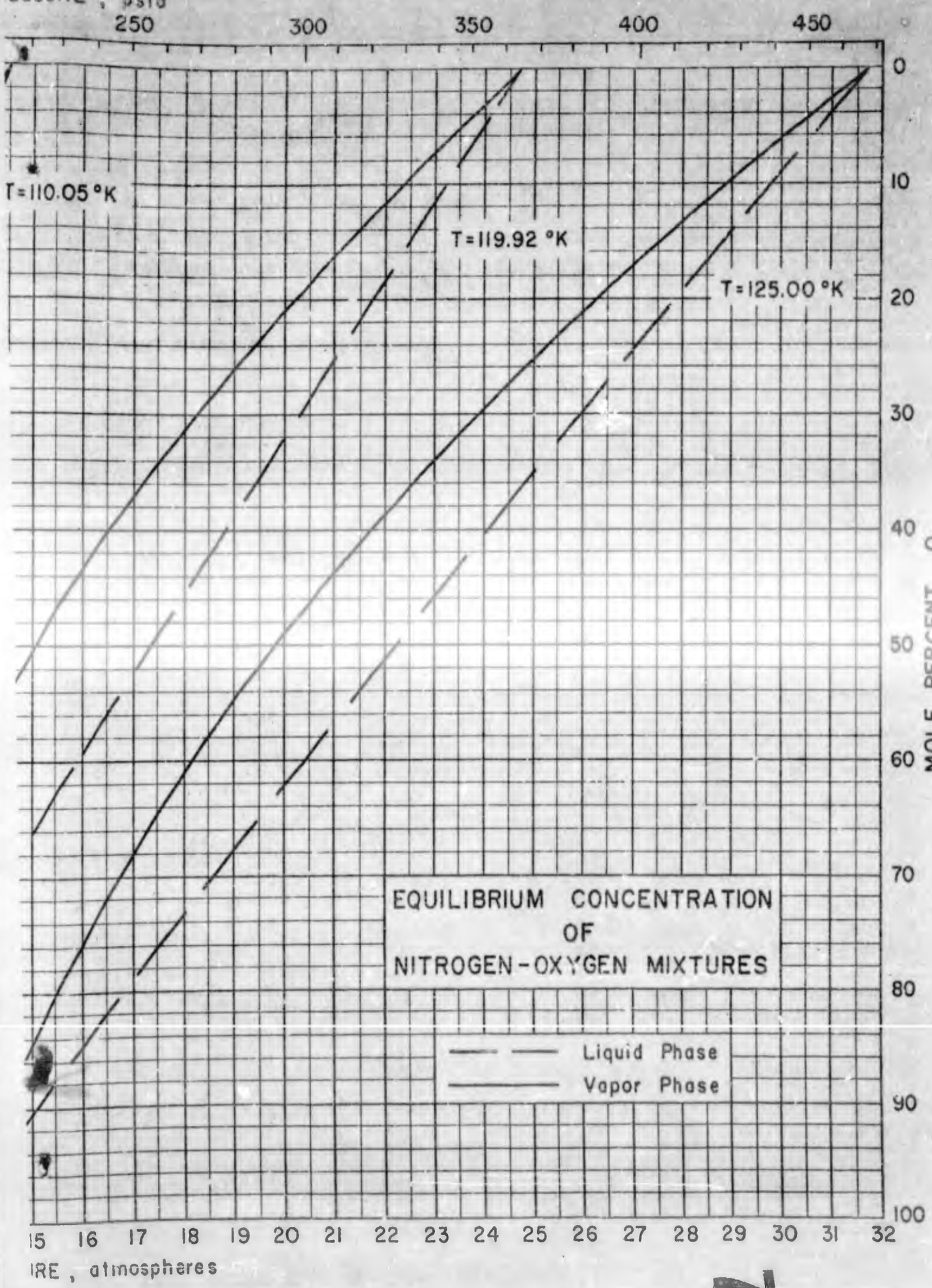
The values for the liquid-vapor equilibrium of the nitrogen-oxygen system for the following tables and graphs, are from the references listed above as sources of data. The concentration versus pressure values tabulated below for the 65°, 70° and 77.5°K isotherms were derived from data given by Armstrong, Goldstein and Roberts. These values are presented graphically on the P-X graph for a pressure range of 0 to 1.02 atmospheres. The concentration versus pressure values for the 90.5°, 99.94°, 110.05°, 119.92° and 125°K isotherms were taken from the paper by Dodge and Dunbar and are presented graphically on the P-X graph for a pressure range of 0 to 32 atmospheres, together with values for the 85°K isotherm reported by Sagenkahn and Fink. The concentration versus temperature values for pressures of 1.0 and 2.0 atmospheres are also from the paper by Sagenkahn and Fink and the data for the isobar at 1.3158 atmospheres is from Cockett's paper. The vapor pressure and temperature values for the single components, i.e., for the 0% and 100% nitrogen concentration, were from NBS Circular 564 by Hilsentrath, et al.

VJJ/RS Issued: 3-17-61


TEMPERATURE, °R
140
150
160
170
EQUILIBRIUM CONCENTRATION
OF
NITROGEN-OXYGEN MIXTURE
MOLE PERCENT OF N_2
MOLE PERCENT OF O_2
100
90
80
70
60
50
40
30
20
10
0
2 Atm
1 Atm
1.3158 Atm.
LIQUID PHASE
VAPOR PHASE
78
80
82
84
86
88
90
92
94
96
98
TEMPERATURE, °K


PRESSURE, psia
0
50
100
150
200
250
T=85°K
T=90.5°K
T=99.94°K
T=110.05°K
MOLE PERCENT N_2
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
PRESSURE, atmospheres

16.004 / 5


ESSURE , psia
250
300
350
400
450
T=110.05 °K
T=119.92 °K
T=125.00 °K
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT O_2
EQUILIBRIUM CONCENTRATION
OF
NITROGEN-OXYGEN MIXTURES
Liquid Phase
Vapor Phase
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
IRE , atmospheres

EQUILIBRIUM CONCENTRATIONS OF NITROGEN - OXYGEN MIXTURES

Table of Selected Values

Press.	Mole % N_2	
atm.	liquid	vapor
65°K		
0.023	0	0
.040	7.20	44.0
.060	18.0	66.0
.080	30.9	78.3
.100	44.5	84.9
.12	58.4	90.3
.140	82.4	94.9
.160	88.0	98.2
.172	100	100
70°K		
0.052	0	0
.10	9.8	48.3
.15	42.2	81.7
.20	69.4	92.7
.25	82.0	96.4
.30	88.2	98.5
.35	85.4	97.4
.375	100	100
77.5°K		
0.209	0	0
.30	9.10	35.1
.40	19.3	57.8
.50	30.2	68.7
.60	43.0	77.4
.70	55.9	85.3
.80	71.0	91.1
.90	85.2	95.7
1.014	100	100
90.5°K		
1.033	0	0
1.174	5.42	17.37

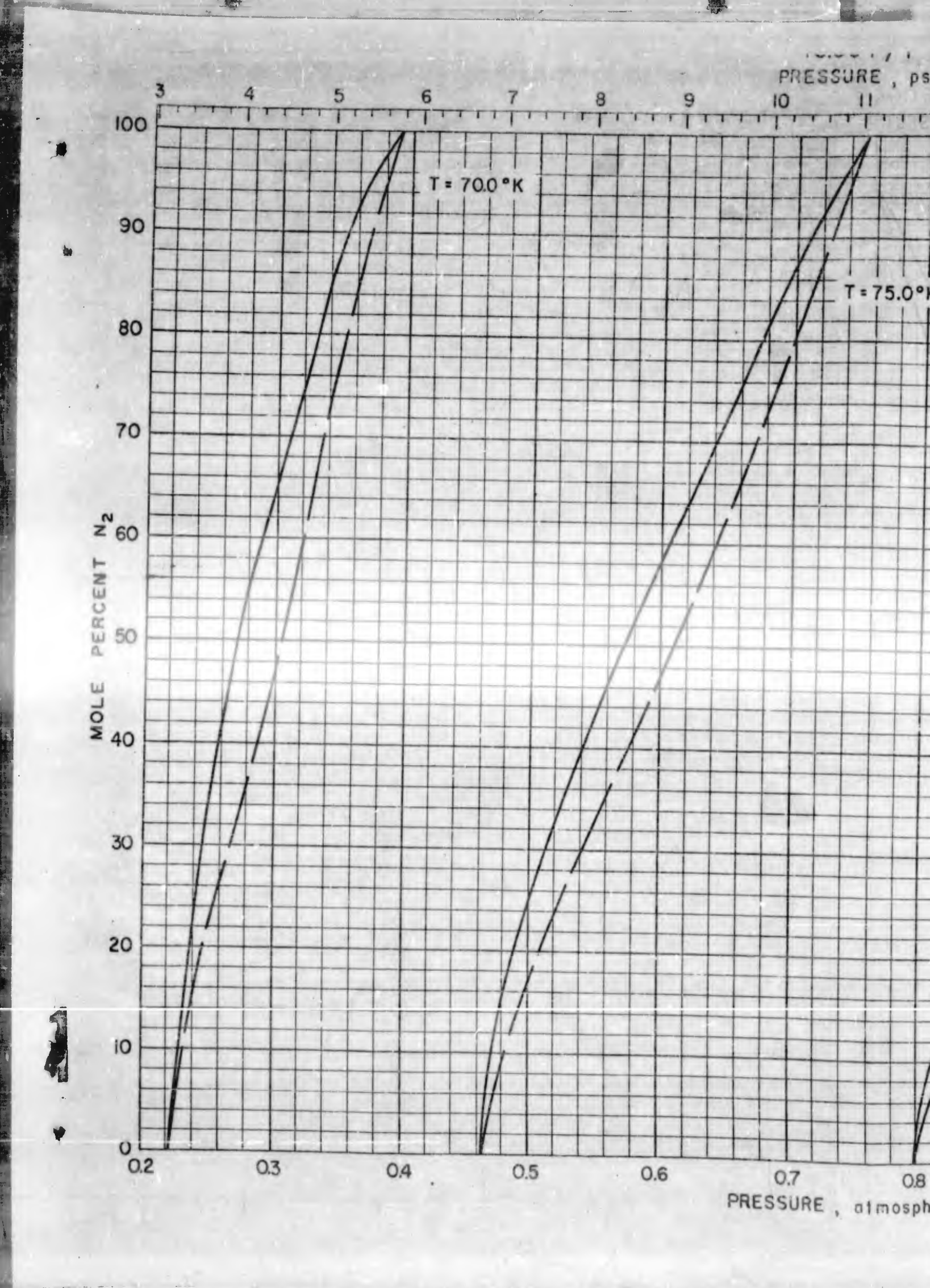
Press.	Mole % N_2	
atm.	liquid	vapor
1.330	11.00	30.94
1.551	17.39	43.02
1.559	17.88	44.11
1.585	19.40	46.57
1.808	27.13	56.59
2.145	39.02	68.21
2.302	44.59	72.80
2.401	49.57	75.87
2.457	50.61	76.55
2.501	53.05	78.09
2.729	64.79	85.04
3.202	85.74	96.70
3.307	100	100
99.9°K		
2.402	0	0
2.429	3.00	13.09
2.903	7.01	18.39
3.022	9.95	24.55
3.253	15.70	32.29
3.492	19.91	38.94
3.845	25.12	49.06
4.760	42.48	69.69
5.043	48.78	71.99
5.323	58.97	78.52
5.841	63.78	81.03
6.340	80.50	90.77
7.180	90.86	95.78
7.67.	100	100
110.05°K		
3.378	0	0
6.033	6.52	15.17
8.000	12.00	20.20
7.280	20.17	39.50
9.231	41.09	61.44

Press.	Mole % N_2	
atm.	liquid	vapor
10.731	64.38	74.30
11.130	68.39	77.80
12.061	78.52	88.39
12.333	82.45	94.73
12.53	100	100
119.92°K		
10.830	0	0
11.532	12.02	21.68
12.830	29.16	52.57
14.524	52.90	73.93
15.982	72.11	86.22
16.238	78.20	88.43
16.919	82.49	94.15
21.482	79.00	85.86
22.961	88.33	92.11
24.71	100	100
125.00°K		
13.316	0	0
15.531	10.93	20.24
16.837	19.50	30.95
20.450	40.37	53.71
22.902	54.08	---
24.298	62.25	71.95
27.349	78.28	83.86
29.332	88.00	90.89
31.71	100	100
85°K		
0.5597	0	0
.038	4.09	17.37
1.218	36.27	70.20
1.421	49.02	79.16
1.563	60.01	87.60
2.243	100	100

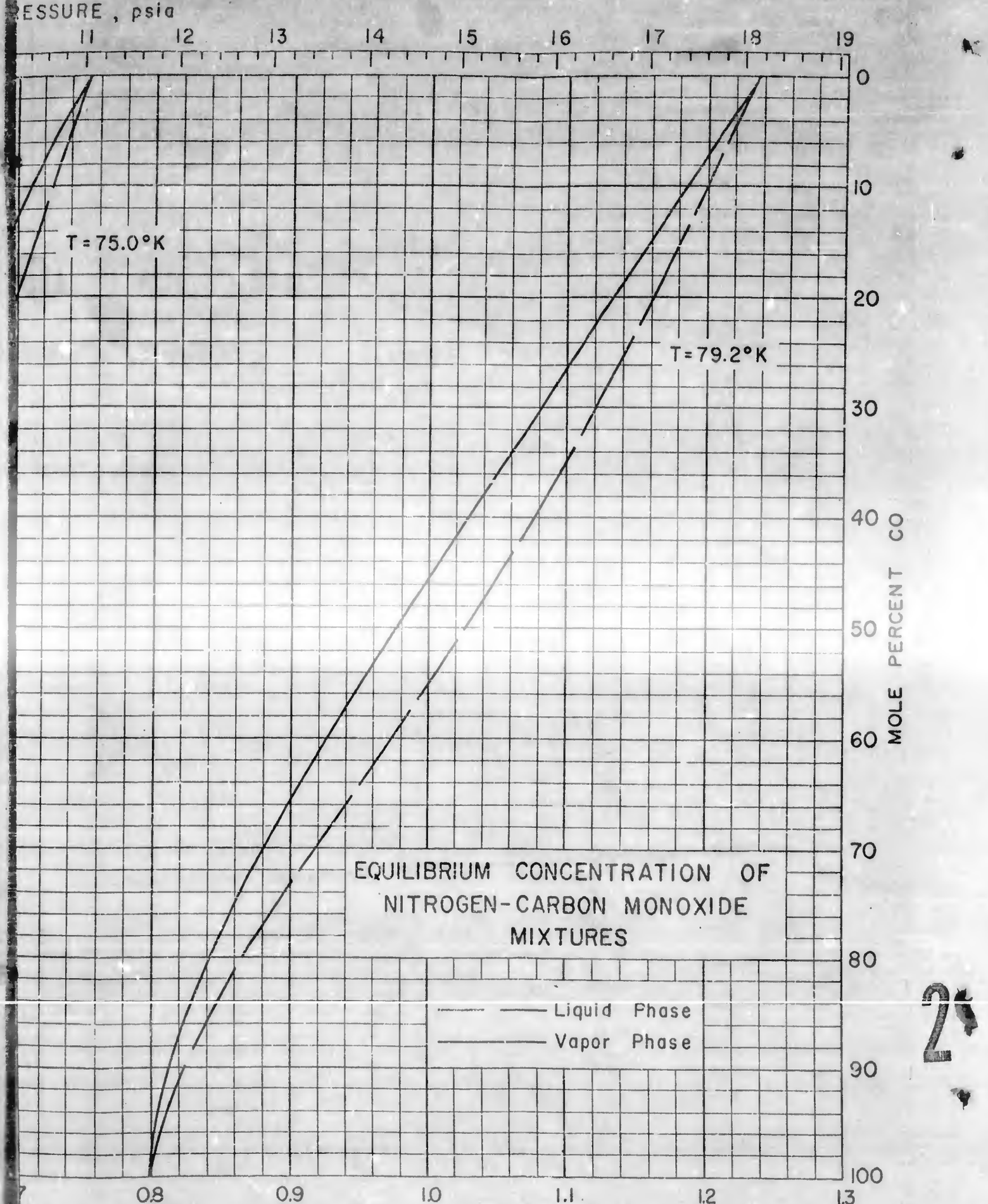
Table of Selected Values

Temp. °K	Mole % N_2	
	liquid	vapor
1 atm.		
77.40	100	100
79.86	67.56	89.92
81.91	46.75	78.78
81.88	46.01	78.33
82.74	38.37	73.04
84.75	25.40	59.64
88.92	4.61	17.53
90.19	0	0
1.3158 atm.		
79.82	100	100
81.076	81.09	94.00
81.314	78.46	92.81
81.856	71.51	90.01
82.589	63.07	86.33
82.826	61.13	85.55
82.956	59.80	84.75
83.056	58.40	83.62
83.749	52.99	80.81
84.398	45.93	76.82
84.952	40.49	72.27
85.922	33.81	66.65
85.938	33.96	66.70
86.850	27.48	59.97
86.886	27.44	59.46
88.033	20.22	50.11
88.064	19.05	48.68
88.067	20.71	50.89
89.022	15.75	42.10
89.734	11.24	33.73
89.806	12.54	35.83
89.816	11.96	35.14
90.662	7.24	23.96
90.979	7.17	21.91
92.89	0	0
2 atm.		
83.85	100	100
86.73	66.01	87.19
88.28	51.16	78.15
92.49	22.67	53.61
96.12	5.32	18.57
97.38	0	0

2


PRESSURE , ps
3
4
5
6
7
8
9
10
11
100
90
80
70
60
50
40
30
20
10
0
T = 70.0 °K
T = 75.0°
MOLE PERCENT N_2
0.2
0.3
0.4
0.5
0.6
0.7
0.8
PRESSURE , atmosph

16.004 / 7


ESSURE , psia
11
12
13
14
15
16
17
18
19
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT CO
T = 75.0°K
T = 79.2°K
EQUILIBRIUM CONCENTRATION OF NITROGEN-CARBON MONOXIDE MIXTURES
Liquid Phase
Vapor Phase
0.8
0.9
1.0
1.1
1.2
1.3
URE , atmospheres

EQUILIBRIUM CONCENTRATION of NITROGEN-CARBON MONOXIDE MIXTURES

Sources of Data:

Yushkevich, N. F. and Torocheshnikov, N. S.; Zhur. Khim. Prom. 13, 1273-83 (1936)

Verschoyle, T. T. H; Trans. Roy. Soc. (London) A230, 189-220 (1931)

Other References:

Schiller, F. C. and Canjar, L. N.; Chem. Engr. Progr. Symposium Ser. 49, No. 7, Applied Thermodynamics 67-72 (1953)

Steckel, F.; Phys. Z. Sowjetunion 8, 337 (1935)

Komarov, P., Likhter, A. and Ruhemann, M.; Zhur. Tekh. Fiz. 5, 1723-8 (1935)

Comments:

The values for the liquid-vapor equilibrium of the nitrogen-carbon monoxide system for the following tables and graphs are from the two references listed above as sources of data. The data reported by Yushkevich and Torocheshnikov include pressures and mole concentrations for liquid and vapor at saturation for isotherms from 70 to 121.8°K.

The data from Verschoyle's paper were for liquid concentrations only and were used to supplement the data for the three isotherms at 70, 75 and 79.2°K also reported by Yushkevich and Torocheshnikov. These two sources of data were found to be in excellent agreement.

Equilibrium Concentrations - Liquid Phase

(Verschoyle)

Temp. °C	Press. cm.	Temp. °C	Press. cm.	Temp. °C	Press. cm.	Temp. °C	Press. cm.
Mole % N_2 = 80.1		Mole % N_2 = 59.95		Mole % N_2 = 40.0		Mole % N_2 = 20.05	
-193.88	88.41	-193.90	81.87	-193.90	74.20	-193.90	65.82
-193.88	88.38	-193.90	81.89	-193.90	74.29	-193.90	65.94
-198.13	53.30	-198.13	49.00	-198.13	44.10	-198.13	38.81
-198.13	53.20	-198.12	48.80	-198.11	43.80	-198.14	38.81
-203.07	27.01	-203.07	24.60	-203.07	21.99	-203.07	18.94
-203.08	27.04	-203.07	24.63	-203.06	22.17	-203.09	19.02

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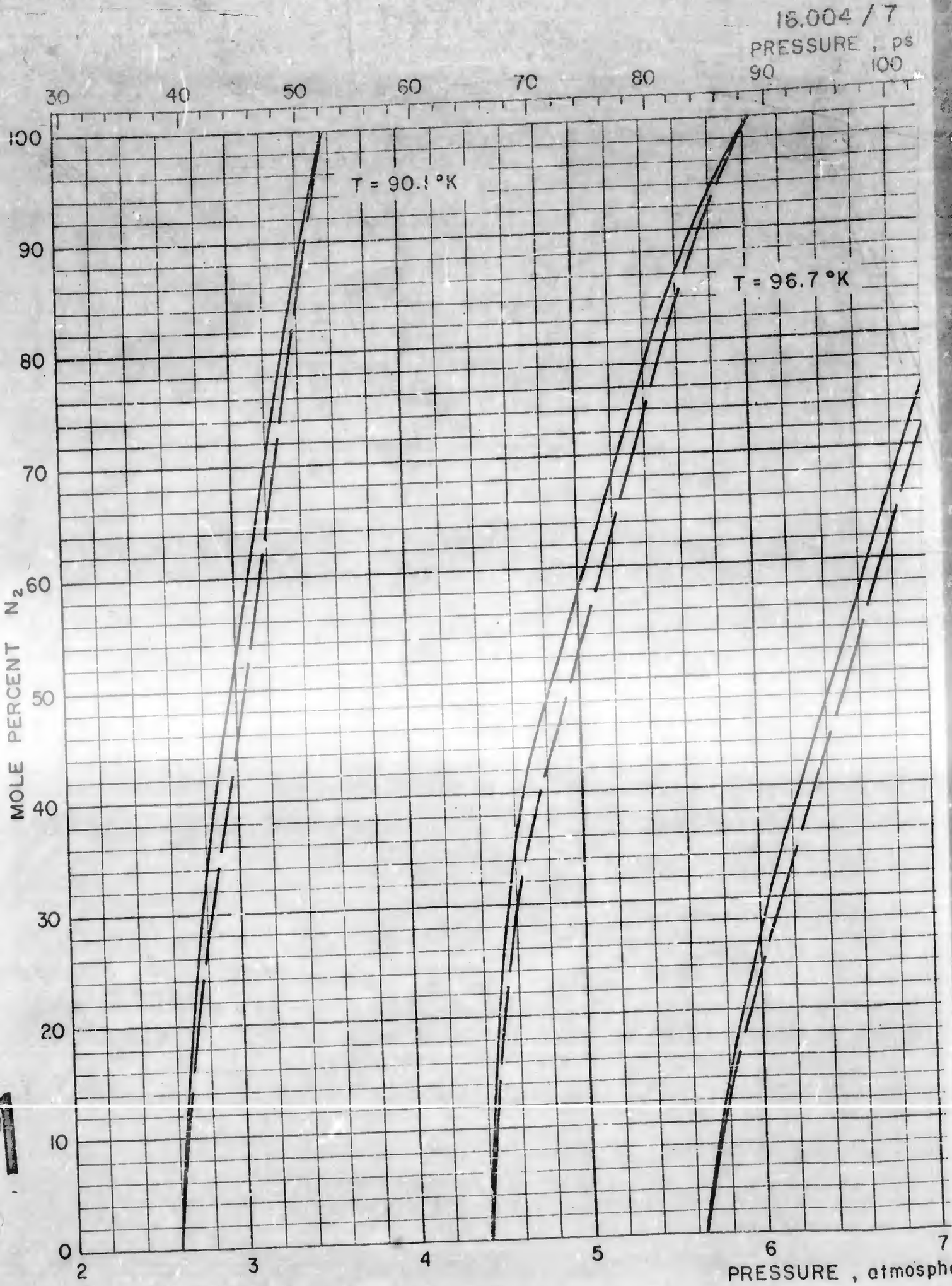
Equilibrium Concentrations - Liquid and Vapor Phases

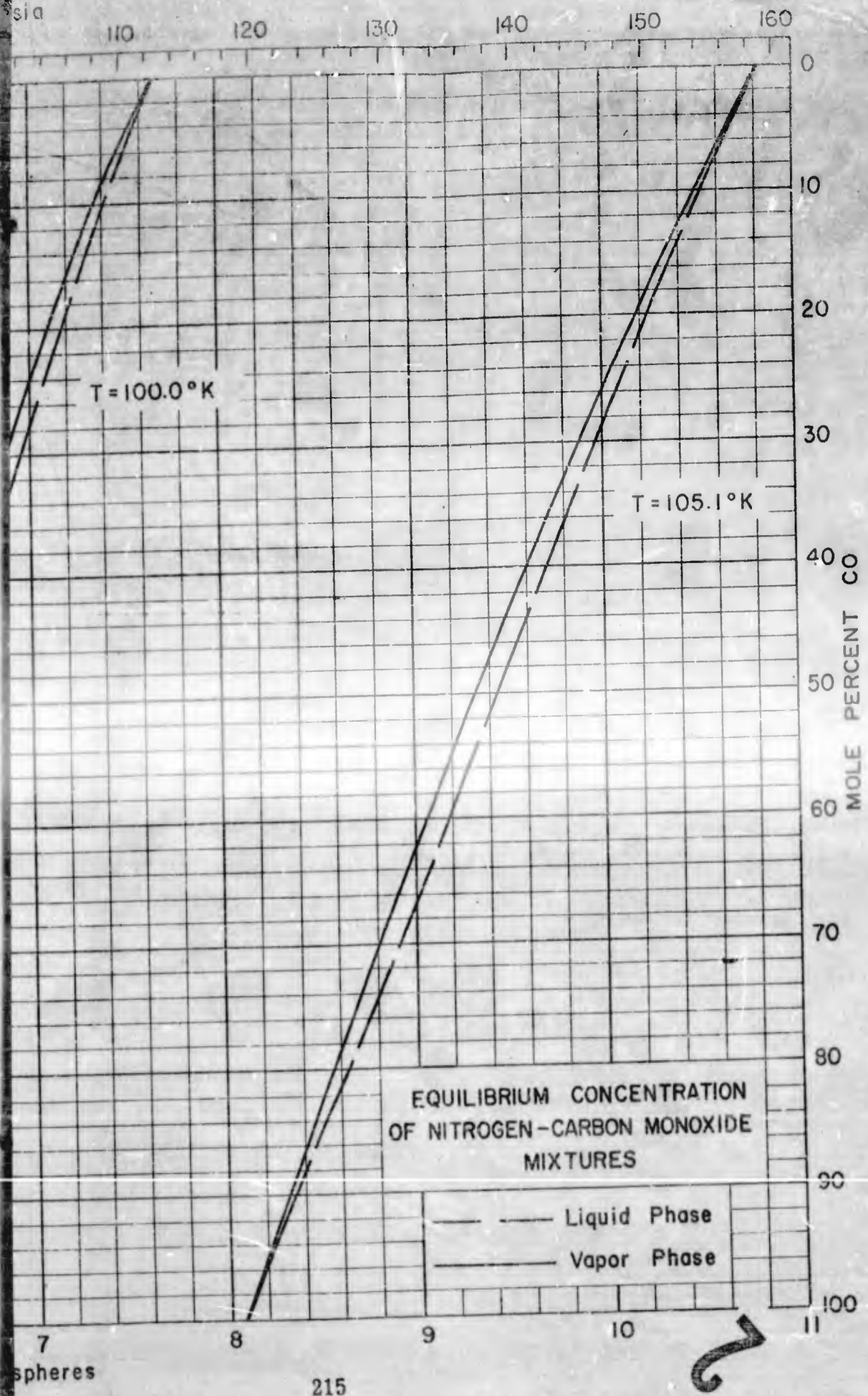
(Yushkevich and Torocheshnikov)

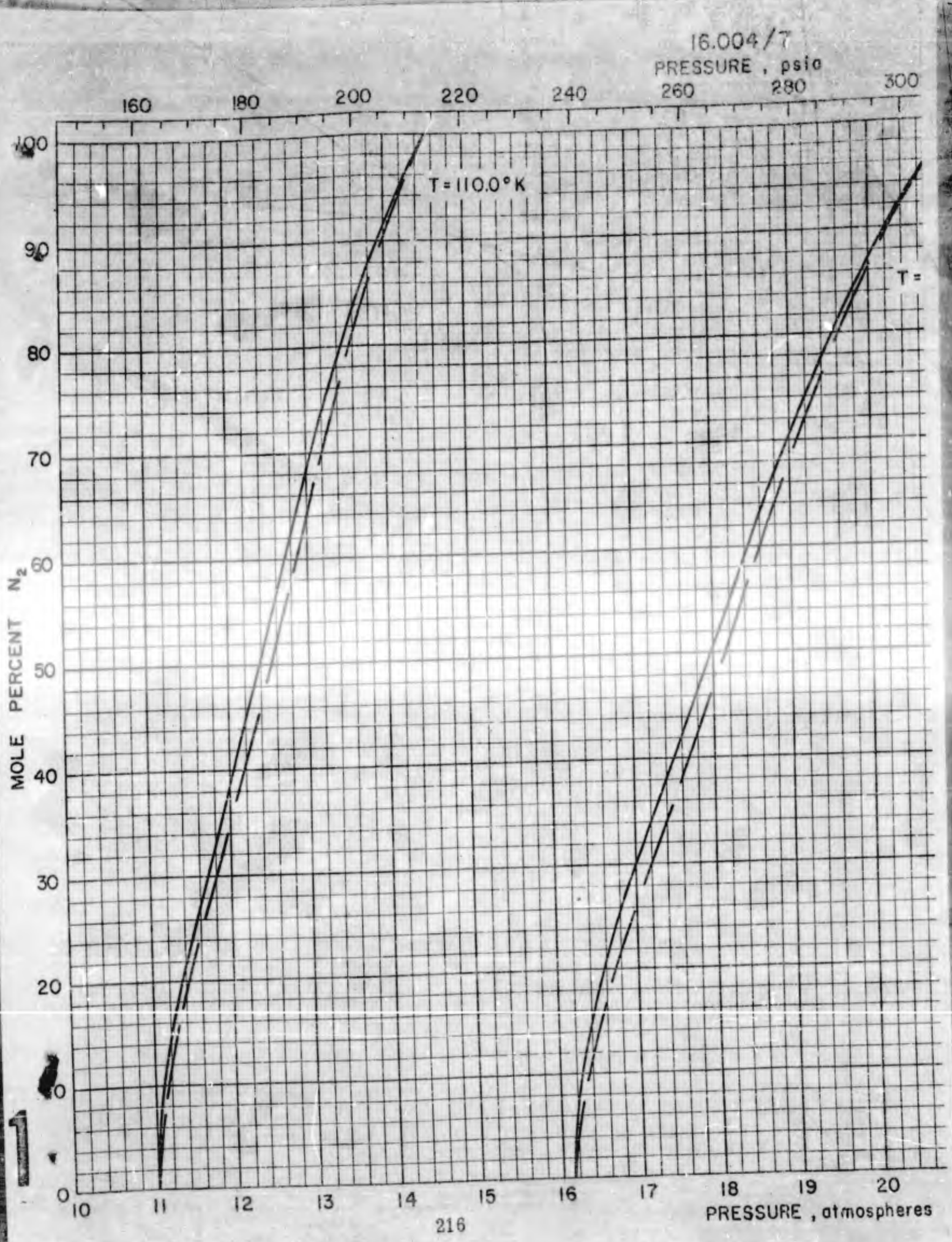
Press. Atm.	Mole % N_2 Liq.	Vap.
70.0°K		
0.393	1.000	1.000
0.355	0.810	0.910
0.323	0.600	0.728
0.290	0.400	0.600
0.249	0.201	0.310
0.223	0.000	0.000
75.0°K		
0.754	1.000	1.000
0.700	0.801	0.875
0.643	0.600	0.700
0.578	0.400	0.520
0.510	0.201	0.290
0.463	0.000	0.000
79.2°K		
1.236	1.000	1.000
1.163	0.860	0.860
1.077	0.600	0.690
0.976	0.400	0.500
0.866	0.201	0.270
0.798	0.000	0.000
90.1°K		
3.566	1.000	1.000
3.341	0.792	0.831
3.323	0.759	0.803
3.22	0.650	0.710
2.914	0.375	0.452

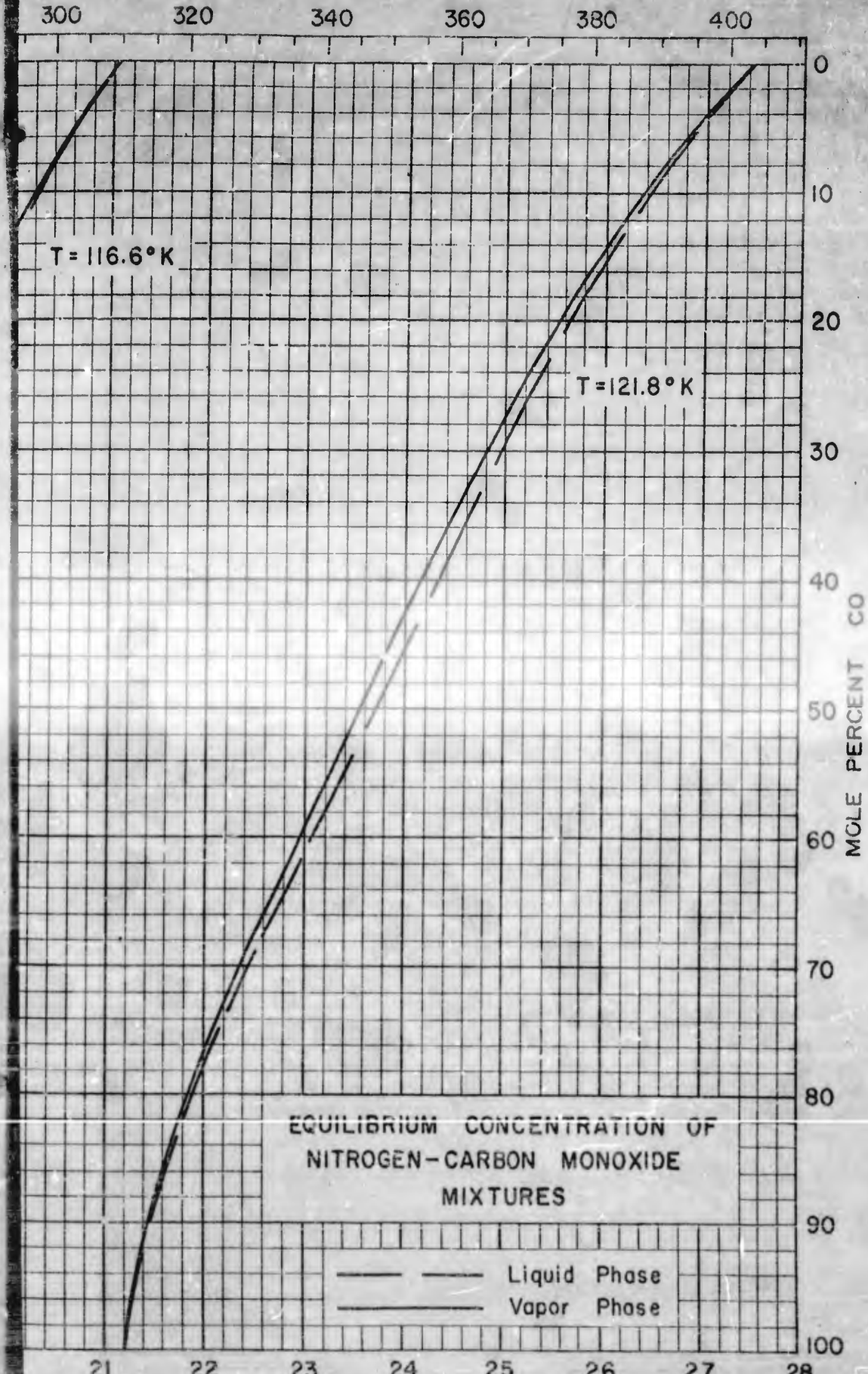
Press. Atm.	Mole % N_2 Liq.	Vap.
2.762	0.224	0.288
2.68	0.135	0.162
2.591	0.000	0.000
96.7°K		
6.04	1.000	1.000
5.57	0.822	0.856
5.34	0.693	0.745
5.30	0.666	0.721
4.62	0.328	0.384
4.53	0.206	0.260
4.45	0.107	0.135
4.39	0.000	0.000
100.0°K		
7.68	1.000	1.000
6.97	0.718	0.755
6.87	0.660	0.700
6.24	0.348	0.395
6.15	0.302	0.355
6.06	0.260	0.300
5.88	0.170	0.198
5.82	0.136	0.160
5.61	0.000	0.000
105.1°K		
10.80	1.000	1.000
9.70	0.600	0.640
9.66	0.584	0.627
9.44	0.475	0.520
8.73	0.228	0.256

Press. Atm.	Mole % N_2 Liq.	Vap.
8.60	0.190	0.216
88.06	0.000	0.000
110.0°K		
14.5	1.000	1.000
13.14	0.680	0.718
13.07	0.660	0.700
12.68	0.534	0.580
12.49	0.485	0.530
12.34	0.440	0.487
12.20	0.397	0.443
12.00	0.350	0.393
11.62	0.246	0.280
11.52	0.215	0.245
11.26	0.149	0.170
10.99	0.000	0.000
116.6°K		
21.03	1.000	1.000
18.54	0.587	0.620
18.40	0.565	0.600
17.81	0.416	0.457
17.76	0.410	0.445
17.52	0.360	0.392
16.94	0.244	0.278
16.13	0.000	0.000
121.8°K		
27.42	1.000	1.000
23.96	0.542	0.570
22.33	0.280	0.300
22.07	0.245	0.256
21.19	0.000	0.000

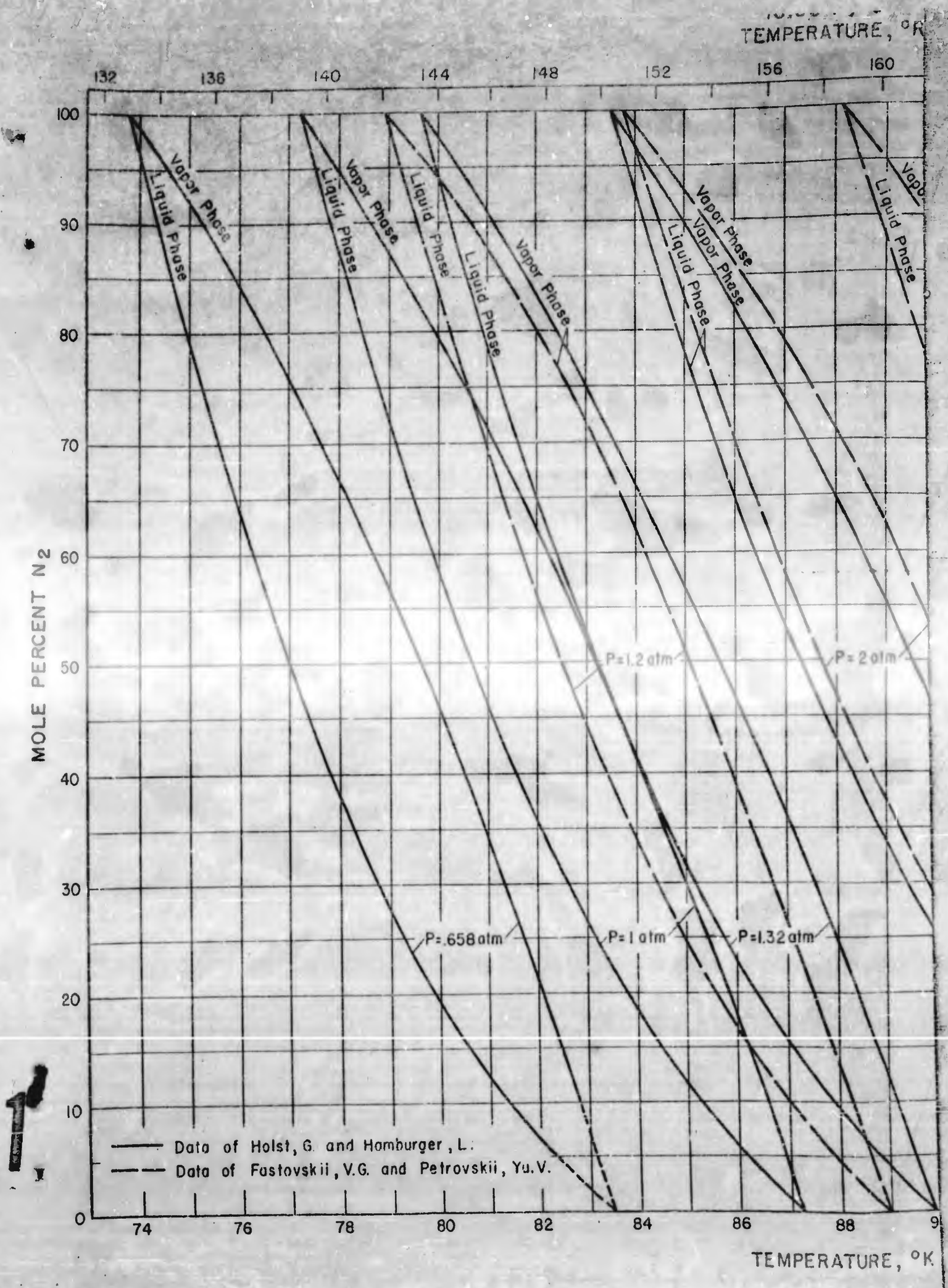

PRESSURE , ps
30
40
50
60
70
80
90
100
T = 90.1 °K
T = 96.7 °K
MOLE PERCENT N_2
100
90
80
70
60
50
40
30
20
10
0
2
3
4
5
6
7
PRESSURE , atmosphe

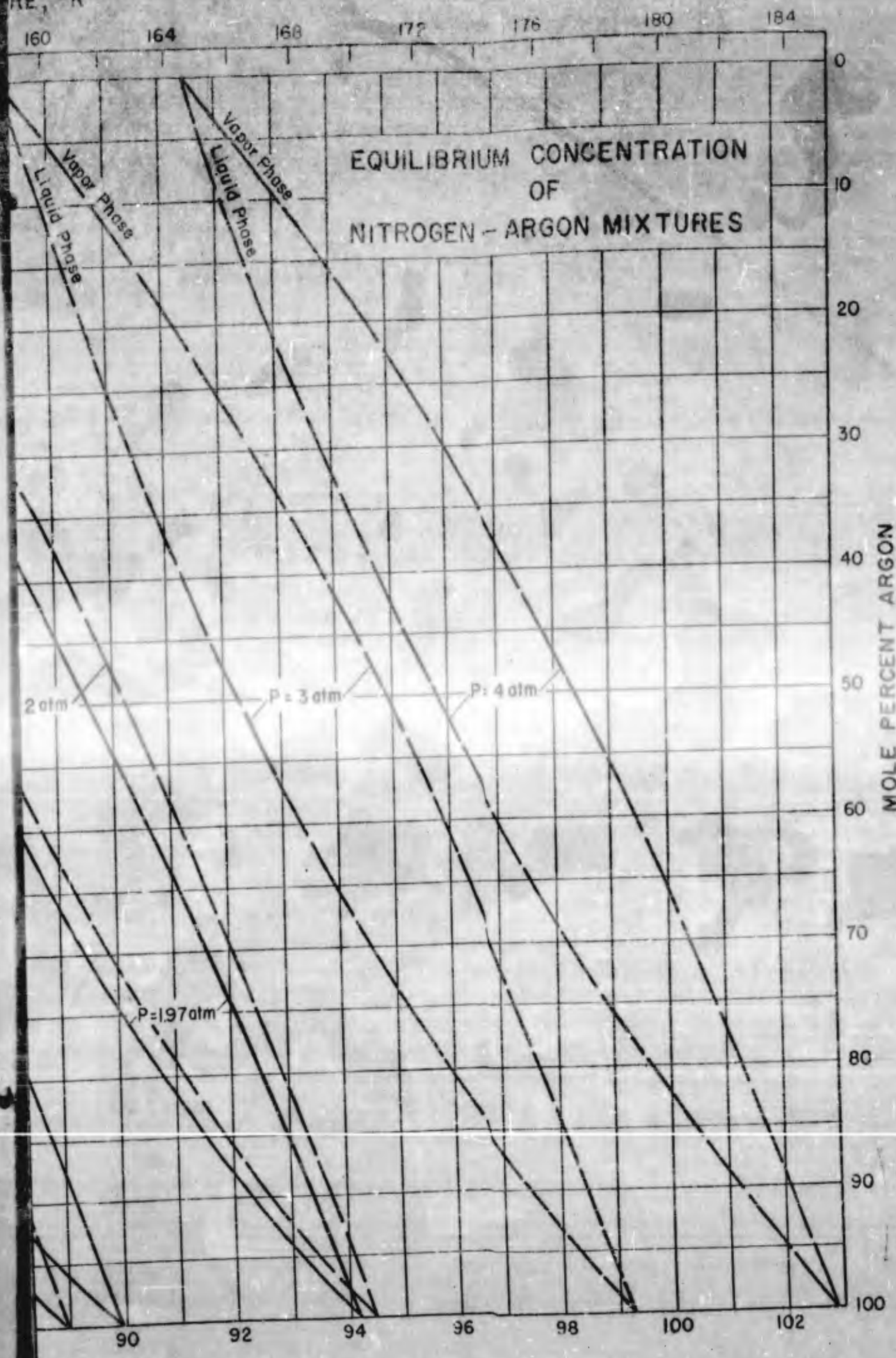

psia
110
120
130
140
150
160
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT CO
T = 100.0 °K
T = 105.1 °K
EQUILIBRIUM CONCENTRATION OF NITROGEN-CARBON MONOXIDE MIXTURES
Liquid Phase
Vapor Phase
7
8
9
10
11
spheres


16.004/7
PRESSURE , psia
160
180
200
220
240
260
280
300
100
90
80
70
60
50
40
30
20
10
0
T = 110.0° K
T =
MOLE PERCENT N_2
10
11
12
13
14
15
16
17
18
19
20
PRESSURE , atmospheres


300
320
340
360
380
400
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT CO
T = 116.6°K
T = 121.8°K
EQUILIBRIUM CONCENTRATION OF
NITROGEN-CARBON MONOXIDE
MIXTURES
Liquid Phase
Vapor Phase
21
22
23
24
25
26
27
28

res


TEMPERATURE, °R
132
136
140
144
148
152
156
160
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT N_2
Vapor Phase
Liquid Phase
P=.658 atm
P=1 atm
P=1.32 atm
P=1.2 atm
P=2 atm
Data of Holst, G. and Hamburger, L.
Data of Fastovskii, V.G. and Petrovskii, Yu.V.
74
76
78
80
82
84
86
88
TEMPERATURE, °K


RE, °R
160
164
168
172
176
180
184
EQUILIBRIUM CONCENTRATION
OF
NITROGEN – ARGON MIXTURES
Vapor Phase
Liquid Phase
Vapor Phase
Liquid Phase
2 atm
P = 3 atm
P = 4 atm
P = 1.97 atm
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT ARGON
90
92
94
96
98
100
102
RE, °K

2

16.004/9

EQUILIBRIUM CONCENTRATIONS of NITROGEN-ARGON MIXTURES

Sources of Data:

Holst, G. and Hamburger, L.; Z. physik. Chem. 91, 513 (1916); Proc. Akad. Wetenschap. 18, 872 (1916)

Fastovskii, V. G. and Petrovskii, Yu. V.; Zhur. Fiz. Khim. 30, 76 (1956)

Other References:

Torocheshnikov, N. S. and Ershova, V. A.; Zhur. Khim. Prom. 17, 30 (1940)

Weishaupt, J.; Angew. Chem. B20, 321 (1948)

Sagenkahn, M. L. and Fink, H. L.; Penn. State College, OSRD Rept. No. 4493 (1944)

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, III, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc. (1928) pp. 309-317

Comments:

The experimental data for the liquid-vapor equilibrium of the nitrogen-argon system listed in the following tables are from the two references listed above as sources of data. These data are also illustrated on the following graph. The data from Holst and Hamburger are represented by the solid lines while dashed lines are used for the data from Fastovskii and Petrovskii.

It should also be noted that the T-X curves for P = 50 cm Hg (P = 0.658 atm.) have been dotted on the argon side as the solid makes its appearance here.

In addition, Weishaupt has reported on the three component system argon-nitrogen-oxygen from which values for the corresponding two component systems may be derived.

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EQUILIBRIUM CONCENTRATIONS of NITROGEN-ARGON MIXTURES

Tables of Selected Values

Holst and Hamburger

Temp. °K	Mole % N_2 Liquid	Mole % N_2 Vapor
P = 50 cm Hg (0.658 atm.)		
73.87	100.0	100.0
73.94	99.0	--
74.82	82.6	--
75.86	65.3	--
77.21	--	74.05
78.65	31.5	--
79.41	--	52.8
81.42	10.0	--
81.79	--	24.3
83.45	0.0	0.0
P = 76 cm Hg (1.0 atm.)		
77.28	100.0	100.0
77.35	99.	--
78.30	82.6	--
79.41	65.3	--
80.66	--	74.0
82.40	31.5	--
82.97	--	52.8
85.25	10.0	--
85.46	--	24.3
87.26	0.0	0.0

Temp. °K	Mole % N_2 Liquid	Mole % N_2 Vapor
P = 100 cm Hg (1.32 atm.)		
79.71	100.0	100.0
79.78	99.	--
80.76	82.6	--
81.95	65.3	--
83.08	--	74.0
85.05	31.5	--
85.40	--	52.8
87.98	10.0	--
88.04	---	24.3
89.93	0.0	0.0
P = 150 cm Hg (1.97 atm.)		
83.57	0.0	0.0
83.64	99.	--
84.70	82.6	--
85.97	65.3	--
86.93	--	74.0
89.29	31.5	--
89.33	--	52.8
92.15	--	24.3
92.32	10.0	--
94.18	0.0	0.0

Press. atm.	Press. cm Hg	Mole % N_2 Liq.	Mole % N_2 Vap.
T = 85.11°K			
2.29	174.3	100	100
2.06	156.2	82.6	--
1.81	137.9	65.3	--
1.63	124.2	--	74.0
1.32	100.5	31.5	--
1.27	96.78	--	52.8
.984	74.75	10.10	--
.963	73.18	--	24.3
.793	60.28	0	0

Temp °K	P
	78.9
	79.5
	80.2
	80.9
	81.6
	82.5
	83.5
	84.4
	85.6
	87.0
	87.9
	89.0
	P =
	83.8
	84.4
	85.2
	86.0
	86.8
	87.7
	88.7
	89.8
	91.0
	92.64
	93.56
	94.43

Fastovskii and Petrovskii

Temp. °K	Mole % N_2	
	Liquid	Vapor
P = 912 mm Hg (1.2 atm.)		
78.90	100	100
79.58	90	96.52
80.26	80	92.46
80.96	70	87.74
81.66	60	82.24
82.50	50	75.60
83.50	40	67.15
84.46	30	56.96
85.64	20	43.47
87.00	10	25.80
87.92	5	14.10
89.00	0	0
P = 1520 mm Hg (2.0 atm.)		
83.80	100	100
84.44	90	90.16
85.24	80	91.73
86.00	70	86.63
86.80	60	80.68
87.72	50	73.47
88.76	40	64.91
89.88	30	54.34
91.08	20	40.87
92.64	10	23.36
93.56	5	12.53
94.43	0	0

Temp. °K	Mole % N_2	
	Liquid	Vapor
P = 2280 mm Hg (3.0 atm.)		
88.11	100	100
88.84	90	95.90
89.66	80	91.08
90.42	70	85.95
91.26	60	79.71
92.24	50	72.34
93.34	40	63.58
94.56	30	52.78
95.96	20	39.43
97.45	10	22.32
98.32	5	12.00
99.22	0	0
P = 3040 mm Hg (4.0 atm.)		
91.40	100	100
92.16	90	95.03
92.98	80	91.06
93.18	70	85.57
94.80	60	79.07
95.86	50	71.50
97.05	40	62.41
98.21	30	51.69
99.68	20	37.97
101.13	10	21.22
102.00	5	19.30
102.88	0	0

EQUILIBRIUM CONCENTRATIONS of NITROGEN-ARGON MIXTURES

Tables of Selected Values

Holst and Hamburger

Temp. °K	Mole % N_2	
	Liquid	Vapor
P = 50 cm Hg (0.658 atm.)		
73.87	100.0	100.0
73.94	99.0	--
74.82	82.6	--
75.86	65.3	--
77.21	--	74.05
78.65	31.5	--
79.41	--	52.8
81.42	10.0	--
81.79	--	24.3
83.45	0.0	0.0
P = 76 cm Hg (1.0 atm.)		
77.26	100.0	100.0
77.35	99.	--
78.30	82.6	--
79.41	65.3	--
80.66	--	74.0
82.40	31.5	--
82.97	--	52.8
85.25	10.0	--
85.46	--	24.3
87.26	0.0	0.0

Temp. °K	Mole % N_2	
	Liquid	Vapor
P = 100 cm Hg (1.32 atm.)		
79.71	100.0	100.0
79.78	99.	--
80.76	82.6	--
81.95	65.3	--
83.08	--	74.0
85.05	31.5	--
85.40	--	52.8
87.98	10.0	--
88.04	---	24.3
89.93	0.0	0.0
P = 150 cm Hg (1.97 atm.)		
83.57	0.0	0.0
83.64	99.	--
84.70	82.6	--
85.97	65.3	--
86.93	--	74.0
89.29	31.5	--
89.33	--	52.8
92.15	--	24.3
92.32	10.0	--
94.18	0.0	0.0

Press. atm.	Press. cm Hg	Mole % N_2	
		Liq.	Vap.
T = 85.11°K			
2.29	174.3	100	100
2.06	156.2	82.6	--
1.81	137.9	65.3	--
1.63	124.2	--	74.0
1.32	100.5	31.5	--
1.27	96.78	--	52.8
.984	74.75	10.10	--
.963	73.18	--	24.3
.793	60.28	0	0

Temp °K	
P	
78.9	
79.5	
80.2	
80.9	
81.6	
82.5	
83.5	
84.4	
85.6	
87.0	
87.9	
89.0	
P =	
83.8	
84.4	
85.2	
86.0	
86.8	
87.7	
88.7	
89.8	
91.0	
92.64	
93.56	
94.43	

Table of Selected Values

Fastovskii and Petrovskii

Temp. °K	Mole % N_2	
	Liquid	Vapor
P = 912 mm Hg (1.2 atm.)		
78.90	100	100
79.58	90	96.52
80.26	80	92.46
80.96	70	87.74
81.66	60	82.24
82.50	50	75.60
83.50	40	67.15
84.46	30	56.96
85.64	20	43.47
87.00	10	25.80
87.92	5	14.10
89.00	0	0
P = 1520 mm Hg (2.0 atm.)		
83.80	100	100
84.44	90	96.16
85.24	80	91.73
86.00	70	86.63
86.80	60	80.68
87.72	50	73.47
88.76	40	64.91
89.88	30	54.34
91.08	20	40.87
92.64	10	23.36
93.56	5	12.53
94.43	0	0

Temp. °K	Mole % N_2	
	Liquid	Vapor
P = 2280 mm Hg (3.0 atm.)		
88.11	100	100
88.84	90	95.90
89.66	80	91.08
90.42	70	85.95
91.26	60	79.71
92.24	50	72.34
93.34	40	63.58
94.56	30	52.78
95.96	20	39.43
97.45	10	22.32
98.32	5	12.00
99.22	0	0
P = 3040 mm Hg (4.0 atm.)		
91.40	100	100
92.16	90	95.83
92.98	80	91.06
93.18	70	85.57
94.80	60	79.07
95.86	50	71.50
97.05	40	62.41
98.21	30	51.69
99.68	20	37.97
101.13	10	21.22
102.00	5	19.30
102.88	0	0

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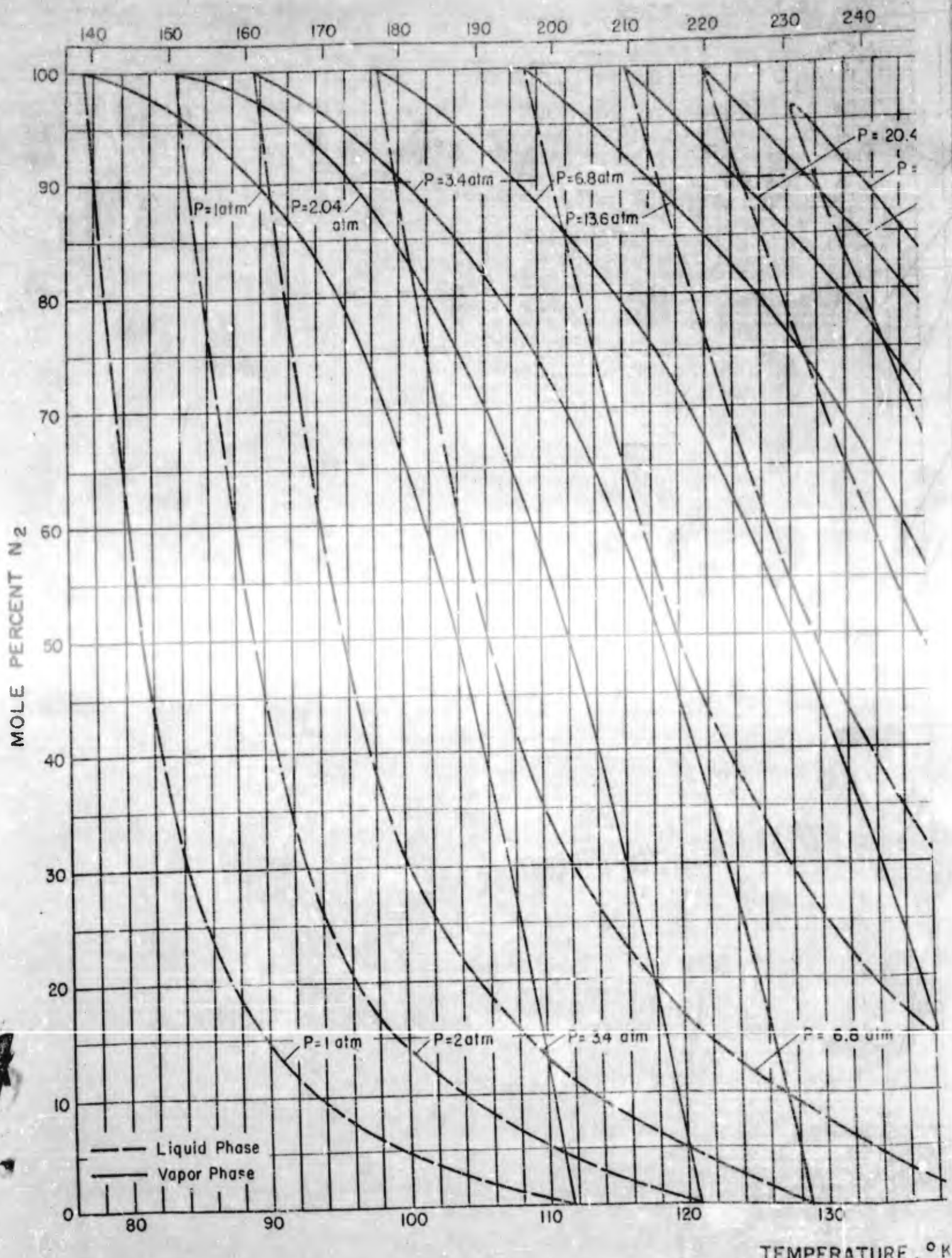
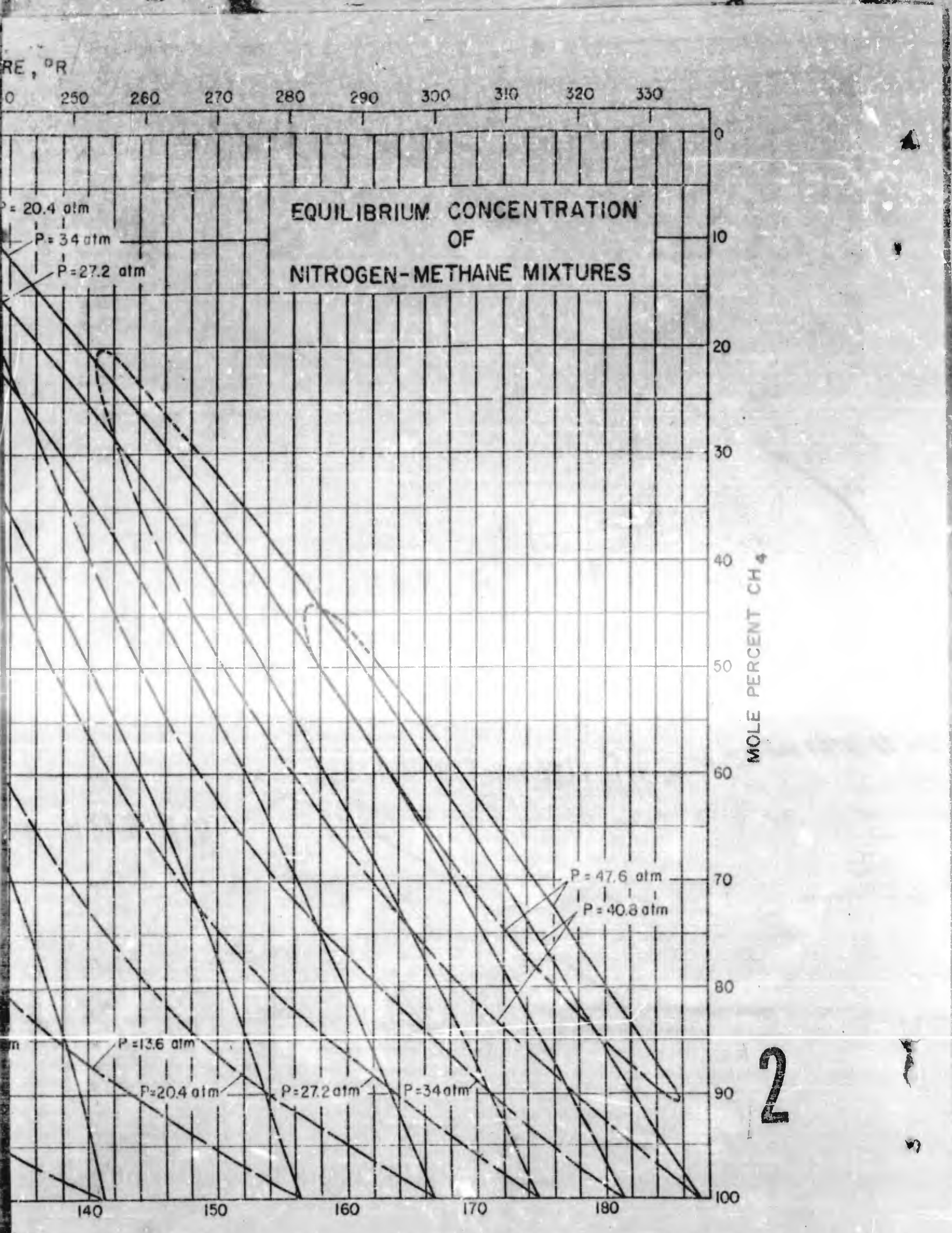

TEMPERATURE, °
140
150
160
170
180
190
200
210
220
230
240
100
90
80
70
60
50
40
30
20
10
0
MOLE PERCENT N2
P=1atm
P=2.04 atm
P=3.4atm
P=6.8atm
P=13.6atm
P= 20.4
P=1 atm
P=2atm
P= 3.4 atm
P= 6.8 atm
Liquid Phase
Vapor Phase
80
90
100
110
120
130
TEMPERATURE, °K


RE, °R
0
250
260
270
280
290
300
310
320
330
EQUILIBRIUM CONCENTRATION
OF
NITROGEN-METHANE MIXTURES
P = 20.4 atm
P = 34 atm
P = 27.2 atm
P = 47.6 atm
P = 40.8 atm
P = 13.6 atm
P = 20.4 atm
P = 27.2 atm
P = 34 atm
MOLE PERCENT CH4
0
10
20
30
40
50
60
70
80
90
100
140
150
160
170
180
RE, °K

2

EQUILIBRIUM CONCENTRATION of NITROGEN-METHANE MIXTURES

Sources of Data:

Bloomer, O. T. and Parent, J. D., Chem. Eng. Progr. Symposium 49, No. 6, 11-24 (1953)

Cines, M. R., Roach, J. T., Hogan, R. J. and Roland, C. H., Chem. Eng. Progr. Symposium 49, No. 6, 1-10 (1953)

Bloomer, O. T. and Rao, K. N., Inst. Gas Technol. Research Bull. 18, 1-28 (1952)

Other References:

Fastovskii, V. G. and Krestinskii, Yu., Zhur. Fiz. Khim. 15, 525-31 (1941)

Fastovskii, V. G. and Petrovskii, Yu. V., Zhur. Fiz. Khim. 31, 2317-20 (1957)

Shtekkel, F. A. and Tsin, N. M., Zhur. Khim. Prom. 16, No. 8, 24-38 (1939)

Stotler, H. H. and Benedict, M., Chem. Eng. Progr. Symposium 49. No. 6, 25-36 (1953)

Torocheshnikov, N. S. and Levius, L. A., Zhur. Khim. Prom. 16, No. 1, 19-22 (1939)

Comments:

The values for the liquid-vapor equilibria for the following table and graph are from the experimental measurements reported by Bloomer and Parent and by Cines, Roach, Hogan and Roland. The values used for mole percent nitrogen of 0% and 100% are the vapor pressures for methane reported by Bloomer and Parent and the vapor pressures for nitrogen reported by Bloomer and Rao. The equilibria data from the two sources are for essentially the same range of values. The data from Bloomer and for Parent are for temperatures from -295° to -116.7°F with pressures from 14.7 to 700 psia and the data from Cines, et al. are for temperatures from -280° to -150°F for pressures from 20 to 650 psia.

A comparison of these data sources was made by Bloomer and Parent and the two sets of values reported in excellent agreement except near the critical point. Bloomer and Parent attribute these larger differences in data to difficulties experienced in sampling in the critical region with the recirculation method used by Cines, et al. A further indication of reliability of these data is the estimated accuracy reported by Bloomer and Parent. In their paper they report the following experimental accuracies:

composition measurements, ± 0.05%
high-pressure dew points, ± 2 psi or ± 0.1°F, whichever is larger
high-pressured bubble points, ± 1 psi
low-pressure dew and bubble points, ± 0.1 psi

In construction of the following graph, the two sets of data appear consistent in all but a few isolated cases. The paper by Stotler and Benedict contributes further to the use of this data by reporting an equation of the Benedict-Webb-Rubin form for the vapor-liquid equilibrium data of Cines, et al.

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EQUILIBRIUM CONCENTRATIONS OF NITROGEN – METHANE MIXTURES

Tables of selected values

Values from Bloomer and Parent

Pressure		Temperature, °K															
		Mole Percent Nitrogen															
		0%	6.11 %		10.02 %		28.88 %		50.38 %		69.70 %		84.22 %		95.15 %		100 %*
psia	atm.		Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	
14.7	1.0	111.7	--	--	110.5	93.39	107.7	84.61	103.8	81.28	99.22	79.61	93.72	78.39	---	--	77.39
30	2.0	120.9	--	--	119.5	103.8	116.2	93.28	111.8	89.06	106.4	86.93	100.1	85.28	--	--	84.00
50	3.4	128.7	--	--	127.3	112.7	123.5	100.7	118.3	95.56	112.1	93.00	104.7	91.11	95.72	90.06	89.56
100	6.8	141.3	140.1	131.7	139.3	126.3	134.6	112.9	127.8	105.9	121.1	102.7	112.9	100.7	104.0	99.11	98.44
200	13.6	156.3	154.9	148.1	153.7	143.2	148.1	128.3	139.8	119.6	131.6	115.0	122.7	112.2	113.8	110.1	108.9
300	20.4	166.8	164.7	159.0	163.4	154.7	156.7	139.3	147.7	129.2	138.1	123.6	128.9	120.1	120.2	117.5	116.3
400	27.2	174.8	172.4	167.8	171.1	163.6	163.6	147.9	153.4	136.6	143.3	130.6	133.6	126.4	125.4	123.4	121.9
500	34.0	181.5	178.8	174.9	177.2	171.0	168.9	155.6	157.7	143.8	146.8	136.8	136.9	131.9	129.4	128.5	--
600	40.8	187.2	183.9	181.2	182.1	177.4	172.8	162.8	160.9	150.1	149.0	142.7	--	--	--	--	--
700	47.6	--	--	--	185.5	184.4	175.3	169.6	162.1	157.5	--	--	--	--	--	--	--

* The vapor pressures of Nitrogen (Mole % N_2 = 100), are from Bloomer and Rao

Values from Cines, Roach, Hogan and Roland

Pressure		Mole Percent Nitrogen															
		Temperature, °K															
		99.83°K		110.9°K		122.1°K		126.1°K		133.2°K		144.3°K		155.4°K		172.1°K	
psia	atm.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.
30	2.04	14.4	82.2	4.7	52.4	--	--	--	--	--	--	--	--	--	--	--	--
50	3.4	31.2	89.9	11.5	72.1	3.6	32.4	1.4	16.3	--	--	--	--	--	--	--	--
100	6.8	90.1	98.5	33.8	87.0	14.4	66.8	10.4	56.6	5.0	33.0	--	--	--	--	--	--
200	13.6	--	--	90.2	97.7	43.2	84.6	33.4	79.3	20.5	66.8	8.9	39.5	0.6	4.0	--	--
300	20.4	--	--	--	--	76.3	93.4	61.8	88.8	40.6	78.9	20.6	59.2	8.9	33.4	--	--
400	27.2	--	--	--	--	98.9	99.7	85.4	95.2	62.1	86.0	35.2	69.2	18.5	47.9	1.8	7.9
500	40.8	--	--	--	--	--	--	--	--	82.2	91.2	50.9	75.2	29.5	56.5	8.2	22.6
600	47.6	--	--	--	--	--	--	--	--	--	--	66.8	78.3	41.5	62.0	16.1	31.8

ELECTRICAL RESISTIVITY of METALLIC ELEMENTS at LOW TEMPERATURES

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ELECTRICAL RESISTIVITY of METALLIC ELEMENTS at LOW TEMPERATURES

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PREFACE to the ELECTRICAL RESISTIVITY of METALLIC ELEMENTS

The electrical resistivities of 53 pure, or nearly pure, metallic elements are presented here as a function of temperature for the range from 1 to 300°K. These metallic elements include only those that exhibit an increase in resistivity with increasing temperature. These values of resistivity are presented as ratios, ρ/ρ_{273}, that is, the resistivity divided by the value of the resistivity at 273.15°K. The resistivity may then be determined as a product of the ratio and the value of ρ_{273} listed on the graph sheet for each metal. Each graph is for a separate metal and generally includes the values reported by several investigators. The several sources of data are listed on the data sheet and the individual curves on the graph are referenced by the author's name.

The several data sources used in this compilation reported the values of electrical resistivity in several forms, such as specific resistivity ρ, or values of resistivity ratio, ρ/ρ_T, where the datum temperature T, is not consistent from one reference to another. Often the value of resistivity for the datum temperature used in the resistivity ratio is not available. In this compilation, where the original data are values of resistivity, a common value of ρ_{273} is used in the calculation of the ratio. Where the original data are values of resistivity ratios, the value of ρ_{273} indicated on the graph sheet for calculation of resistivity is either the value of ρ_{273} from the original data in those instances where it was given, or the most probable value of ρ_{273} from another source when it is not available from the original experimenters. Where the original data are resistivity ratios, ρ/ρ_T, and T is not 273°K, a suitable correction has been used to convert the ratio to ρ/ρ_{273}.

Comments on sample purity, accuracy of the tabulated data and other pertinent information reported in the source of data are included in the comments for each data sheet. Some of the references list interpolated values between experimental data points. Where these interpolated values have been used in the construction of the graphs, the interpolated values are also listed in the tables of values and so indicated in a footnote.

The graphs of the electrical resistivity ratios are presented on linear, semi-log or logarithmic coordinates as necessary for satisfactory representation of the data. The use of logarithmic coordinates serves to emphasize the differences in the values reported by the several experimenters at low temperatures. This variation may be attributed primarily to differences in the purity of the sample measured or in some cases to the use of a sample with residual mechanical strains that were not relieved by annealing.

The graphs also serve to illustrate Matthiessen's rule that the increase of resistance in pure metals due to imperfections in the crystal lattice structure is independent of temperature. The resistivity of these nearly pure metals may thus be separated into two independent parts,

$$\rho = \rho_i + \rho_o$$

where ρ_i is the intrinsic resistivity (the electron-lattice interaction) and

PREFACE to the ELECTRICAL RESISTIVITY of METALLIC ELEMENTS (Cont.)

is a function of temperature, and ρ_o is the imperfection resistivity (the electron-imperfection interaction) and is dependent on the type and concentration of the imperfections and is almost independent of temperature. The imperfections are either chemical impurities, isotopes, or mechanical imperfections such as vacancies, dislocations, etc., in the lattice structure. The effect of impurities is then to shift the curve uniformly upward. At very low temperatures ρ_o is much greater than ρ_i so that temperature change has little effect on the resistivity, while at high temperatures ρ_i is much greater than ρ_o, so that the differences in resistivity for various samples becomes relatively insignificant. The graphs on linear coordinates illustrates the above for those metals where alternate data sources are represented in a temperature range where ρ_o is much less than ρ_i and is evidenced by a constant vertical displacement of the data. Several theoretical and empirical equations have been proposed for the ideal resistivity as a function of temperature, but no general law, valid for all conductors, has come forward. The intrinsic electrical resistivity of most simple metals at intermediate temperatures however, may be adequately represented by an empirical equation of the form $\rho_i = aT^b$, where b varies from 4 to 5. This is further indicated on these data sheets, where a straight line may be used on the logarithmic coordinates to represent the data for large intervals of temperature.

When considering the resistivity of the metallic elements at low temperatures, the phenomenon of superconductivity should also be noted. Superconductivity is attributed to the complete absence of resistance to an electric current. Twenty-three metallic elements are presently known to exhibit superconductivity at various temperatures below 12°K.

This graphical presentation of the electrical resistivity of the superconducting elements does not include data in the superconducting temperature range. An exception is the data sheet for lead, where electrical resistivity data extending into the superconducting region appeared in the reference and were included in this compilation. These data below the transition temperature were based on actual observations of electrical resistance in lead in a super critical magnetic field at temperatures which would normally make lead a superconductor.

As in the case of lead, elements in the superconducting state when subjected to an external magnetic field of a given strength, will regain normal resistance to an electric current. The strength of this critical magnetic field depends on the element concerned and temperature. This relationship may be approximated by:

$$H_c = H_o \left[1 - (T/T_c)^2\right]$$

where H_o is the value of the critical magnetic field (in oersteds) at 0°K, T_c is the transition temperature (in °K) and H_c is the value of the critical field at a temperature T. Values for T_c and H_o are given in Table 2.

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PREFACE to the ELECTRICAL RESISTIVITY of METALLIC ELEMENTS (Cont.)

Table 1

Conversion Factors for Electrical Resistivity

ρ	ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm =	1.000	0.3937	6.015×10^{6}
1 ohm-in =	2.540	1.000	1.528×10^{7}
1 ohm-cir mil/ft =	1.662×10^{-7}	6.545×10^{-8}	1.000

Table 2

Transition Temperatures for Superconducting Elements *

Element	Transition Temp., °K	Critical Magnetic Field Ho, Oersteds
Aluminum	1.175	106
Cadmium	0.56 - 0.65	27 - 28.8
Gallium	1.103	47 - 50.3
Hafnium	0.37	
Mercury	4.160	400 - 419
Indium	3.374 - 3.432	269 - 275
Lanthanum	4.8, 5.8	
Niobium	8.7 - 8.9	1960
Osmium	0.71	65
Lead	7.22	800
Rhenium	1.70	188
Rhodium	0.9	
Ruthenium	0.47	46
Tin	3.74	304 - 310
Tantalum	4.38	860
Technetium	11.2	
Thorium	1.388 - 1.40	131
Titanium	0.39	100
Thallium	2.392	171
Uranium	1.1	
Vanadium	4.89	1340
Zinc	0.93	42 - 52.5
Zirconium	0.55	46.6

* American Institute of Physics Handbook, McGraw-Hill Book Co. Inc., New York (1957) Sec. 4, P. 49

ELECTRICAL RESISTIVITY of LITHIUM, Li

(Atomic Number 3)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc. (1929) pp. 124-135

MacDonald, D. K. C.; White, G. K. and Woods, S. B.; Proc. Roy. Soc. (London) A235, 358 (1956)

Other References:

Guntz, A. and Broniewski, W.; Compt. rend. 148, 204 (1909)

Meissner, W.; Z. Physik. 2, 373 (1920)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

MacDonald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London) A202, 103 (1950)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for lithium to be used in calculating values of electrical resistivity is 8.55×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Guntz and Broniewski; Meissner and Voigt; and MacDonald and Mendelssohn; while those values listed by the International Critical Tables are from Meissner. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature. (For the ratios listed with a datum value other than 273°K, ratios were calculated for ρ/ρ_{273}.) The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Guntz and Broniewski ($\rho_{273} = 8.55 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The values of resistivity ratio attributed to MacDonald, White and Woods were calculated by using ρ_{273} from Guntz and Broniewski. The resistivity was determined as the sum of the residual and ideal resistivities, $\rho = \rho_o + \rho_i$ using the values reported in this paper for a specimen of high purity as follows with ρ in ohm-cm. $\rho_o = 0.0372 \times 10^{-6}$, $\rho_i = 4.9 \times 10^{-15} T^5$ for $T < 16$°K.

(Continued on following page.)

ELECTRICAL RESISTIVITY of LITHIUM (Cont.)

Comments: (cont.)

The Landolt-Börnstein tables list the samples used by all three authors as polycrystalline with a very small amount of impurities in the sample used by MacDonald and Mendelssohn. No other pertinent information was given for any of the samples used by any of the other authors.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

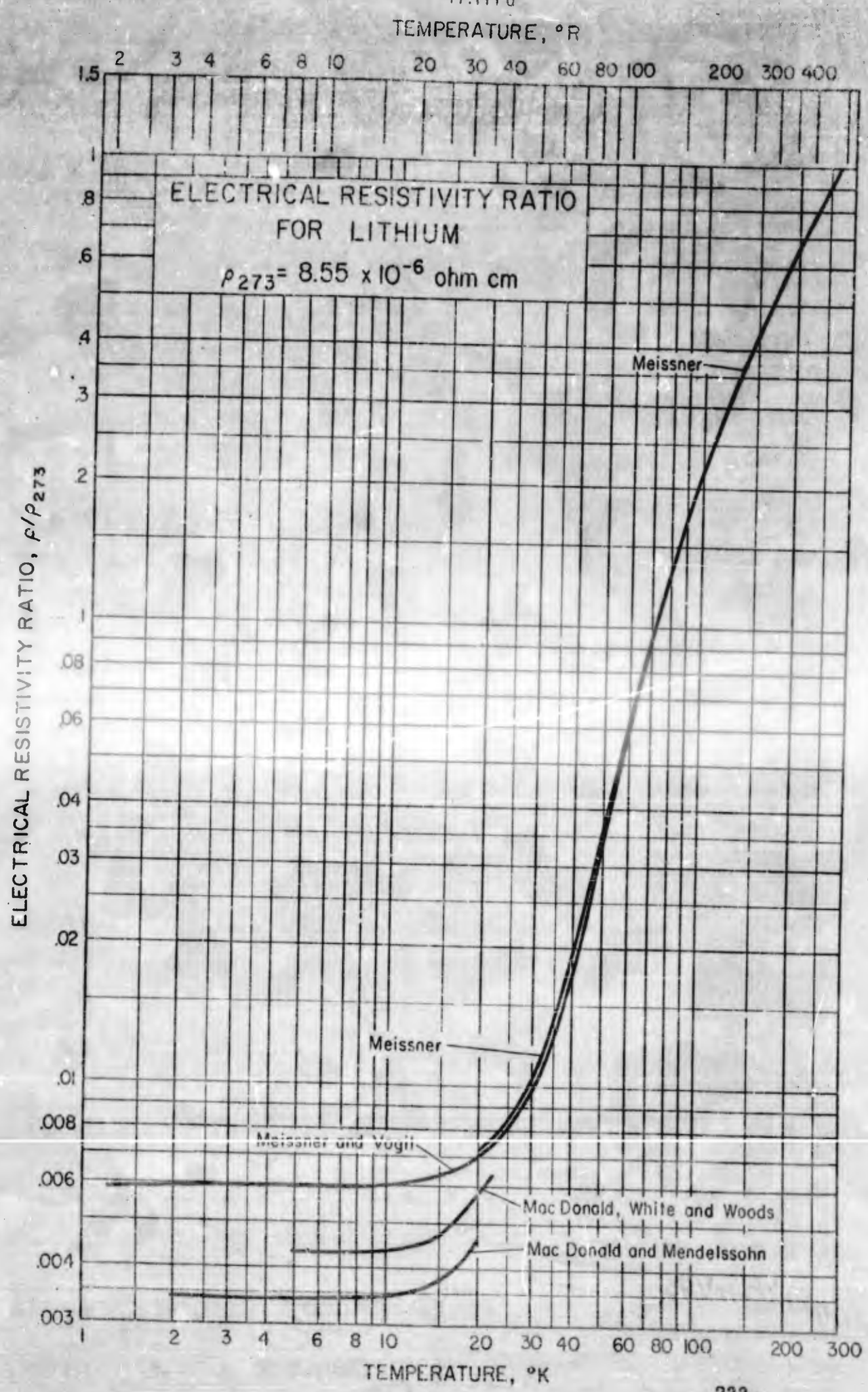
ρ_{290} = Resistivity at 290°K, (ohm-cm)

Meissner and Voigt		MacDonald and Mendelssohn	
Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{290}
1.2	0.0059	2	0.0032
4.2	0.0060	8	0.0032
20.4	0.0071	12	0.0033
77.7	0.1220	16	0.0036
86.3	0.1514	20	0.0043

Meissner			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 80	62.3	- 182.20*	17.37*
- 100	53.0	- 192.95*	13.06*
- 120	44.0	- 200	10.4
- 140	35.2	- 220	4.4
- 160	26.6	- 240	1.2
- 180	18.3	- 252.67*	0.73*

*Actual experimental results. The rest of the Meissner data have been interpolated from the observed values.

RDM/RS Issued: 1/27/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR LITHIUM
ρ_{273} = 8.55 x 10^{-6} ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
Meissner
Meissner
Meissner and Voigt
Mac Donald, White and Woods
Mac Donald and Mendelssohn
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

17.111b

ELECTRICAL RESISTIVITY of SODIUM (Na)
(Atomic Number 11)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Bank, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc. (1929) pp. 124-135

MacDonald, D. K. C., White, G. K. and Woods, S. B.; Proc. Roy. Soc. (London) A235, 358-374 (1956)

Other References:

Justi, E.; Ann. Physik (6) 3, 183 (1948)

MacDonald, D. K. C. and Mendelssohn, K.; Proc. Soc. (London) A202, 103-27 (1950)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Woltjer, H. R. and Onnes, H. K.; Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 173a (1924)

Hackspill, L.; Compt. rend. 151, 305 (1910)

Comments:

Reference should be made to the prefa e at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for sodium to be used in calculating electrical resistivity is 4.28×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by E. Justi; D. K. C. MacDonald and K. Mendelssohn; and W. Meissner and B. Voigt; while those values listed by the International Critical Tables are from H. R. Woltjer and H. K. Onnes. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data reported in the Landolt-Börnstein tables and in the International Critical Tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature, as listed in the following tabular data. (For the ratios listed with a datum value other than at 273°K ratios were calculated for ρ/ρ_{273}.) The actual values of ρ_{273} are not available for the samples used by the several investigators so that a datum value reported by L. Hackspill ($\rho_{273} = 4.28 \times 10^{-6}$) is suggested for calculating values of resistivity from these ratios.

The values of resistivity ratio attributed to D. K. C. MacDonald, G. K. White and S. B. Woods were calculated by using ρ_{273} from L. Hackspill. The resistivity was determined as the sum of the residual and ideal resistivities, $\rho = \rho_o + \rho_i$, using the values reported in this paper for

(Continued on following page.)

ELECTRICAL RESISTIVITY of SODIUM (cont.)

Comments: (cont.)

a specimen of high purity as follows with ρ in ohm-cm, $\rho_o = .001472 \times 10^{-6}$, $\rho_i = 8.6 \times 10^{-15} T^6$ ($4°K < T < 9°K$), $\rho_i = 8.4 \times 10^{-15} T^5$ ($8°K < T < 15°K$).

The Landolt-Börnstein tables list the samples of all three authors as polycrystalline with 0.05% impurities in the sample used by Mac Donald and Mendelssohn and a very small amount of impurity in that used by Justi. No reference is made to the amount of impurity for the samples used by the other experimenters, and no information is available on mechanical strain or heat treatment for any of the samples from any of the sources of data.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

ρ_{290} = Resistivity at 290°K, (ohm-cm)

Justi

Temp. °K	ρ/ρ_{273}
14.0	0.00117
20.4	0.00435
64.0	0.1337
77.6	0.1893

Mac Donald and Mendelssohn

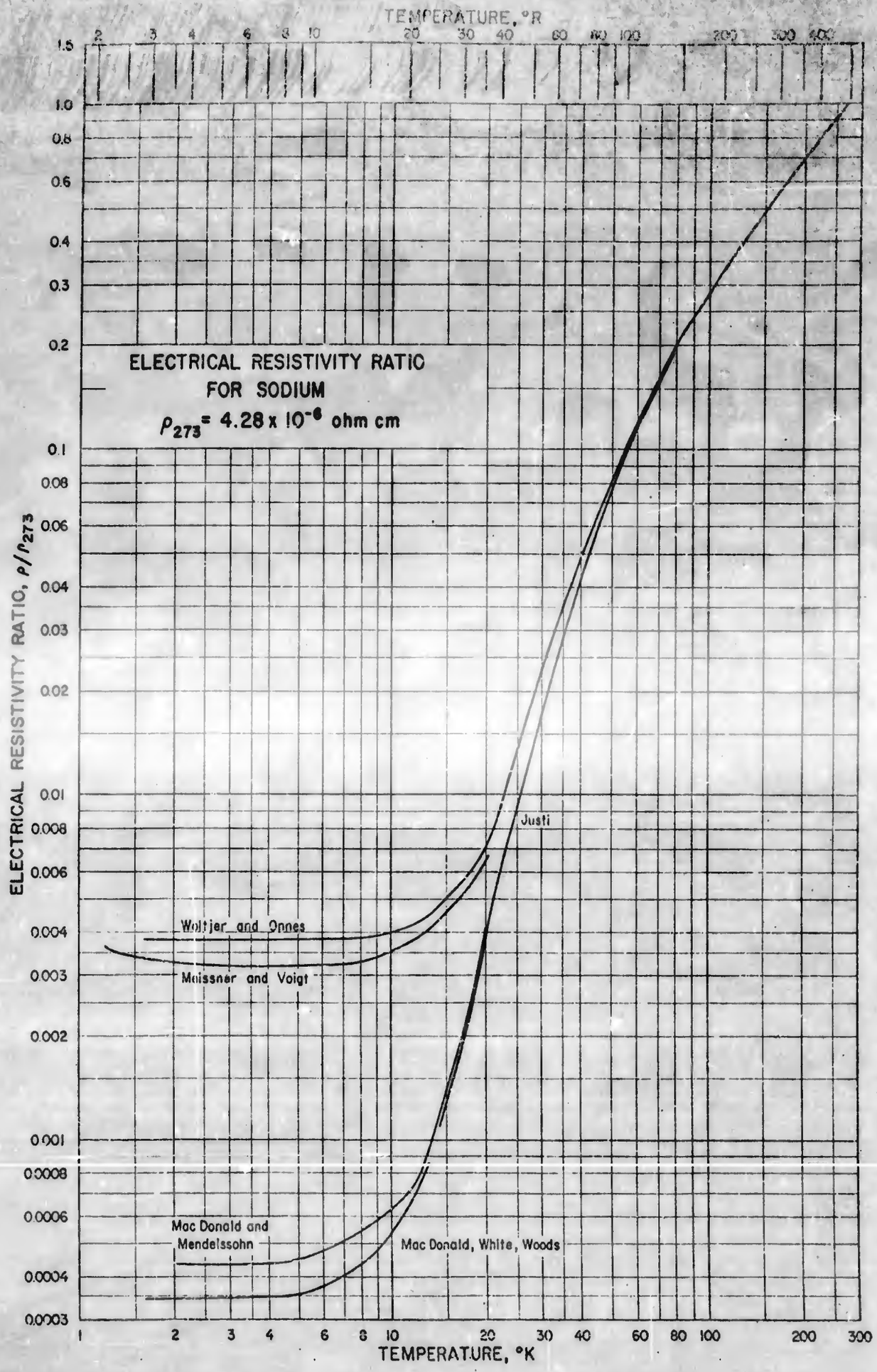
Temp. °K	ρ/ρ_{290}
2	0.0004
4	0.0004
8	0.0005
12	0.0007
16	0.0016
20	0.0038

Meissner & Voigt

Temp. °K	ρ/ρ_{273}
1.2	0.0037
1.3	0.0035
4.2	0.0032
20.4	0.0067
77.6	0.1875
87.8	0.2304

Woltjer & Onnes

Temp. °C	$100\rho/\rho_{273}$
- 80	66.0
-100	57.8
-102.22	56.89
-120	49.7
-140	41.7
-160	33.7
-164.37	31.94
-180	25.7
-182.95	24.40
-200	17.6
-200.96	17.04
-216.32	10.89
-220	9.4
-240	3.1
-260	0.45
-268.9	0.381
-269.6	0.382
-270.9	0.382
-271.6	0.382


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1.0
0.8
0.6
0.4
0.3
0.2
ELECTRICAL RESISTIVITY RATIO
FOR SODIUM
$\rho_{273} = 4.28 \times 10^{-6}$ ohm cm
0.1
0.08
0.06
0.04
0.03
0.02
0.01
0.008
0.006
0.004
0.003
0.002
0.001
0.0008
0.0006
0.0004
0.0003
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
Justi
Woltjer and Onnes
Meissner and Voigt
Mac Donald and Mendelssohn
Mac Donald, White, Woods
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of POTASSIUM, K
(Atomic Number 19)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Mac Donald, D. K. C., White, G. K. and Woods, S. B.; Proc. Roy. Soc. (London), A235, 358-374 (1956)

Other References:

Hackspill, L.; Compt. rend. 151, 305 (1910)

Justi, E.; Ann. Physik (6) 3, 183 (1948)

Mac Donald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London), A202, 103 (1950)

Van den Berg, G. J.; Physica 14, 111 (1948)

Woltjer, H. R. and Onnes, H. K.; Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 173a (1924)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for potassium to be used in calculating values of electrical resistivity (ρ_T) is ρ_{273} = 6.1 x 10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Van den Berg; Hackspill; Justi; and Mac Donald and Mendelssohn. Values reported by Woltjer and Onnes appear in both the Landolt-Börnstein tables and the International Critical Tables. These primary sources are listed under "Other References". The original authors are used in labeling the several curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature. (For the ratios listed with a datum value other than 273°K, ratios were calculated for ρ/ρ_{273}.) The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value

(Continued on following page)

ELECTRICAL RESISTIVITY of POTASSIUM (Cont.)

Comments: (cont.)

reported by Hackspill ($\rho_{273} = 6.1 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The values of electrical resistivity ratio attributed to MacDonald, White and Woods were calculated by using ρ_{273} from Hackspill. The electrical resistivity was determined as the sum of the residual and ideal resistivities, $\rho = \rho_o + \rho_i$, using the values reported in this paper for a specimen of high purity as follows with ρ in ohm-cm, $\rho_o = 0.01331 \times 10^{-6}$, $\rho_i = 2.8 \times 10^{-13}\ T^5$ $(T < 8°K)$.

All of the investigators appearing in Landolt-Börnstein are reported to have used polycrystalline samples. No mention is made of the impurities present in any of the samples with the exception of Justi who reports a very small amount of impurities present. The data reported by Van den Berg are in two groups. Both sets of data were obtained from the same sample. The data in Group I were taken eight days before Group II during which time the sample was stored in liquid air. No other pertinent information was given about any of the samples from any of the investigators.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

ρ_{290} = Resistivity at 290°K, (ohm-cm)

Justi		MacDonald and Mendelssohn	
Temp. °K	ρ/ρ_{273}*	Temp. °K	ρ/ρ_{290}*
0.77	0.0010	2	0.0075
4.22	0.0014	5	0.0077
14.0	0.0074	10	0.0099
20.4	0.0200	15	0.0145
		20	0.0240

*The forth decimal place of the electrical resistivity ratio values is somewhat in doubt.

(Continued on following page)

ELECTRICAL RESISTIVITY of POTASSIUM (Cont.)

Tables of Values of Electrical Resistivity

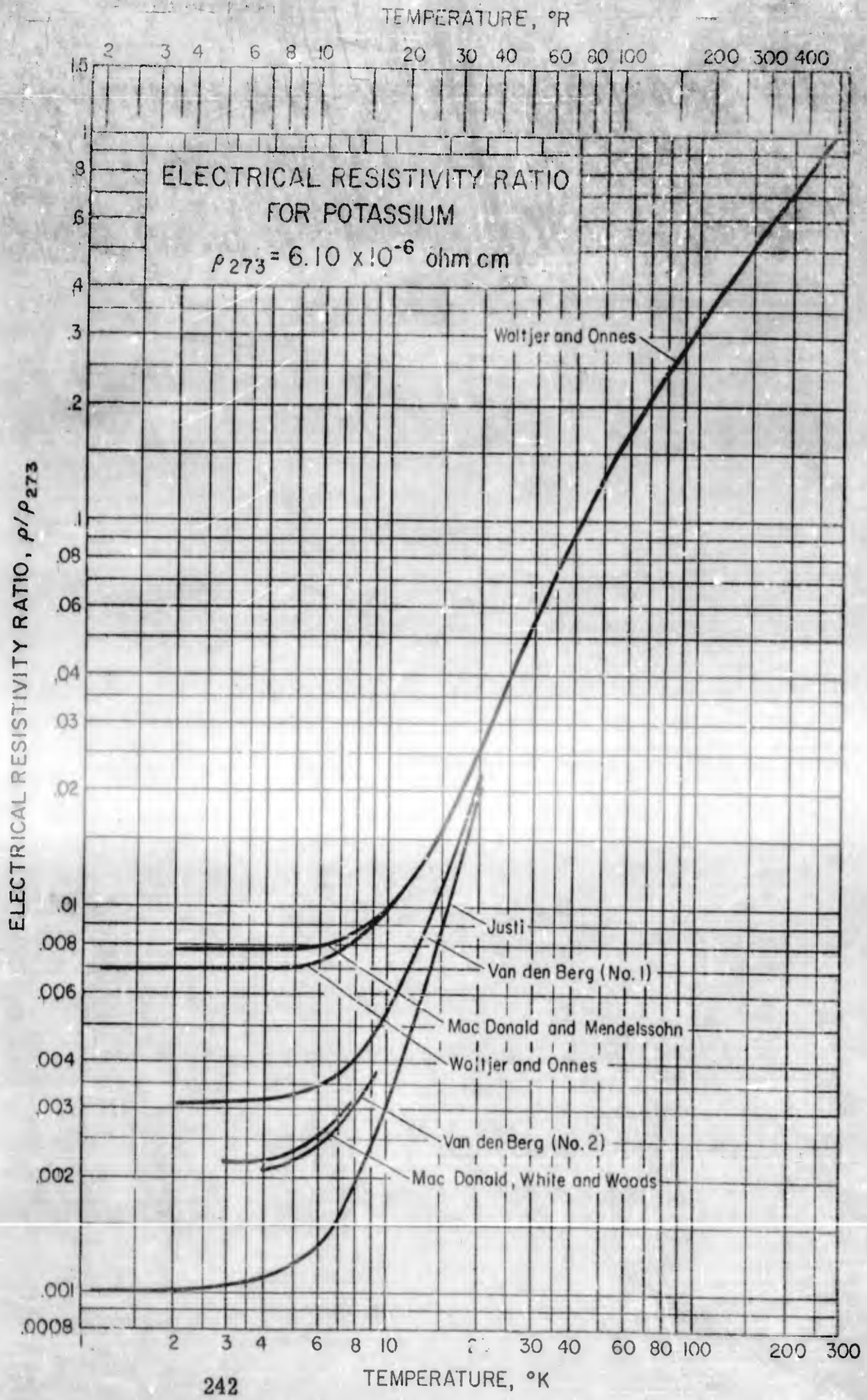
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Van den Berg			
(Group I)		(Group II)	
Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
2.05	0.0031	4.00	0.0021
4.66	0.0032	5.60	0.0023
9.35	0.0049	7.03	0.0027
15.14	0.0112	9.30	0.0037
20.33	0.0222		

Woltjer and Onnes					
(International Critical Tables)				(Landolt-Börnstein)	
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp. °K	ρ/ρ_{273}
- 80*	65.8*	-252.54	2.708	1.2	0.0069
-100*	57.7*	-252.74	2.703	4.2	0.0070
-102.22	56.88	-254.69	2.213	20.4	0.0270
-164.37	33.87	-255.97	1.943	77.6	0.2267
-182.6	27.47	-256.77	1.787	87.8	0.2635
-200.2	21.11	-258.89	1.434		
-200.96	20.70	-258.96	1.429		
-216.32	15.14	-268.9	0.702		
-216.75	15.14	-270.9	0.695		
* Values from interpolation					

RDM/RS Issued: 1/30/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR POTASSIUM
$\rho_{273} = 6.10 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
.0008
Woltjer and Onnes
Justi
Van den Berg (No. 1)
Mac Donald and Mendelssohn
Woltjer and Onnes
Van den Berg (No. 2)
Mac Donald, White and Woods
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of RUBIDIUM, Rb

(Atomic Number 37)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Other References:

Hackspill, L.; Compt. rend. 151, 305 (1910)

Justi, E.; Ann. Physik. (6) 3, 183 (1948)

Kurnakow, N. and Nikitinski, A. J.; Z. anorg. allgem. Chem. 88, 151 (1914)

MacDonald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London) A202, 103 (1950)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for rubidium to be used in calculating values of electrical resistivity (ρ_T) is listed below the authors' names labeling each individual curve on the graph.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Justi; Kurnakow and Nikitinski; MacDonald and Mendelssohn; and Meissner and Voigt; while those values listed by the International Critical Tables are from Hackspill. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data in the Landolt-Bornstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature. (For ratios listed with a datum value other than at 273°K, ratios were calculated for ρ/ρ_{273}.) The value of ρ_{273} reported by Hackspill and suggested here for calculating values of electrical resistivity from the Hackspill data is $\rho_{273} = 11.6 \times 10^{-6}$ ohm-cm. The actual values of ρ_{273} are not available for the samples used by the other investigators so a datum value reported by Kurnakow and Nikitinski ($\rho_{273} = 11.29 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from the remaining ratios.

The Landolt-Börnstein tables report the samples of all the investigators are considered as polycrystalline with a small amount of impurities of unknown compositon. No other pertinent information is reported for any of the samples from any of the sources of data.

(Continued on following page.)

ELECTRICAL RESISTIVITY of RUBIDIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

ρ_{290} = Resistivity at 290°K, (ohm-cm)

Meissner and Voigt		Justi		MacDonald and Mendelssohn	
Temp.* °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{290}**
1.25	0.0380	0.88	0.0124	2	0.0311
4.20	0.0391	4.22	0.0133	5	0.0325
20.4	0.0817	14.0	0.0339	10	0.0387
77.6	0.2701	20.4	0.0554	15	0.0487
87.8	0.3043			20	0.0628

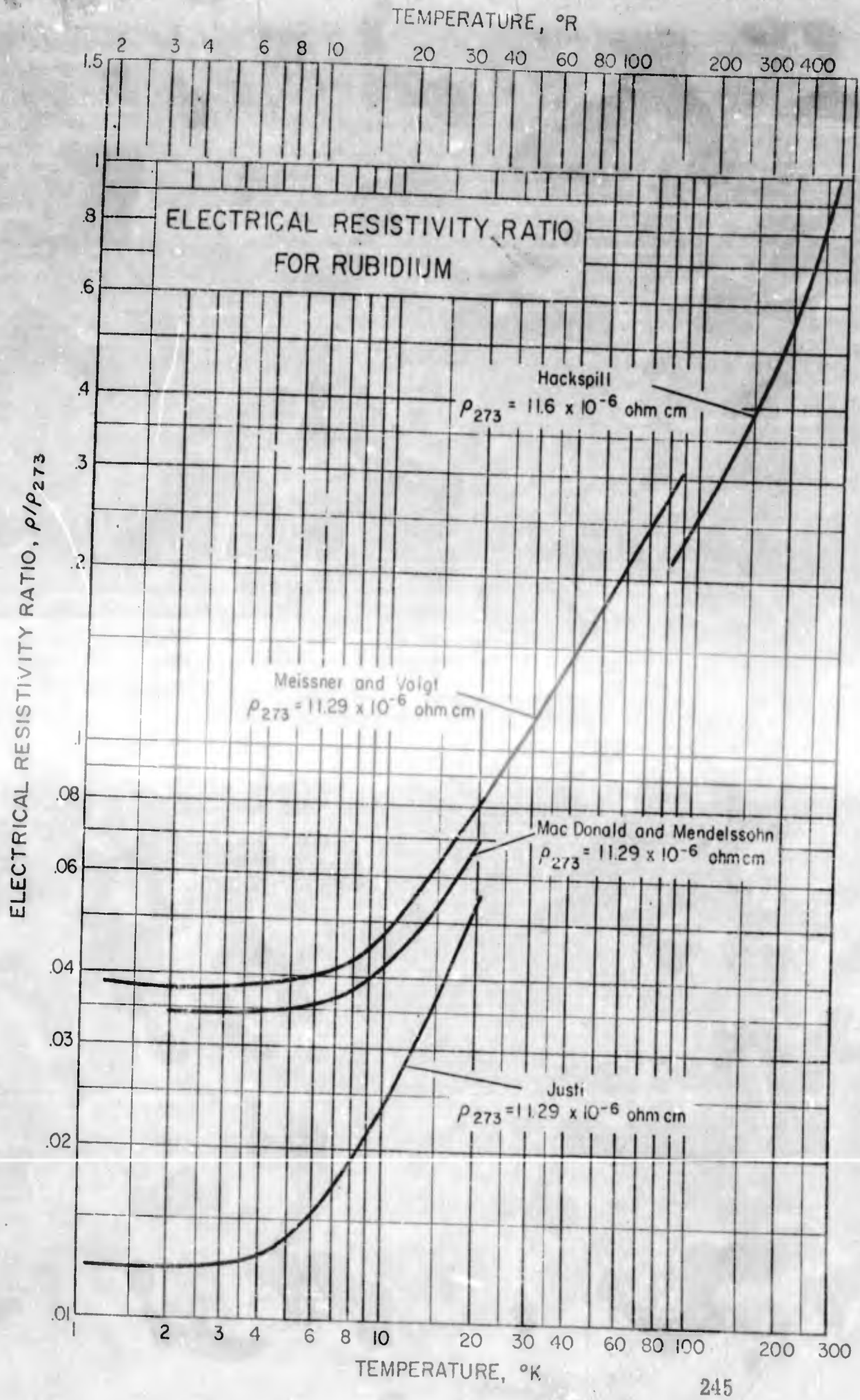
* The second decimal place of the temperature values is somewhat in doubt.

** The fourth decimal place of the values of the electrical resistivity ratios is somewhat in doubt.

Hackspill			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78*	54.3*	-140	34.2
- 80	53.5	-160	28.8
-100	46.3	-180	23.8
-120	39.9	-190*	21.6*

*Observed values. Other values have been interpolated.

RDM/RS Issued: 2/10/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
ELECTRICAL RESISTIVITY RATIO FOR RUBIDIUM
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
Hackspill
ρ_{273} = 11.6 x 10^{-6} ohm cm
Meissner and Voigt
ρ_{273} = 11.29 x 10^{-6} ohm cm
Mac Donald and Mendelssohn
ρ_{273} = 11.29 x 10^{-6} ohm cm
Justi
ρ_{273} = 11.29 x 10^{-6} ohm cm
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of CESIUM, Cs

(Atomic Number 55)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Other References:

Hackspill, L.; Compt. rend. 151, 305 (1910)

Justi, E.; Ann. Physik (6) 3, 183 (1948)

MacDonald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London) A202, 523 (1950)

McLennan, J. C., Niven, C. D. and Wilhelm, J. O.; Phil. Mag. 6, 672 (1928)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930).

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for cesium to be used in calculating values of electrical resistivity (ρ_T) is listed below the authors' names labeling each individual curve on the graph.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Justi; MacDonald and Mendelssohn; McLennan, Niven and Wilhelm; and Meissner and Voigt; while those values listed by the International Critical Tables are from Hackspill. These primary sources are listed under "Other References". The original authors are used in labeling the several curves on the graph.

The data reported in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature. (For the ratios listed with a datum value other than at 273°K, ratios were calculated for ρ/ρ_{273}.) The actual values of ρ_{273} are not available for Meissner and Voigt; Justi; MacDonald and Mendelssohn, so a datum value reported by Hackspill ($\rho_{273} = 18.1 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios. The actual values of ρ_{273} for Hackspill and for McLennan, Niven and Wilhelm are available ($\rho_{273} = 18.1 \times 10^{-6}$ ohm-cm and $\rho_{273} = 19.0 \times 10^{-6}$ ohm-cm) respectively. These values are suggested for calculating values of electrical resistivity from the ratios attributed to the respective authors.

(Continued on following page.)

ELECTRICAL RESISTIVITY of CESIUM (Cont.)

Comments: (cont.)

The Landolt-Börnstein tables list the samples used in all five citations as polycrystalline. The samples used by Hackspill is reported to have a small amount of impurities present and the sample used by MacDonald and Mendelssohn is reported to have less than 0.001% impurities present. No information was given on the mechanical or heat treatment for any of the samples from any of the sources of data.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

ρ_{290} = Resistivity at 290°K, (ohm-cm)

McLennan, Niven and Wilhelm		Meissner and Voigt		Justi		MacDonald and Mendelssohn	
Temp. °K	ρ/ρ_{273}*	Temp.** °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{290}
2.2	0.017	1.15	0.0395	4.22	0.0196	2	0.017
4.2	0.0189	1.43	0.0399	14.0	0.0504	5	0.027
20.6	0.0674	4.21	0.0427	20.4	0.0746	10	0.065
82.0	0.265	20.4	0.1318			14	0.103
		77.6	0.2982				
		87.8	0.3310				

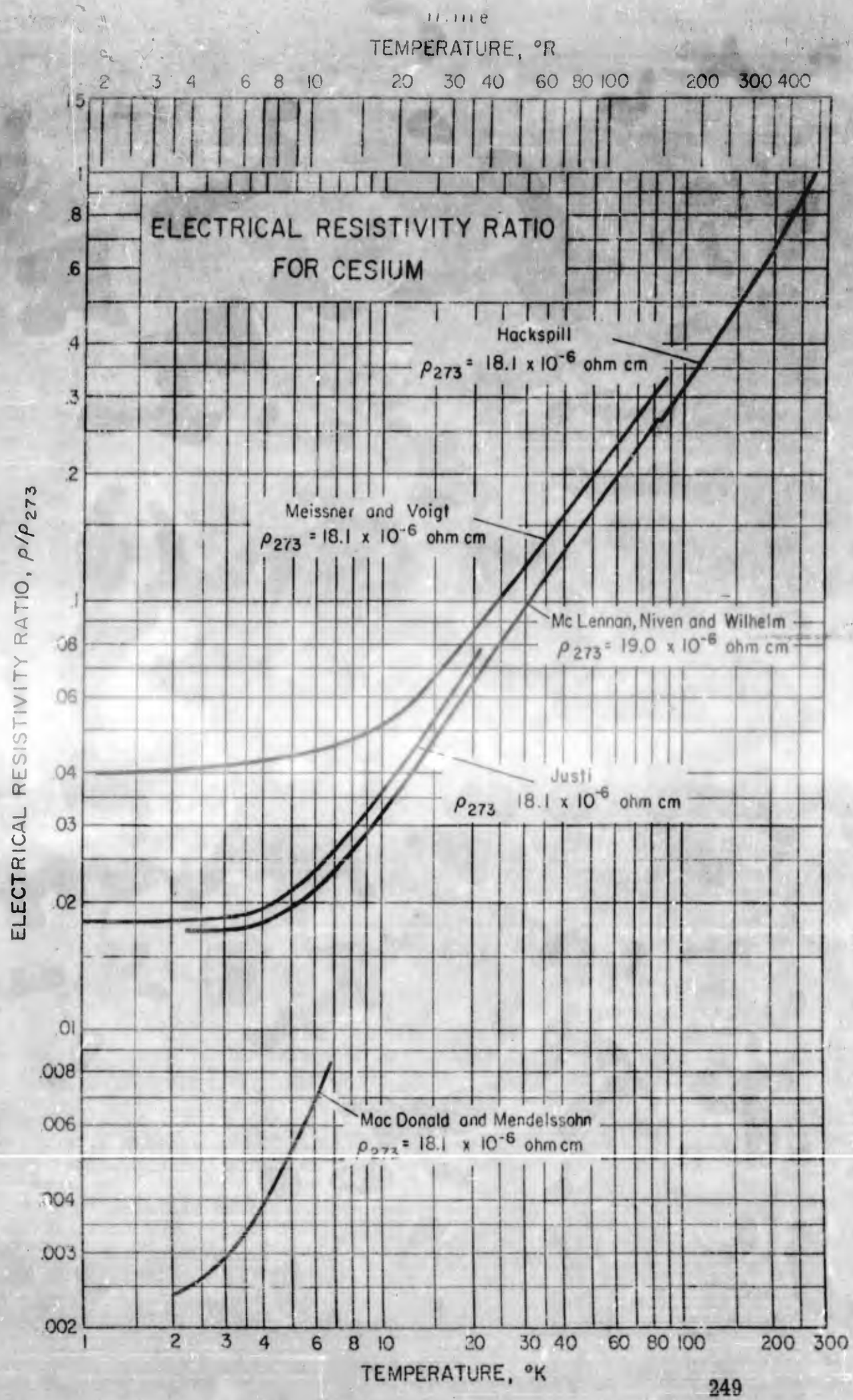
* The fourth decimal place of the electrical resistivity ratio values is somewhat in doubt.

** The second decimal place of the temperature values is somewhat in doubt.

Hackspill			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 75*	65.9*	-140	41.9
- 80	63.9	-160	35.6
-100	56.0	-180	29.5
-120	48.6	-190*	26.4*

*Observed values. Values without asterisks have been interpolated.

RDM/RS Issued: 2/13/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR CESIUM
Hackspill
ρ_{273} = 18.1 x 10^{-6} ohm cm
Meissner and Voigt
ρ_{273} = 18.1 x 10^{-6} ohm cm
Mc Lennan, Niven and Wilhelm
ρ_{273} = 19.0 x 10^{-6} ohm cm
Justi
ρ_{273} 18.1 x 10^{-6} ohm cm
Mac Donald and Mendelssohn
ρ_{273} = 18.1 x 10^{-6} ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of COPPER, Cu

(Atomic Number 29)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, Vol. 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

de Haas, W. J. de Boer, J. H. and Van den Berg, G. J.; Physica II, 1115 (1934)

Henning, F.; Z. Physik. 5, 264 (1921)

Holborn, L.; Ann. Physik 59, 145 (1919)

Meissner, W.; Ann. Physik (4) 47, 1001 (1915)

Meissner, W.; Physik. Z. 29, 897 (1928)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for copper to be used in calculating values of electrical resistivity (ρ_T) is 1.55×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by de Haas, de Boer and Van den Berg; Holborn; and Meissner; while those values appearing in the International Critical Tables are from Henning. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the original investigators are not available so a datum value determined by Meissner in 1915 ($\rho_{273} = 1.55 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables report the samples used by the authors appearing in their compilation as annealed polycrystalline specimens with a small amount of impurities present. No other pertinent information is given about any of the samples in any of the sources of data.

(Continued on following page.)

ELECTRICAL RESISTIVITY of COPPER (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

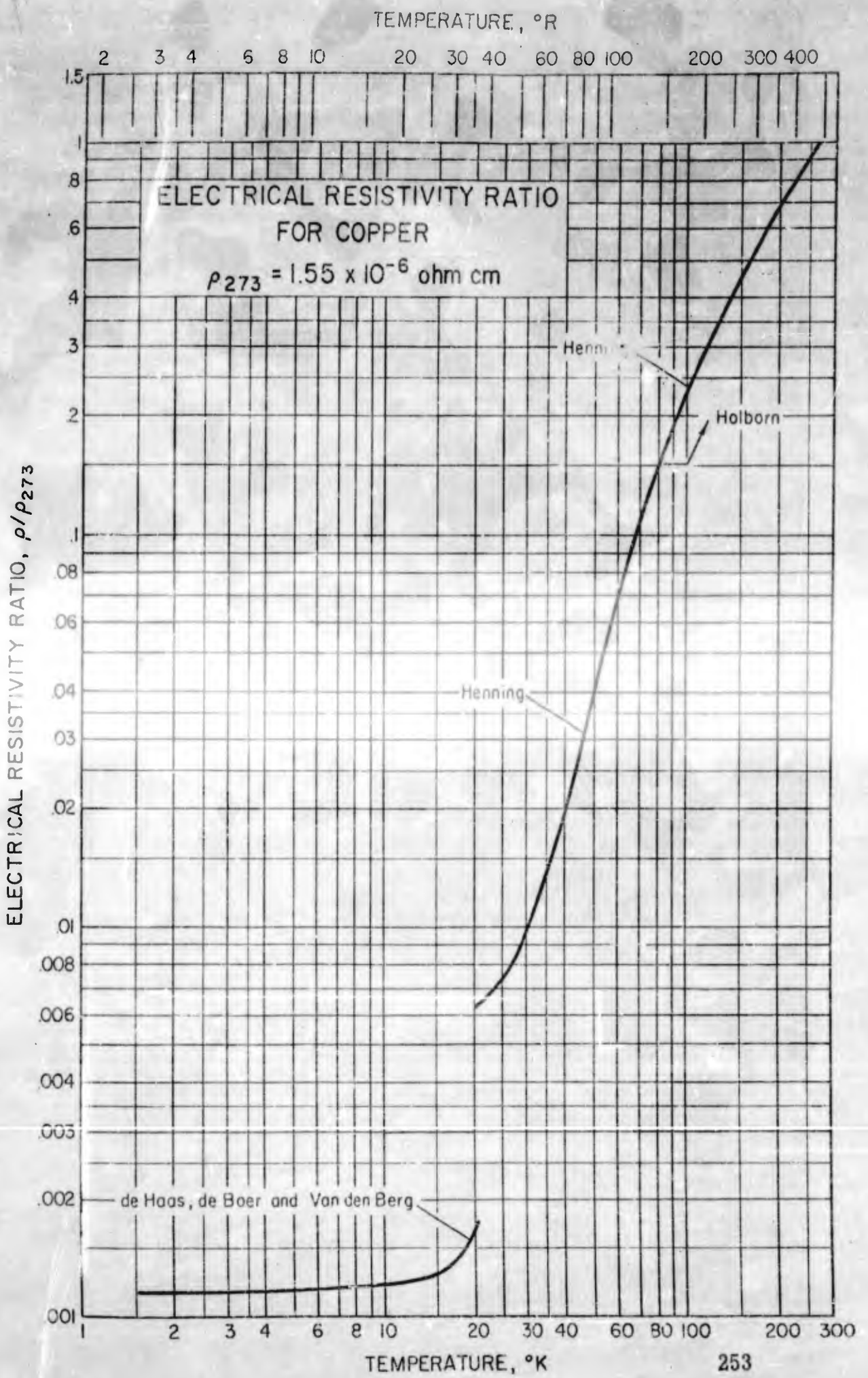
de Haas, de Boer and Van den Berg		Henning	
Temp. °K	ρ/ρ_{273}	Temp. °C	$100\rho/\rho_{273}$
1.55	0.00117	- 76	65.739
4.23	0.00119	-183	18.868
14.26	0.00128	-252.8	0.6291
20.47	0.00176		

Holborn		Meissner	
Temp. °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}**
81	0.1502	1.32	0.00029
195	0.6602	1.97	0.00028
		4.20	0.00029
		20.42	0.00078
		81.6	0.144

* The second decimal place of the temperature values is somewhat in doubt.

**The fifth decimal place of the electrical resistivity ratio values is somewhat in doubt.

RDM/RS Issued: 2/7/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR COPPER
$\rho_{273} = 1.55 \times 10^{-6}$ ohm cm
Henning
Holborn
Henning
de Haas, de Boer and Van den Berg
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of SILVER, Ag

(Atomic Number 47)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Dewar, J. and Fleming, J. A.; Phil. Mag. J. Sci. (5) 36, 271 (1893)

Holborn, L.; Ann. Physik 59, 145 (1919)

de Haas, W. J. and Van den Berg, G. J.; Physica 3, 440 (1936)

Meissner, W.; Physik. Z. 27, 725 (1926)

Onnes, K. H. and Clay, J. Proc. Acad. Sci. Amsterdam 10, 207 (1908)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for silver to be used in calculating values of electrical resistivity is 1.47×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Dewar and Fleming; Holborn; de Haas and Van den Berg; and Meissner; while those values appearing in the International Critical Tables are from Onnes and Clay. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Dewar and Fleming ($\rho_{273} = 1.47 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The samples used by the investigators appearing in Landolt-Börnstein are all reported as polycrystalline with a small amount of impurities present. The samples used by Holborn; and de Haas and Van den Berg were annealed. The sample used by Meissner was aged. No other pertinent information was listed for any of the samples in any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of SILVER (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Onnes and Clay					
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 80 +	67.8	-140 +	43.2	-204.67	15.528
-100 +	59.6	-160 +	34.8	-220 +	9.2
-103.81	58.087	-180 +	26.3	-240 +	2.6
-120 +	51.4	-183.57	24.679	-252.92	0.8913
-139.87	43.282	-195.17	19.703	-259.22	0.6942
		-200 +	17.6		

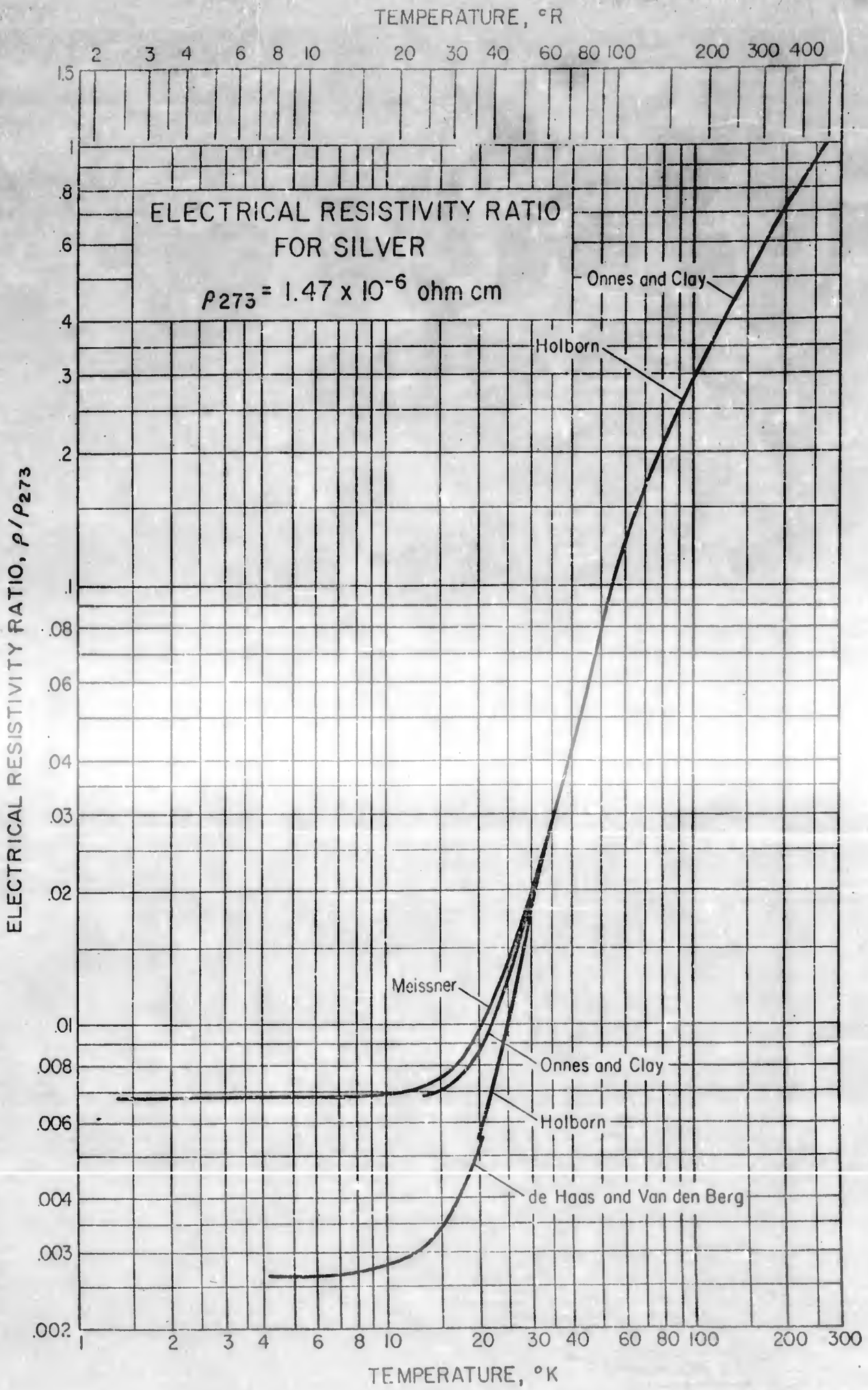
Holborn		Meissner		de Haas and Van den Berg	
Temp. °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}**	Temp. °K	ρ/ρ_{273}
20	0.0054	1.34	0.00679	4.2	0.00266
81	0.2071	4.21	0.00682	6.0	0.00268
195	0.6841	20.4	0.01000	8.4	0.00274
		78.8	0.1974	10.8	0.00288
		87.4	0.2349	20.4	0.00543

* The second decimal place of the temperature values is somewhat in doubt.

** The fifth decimal place of the electrical resistivity ratio values is somewhat in doubt.

\+ Values from interpolation.

RDM/RS Issued: 2/6/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
ELECTRICAL RESISTIVITY RATIO
FOR SILVER
$\rho_{273} = 1.47 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
Onnes and Clay
Holborn
Meissner
Onnes and Clay
Holborn
de Haas and Van den Berg
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of GOLD, Au

(Atomic Number 79)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Cath, P. G., Onnes, H. K. and Burgers, W. G.; Proc. Acad. Sci. Amsterdam 20, 1163 (1918)

Holborn, L.; Ann. Physik 59, 145 (1919)

Justi, E.; Physik. Z. 41, 486 (1940)

Meissner, W.; Ann. Physik (4) 47, 1001 (1915)

Meissner, W.; Physik. Z. 27, 725 (1926)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for gold to be used in calculating values of electrical resistivity (ρ_T) is 2.06×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Holborn; Justi; and Meissner; while the values appearing in the International Critical Tables are those from Cath, Onnes and Burgers. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Meissner in 1915 ($\rho_{273} = 2.06 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables report the samples used by Meissner are polycrystalline with less than 0.001% impurities present. The sample used by Meissner in the 1915 reference was a cast sample; while the sample he used in the 1926 reference was aged. The samples used by Holborn and Justi are reported as annealed polycrystalline with a small amount of impurities present. No other pertinent information is given about any of the samples in any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of GOLD (Cont.)

Tables of Values of Electrical Resistivity

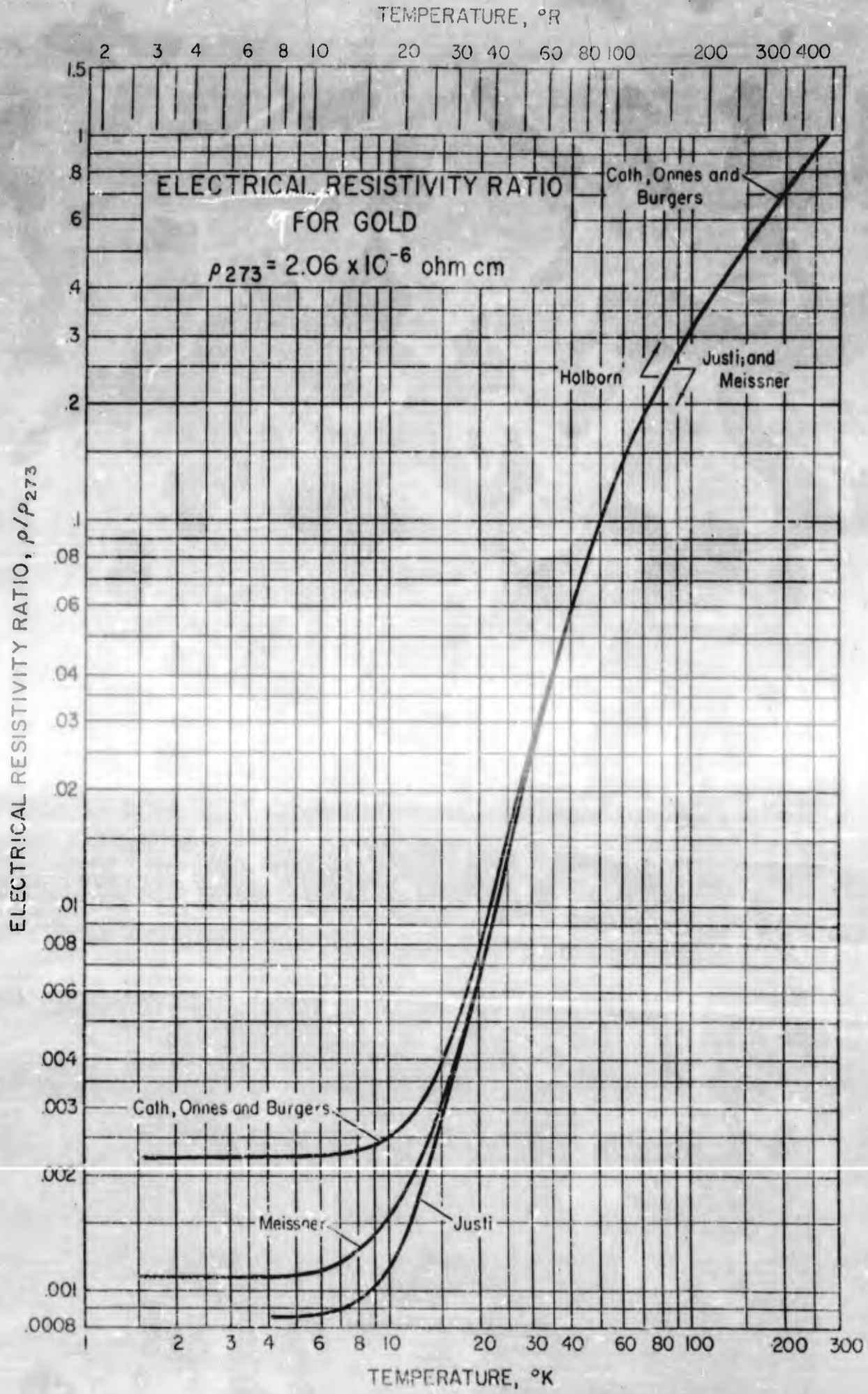
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Cath, Onnes and Burgers					
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 84.97	66.443	-208.18	16.365	-243.68	2.553
-102.22	59.628	-216.26	12.906	-245.80	2.039
-130.28	48.507	-222.78	10.130	-252.57	0.845
-145.86	42.273	-228.73	7.680	-255.01	0.594
-164.37	34.764	-233.62	5.804	-258.35	0.379
-183.95	26.660	-236.62	4.667	-268.88	0.223
-195.88	21.622	-240.25	3.538	-269.57	0.223
-205.31	17.596			-271.61	0.223

Holborn		Meissner		Justi	
Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
81	0.2375	1.6	0.00109	4.2	0.00085
195	0.6995	4.2	0.00109	14.0	0.00227
		20.4	0.00707	20.4	0.00709
		81.7	0.2341	79	0.219
		84.9	0.2480		

RDM/RS Issued: 2/9/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
.0008
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
ELECTRICAL RESISTIVITY RATIO FOR GOLD
$\rho_{273} = 2.06 \times 10^{-6}$ ohm cm
Cath, Onnes and Burgers
Holborn
Justi and Meissner
Cath, Onnes and Burgers
Meissner
Justi
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISITIVITY of BERYLLIUM, Be

(Atomic Number 4)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Lewis, E. J.; Phys. Rev. 34, 1575 (1929)

Mac Donald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London) A202, 523 (1950)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930).

Powell, R. W.; Phil. Mag. 44, 645 (1953)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for beryllium to be used in calculating values of electrical resistivity (ρ_T) is 3.2×10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from Landolt-Börnstein tables are those reported by the authors listed above under "Other References". The original authors are used in labeling the three curves on the graph.

The data reported in Landolt-Börnstein and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of ρ_{273} is not available for the several authors' data appearing on the graph so a datum value reported by R. W. Powell ($\rho_{273} = 3.2 \times 10^{-6}$ ohm-cm) is suggested for calculating values of resistivity from these ratios. Powell reports 0.4% impurities of unknown composition in the polycrystalline sample used in determining ρ_{273}.

The Landolt-Börnstein tables list the samples used by all of the authors as being of the polycrystalline type. No mention of impurities is made for the samples used by MacDonald and Mendelssohn; and Lewis. The sample used by Meissner and Voigt is reported to have had 2% Fe and 0.5% Bi impurities present. No mention is made of the mechanical or heat treatment of any of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY of BERYLLIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Lewis	
Temp. °K	ρ/ρ_{273}
84.2	0.273
196.2	0.586
294.2	1.174

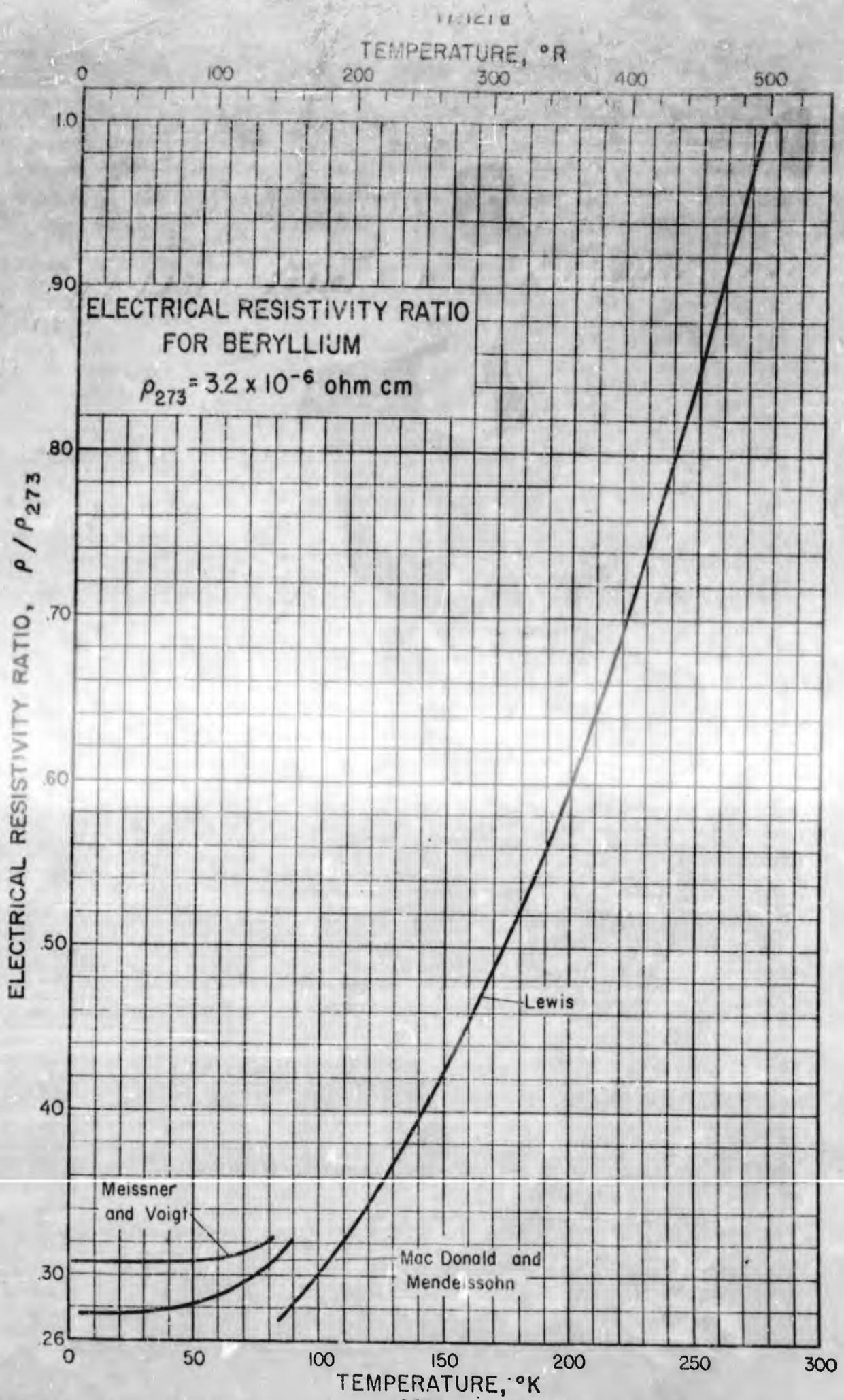
MacDonald and Mendelssohn	
Temp. °K	ρ/ρ_{290} *
4.2	0.276
20.4	0.276
90.0	0.322

Meissner and Voigt	
Temp.** °K	ρ/ρ_{273}
1.35	0.3077
2.38	0.3075
4.22	0.3075
20.44	0.3075
81.7	0.3229

* The third decimal place of the resistivity values is somewhat in doubt.

** The second decimal place of the temperature values is somewhat in doubt.

RDM/RS Issued: 11/9/60


TEMPERATURE, °R
0
100
200
300
400
500
1.0
.90
.80
.70
.60
.50
40
.30
.26
ELECTRICAL RESISTIVITY RATIO FOR BERYLLIUM
$\rho_{273} = 3.2 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ / ρ_{273}
Lewis
Meissner and Voigt
Mac Donald and Mendelssohn
0
50
100
150
200
250
300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of MAGNESIUM, Mg
(Atomic Number 12)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Other References:

Dewar, J. and Fleming, J. A.; Phil. Mag. (5) 36, 271 (1893)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Niccolai, G.; Physik. Z. 9, 367 (1908)

Rosenberg, H. M.; Phil. Mag. 45, 73 (1954)

Yntema, G. B.; Phys. Rev. 91, 1388 (1953)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for magnesium to be used in calculating values of electrical resistivity (ρ_T) is 4.31×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; Niccolai; Rosenberg; and Yntema; while those values listed by the International Critical Tables are from Dewar and Fleming. Those primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The data reported in the Landolt-Börnstein tables, the International Critical Tables, and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Niccolai ($\rho_{273} = 4.31 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The sample used by Meissner and Voigt is reported by Landolt-Börnstein as polycrystalline and annealed in a vacuum at 250°C. The sample used by Yntema was of a polycrystalline nature with less than 0.02% impurities present. The Yntema sample was also annealed but no mention is made of conditions. The samples used by Rosenberg and Niccolai are reported as polycrystalline with very few impurities present. No other pertinent information was given about any of the samples used by any of the authors.

(Continued on following page.)

ELECTRICAL RESISTIVITY of MAGNESIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K (ohm-cm)

Meissner and Voigt		Rosenberg	
Temp.* °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}**
1.27	0.0329	2.5	0.00630
3.16	0.0326	5	0.00623
4.20	0.0323	10	0.00632
20.46	0.0344	15	0.0068
77.6	0.1576	25	0.0096
88.2	0.2006		

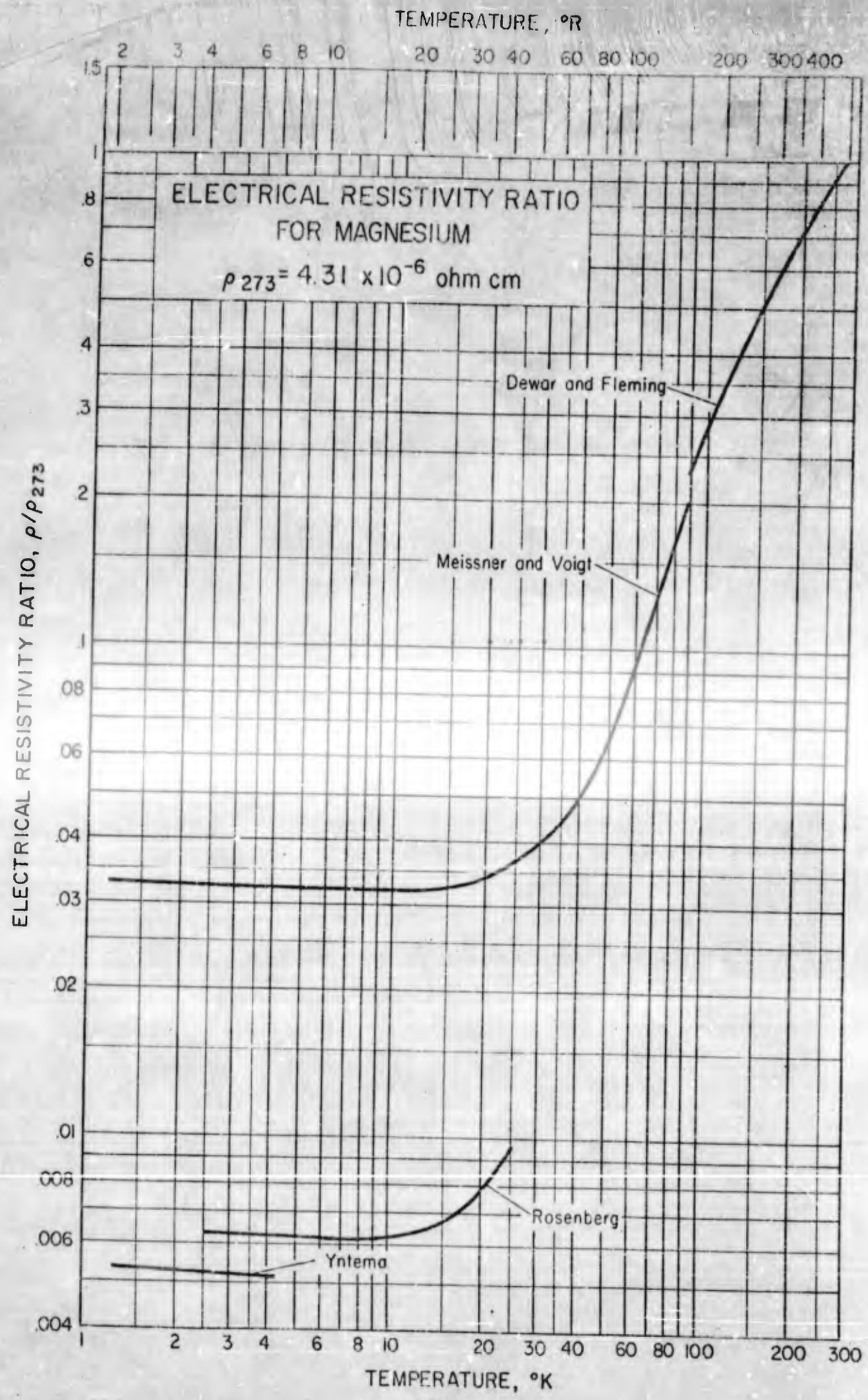
* The second decimal place is in doubt.

** The fifth decimal place is in doubt.

Yntema		Dewar and Fleming	
Temp. °K	ρ/ρ_{273}	Temp. °C	$100\rho/\rho_{273}$
1.30	0.00537	- 78.3*	68.2*
4.21	0.00516	- 80	67.4
		-100	59.0
		-120	50.5
		-140	41.9
		-160	33.2
		-180	24.4
		-182.9*	23.0*

* Results of actual observations.
All other values from interpolations.

RDM/RS Issued: 1/26/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR MAGNESIUM
$\rho_{273} = 4.31 \times 10^{-6}$ ohm cm
Dewar and Fleming
Meissner and Voigt
Rosenberg
Yntema
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of CALCIUM, Ca

(Atomic Number 20)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

MacDonald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London) A202, 523 (1950)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Rinck, E.; Compt. rend. 192, 421 (1931)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for calcium to be used in calculating values of electrical resistivity (ρ_T) is 4.06×10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from Landolt-Börnstein are those reported by the authors listed above under "Other References". The original authors are used in labeling the two curves on the graph.

The data reported in Landolt-Börnstein are ratios of electrical resistivity at a datum temperature, as shown in the following tabular data. (For the ratios listed with a datum value other than 273°K ratios were calculated for ρ/ρ_{273}.) The actual values of ρ_{273} are not available for the samples used by the investigators whose data appear on the graph so a datum value reported by Rinck ($\rho_{273} = 4.06 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios. Rinck reports a small amount of impurity present in the polycrystalline sample used in determining ρ_{273}.

The Landolt-Börnstein tables reports the sample used by MacDonald and Mendelssohn as polycrystalline with no mention of impurities made. The sample used by Meissner and Voigt is reported as polycrystalline with a small amount of impurities of unknown composition present. No mention is made of the mechanical or heat treatment of any of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY of CALCIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

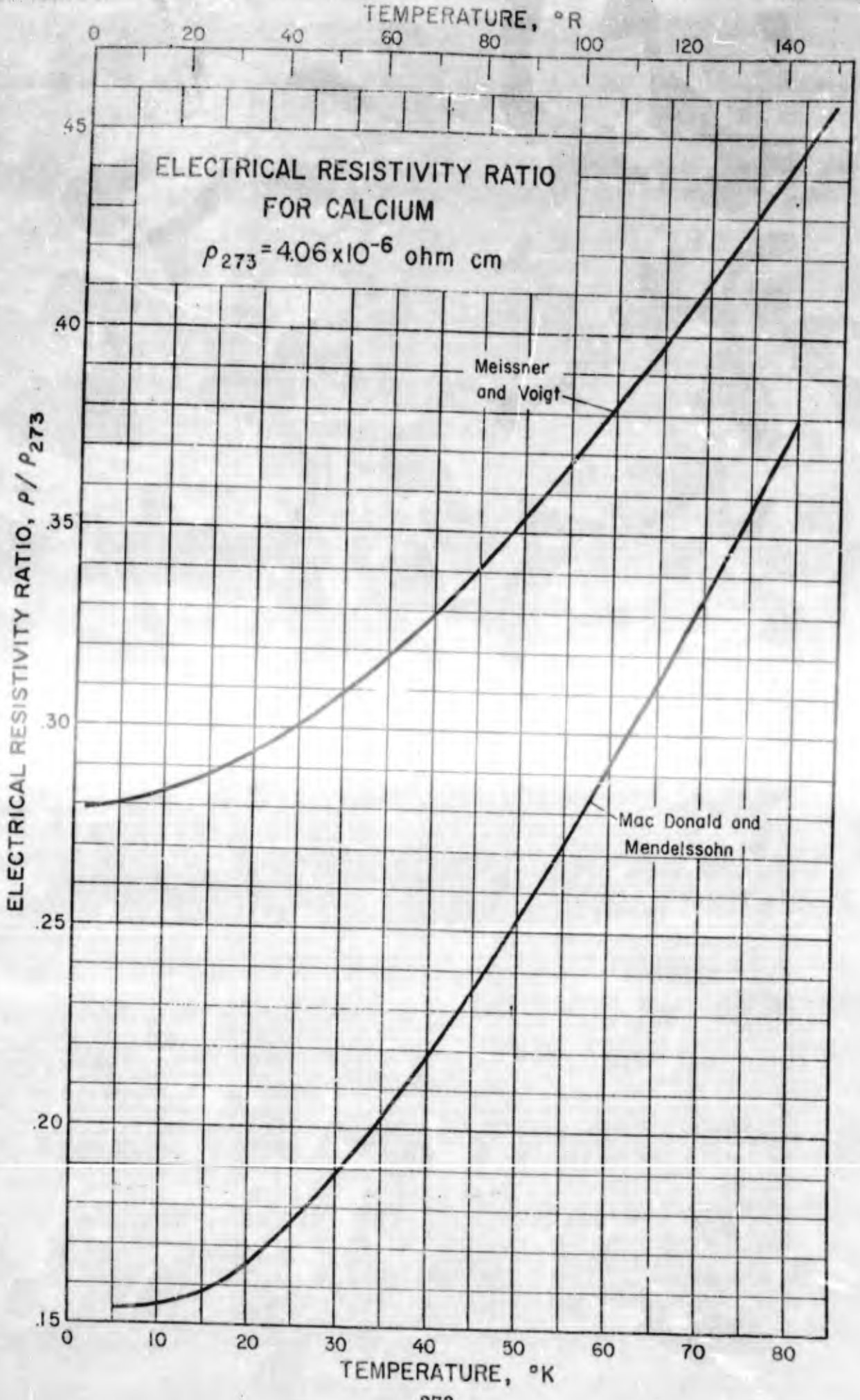
ρ_{273} = Resistivity at 273°K, (ohm-cm)

ρ_{290} = Resistivity at 290°K, (ohm-cm)

MacDonald and Mendelssohn	
Temp. °K	ρ/ρ_{290}
5	0.143
10	0.144
20	0.155
40	0.205
60	0.275
80	0.355

Meissner and Voigt	
Temp. °K	ρ/ρ_{273}
1.3	0.2792
4.2	0.2807
20.4	0.3536
77.7	0.4398
83.6	0.4582

RDM/RS Issued: 11/8/60


TEMPERATURE, °R
0
20
40
60
80
100
120
140
ELECTRICAL RESISTIVITY RATIO
FOR CALCIUM
$\rho_{273} = 4.06 \times 10^{-6}$ ohm cm
Meissner
and Voigt
Mac Donald and
Mendelssohn
ELECTRICAL RESISTIVITY RATIO, ρ / ρ_{273}
.45
.40
.35
.30
.25
.20
.15
0
10
20
30
40
50
60
70
80
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of STRONTIUM, Sr

(Atomic Number 38)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Bridgman, P. W.; Proc. Am. Acad. Arts Sci. 56, 61 (1921)

MacDonald, D. K. C. and Mendelssohn, K.; Proc. Roy. Soc. (London) A202, 523 (1950)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for strontium to be used in calculating values of electrical resistivity (ρ_T) is 30.7 x 10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from Landolt-Börnstein tables are those reported by the author listed above under "Other References". The original authors are used in labeling the two curves on the graph.

The data reported in Landolt-Börnstein are ratios of electrical resistivity with respect to the resistivity at a datum temperature, as shown in the following tabular data. (For the ratios listed with a datum value other than at 273°K ratios were calculated for ρ/ρ_{273}.) The actual values of ρ_{273} are not available for the samples used by the investigators whose data appear on the graph so a datum value reported by Bridgman (ρ_{273} = 30.7 x 10^{-6} ohm-cm) is suggested for calculating values of electrical resistivity from these ratios. Bridgman reports a very small amount of impurity present in the sample used in determining ρ_{273}.

The Landolt-Börnstein tables report the sample used by MacDonald and Mendelssohn as polycrystalline with no mention of impurities made. The sample used by Meissner and Voigt is reported as polycrystalline with less than 0.1% Fe impurities present. No mention of mechanical or heat treatment is made for any of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY of STRONTIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

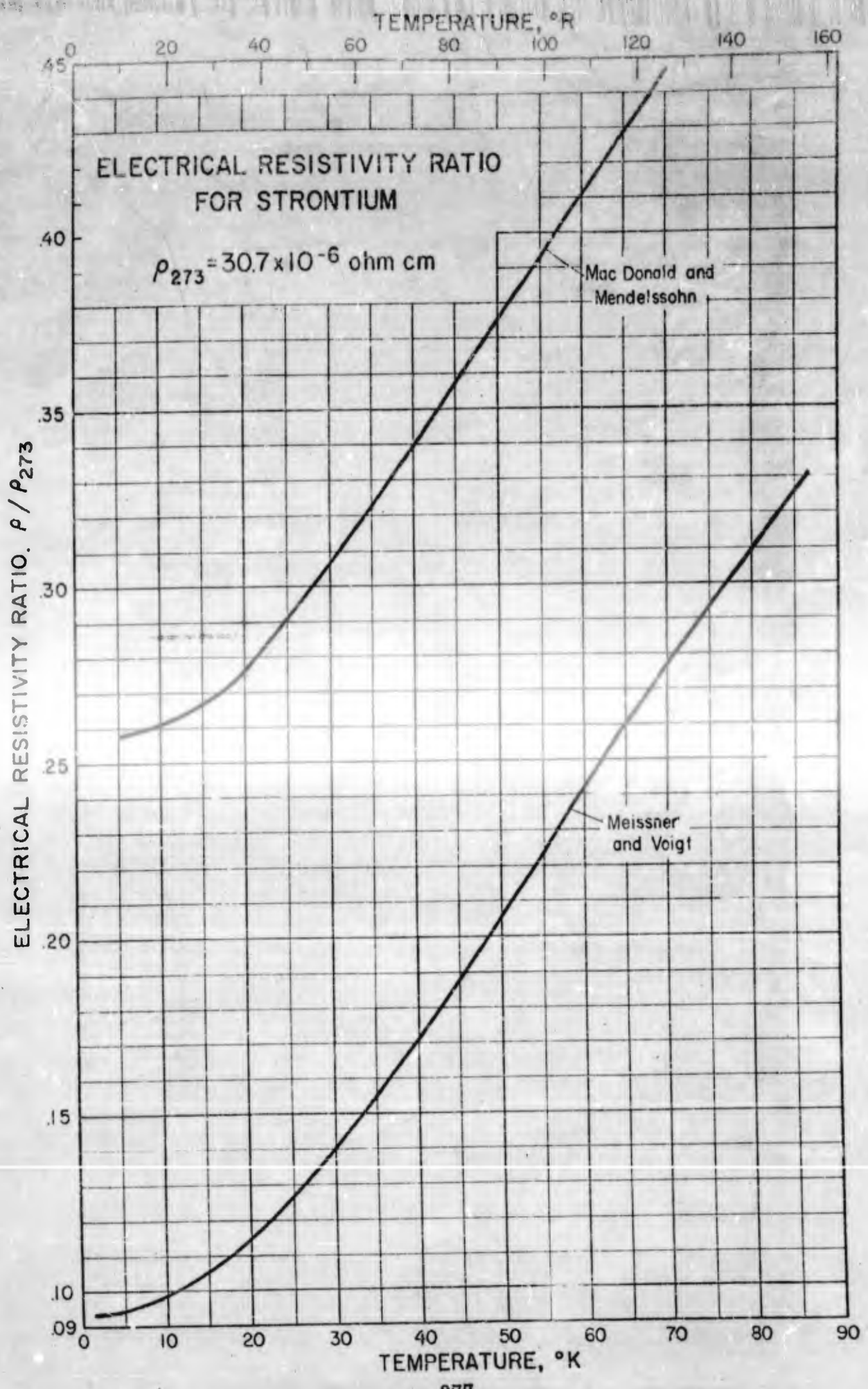
ρ_{290} = Resistivity at 290°K, (ohm-cm)

Meissner and Voigt	
Temp. °K	ρ/ρ_{273}
1.3	0.0932
4.2	0.0937
20.4	0.1162
77.7	0.3022
86.3	0.3313

MacDonald and Mendelssohn	
Temp. °K	ρ/ρ_{290}*
5	0.243
10	0.246
20	0.260
40	0.320
70	0.420

* The third decimal place of the resistivity values is somewhat in doubt.

RDM/RS Issued: 11/8/60


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO
FOR STRONTIUM
$\rho_{273} = 30.7 \times 10^{-6}$ ohm cm
Mac Donald and
Mendelssohn
Meissner
and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ / ρ_{273}
.45
.40
.35
.30
.25
.20
.15
.10
.09
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of BARIUM, Ba

(Atomic Number 56)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Justi, E. and Kramer, J.; Physik. Z. 41, 197 (1940)

Meissner, W., Franz, H. and Westerhoff, H.; Ann. Physik. (5) 13, 555 (1932)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Rinck, E.; Compt. rend. 193, 1328 (1931)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for barium to be used in calculating electrical resistivity (ρ_T) is given for each individual curve on the graph.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from the Landolt-Börnstein tables are those reported by the authors cited above under "Other References". The original authors are used in labeling the several curves shown on the graph.

The data as reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by two of the investigators so a datum value reported by Rinck ($\rho_{273} = 36.0 \times 10^{-6}$ ohm-cm) is suggested for calculating these ratios. A polycrystalline sample of small impurities was used by Rinck to determine ρ_{273}.

The Landolt-Börnstein tables list the samples of the three authors as polycrystalline with a small amount of impurities present in the samples used by Meissner, Franz and Westerhoff; and Justi and Kramer. No mention is made of the impurities present in the sample used by Meissner and Voigt. No information is available on mechanical strain or heat treatment for any of the samples from any of the authors.

(Continued on following page.)

ELECTRICAL RESISTIVITY of BARIUM, Ba (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

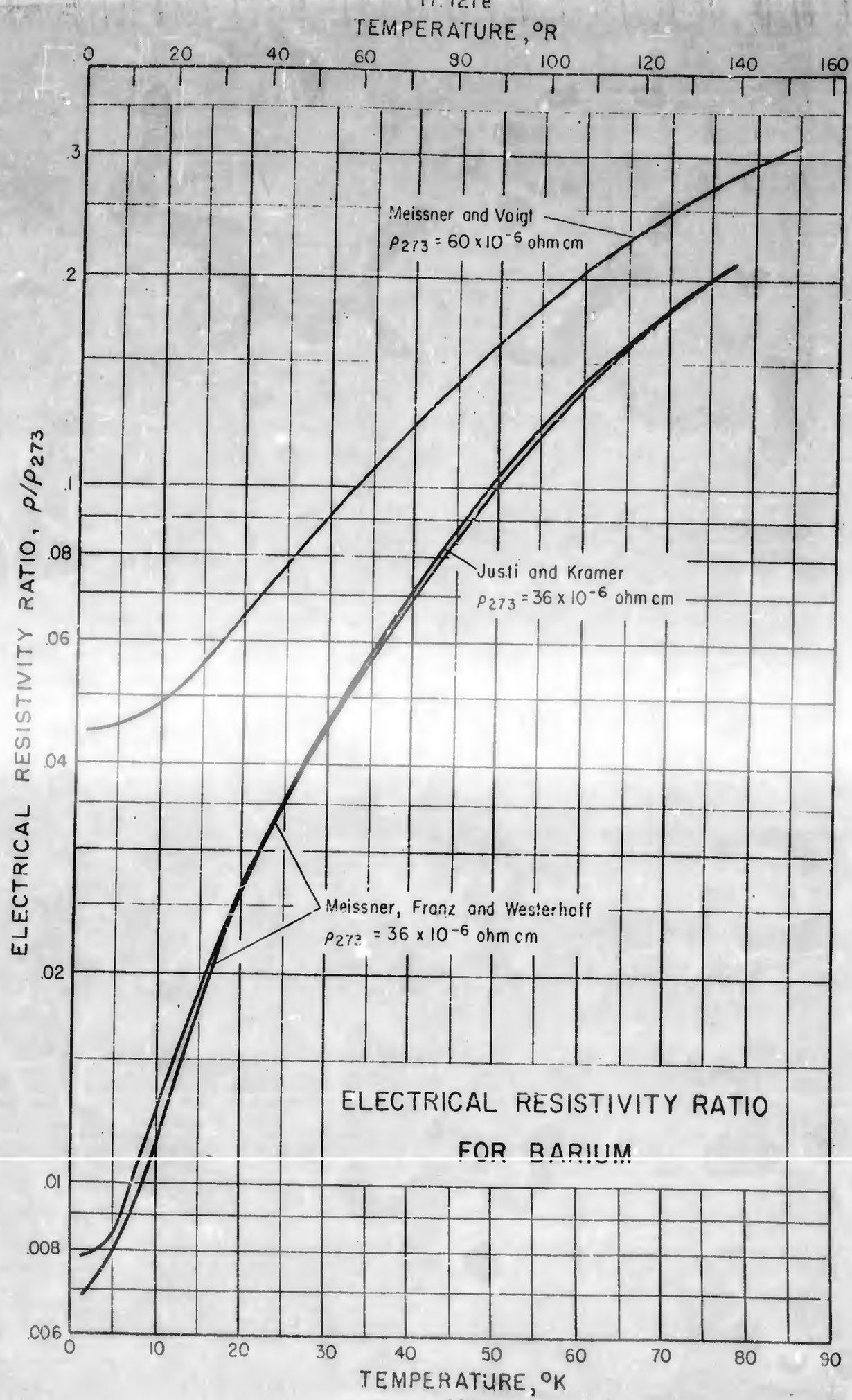
ρ_{273} = Resistivity at 273°K, (ohm-cm)

Justi and Kramer		Meissner, Franz and Westerhoff	
Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
1.85	0.0070	1.30	0.0079
4.22	0.0078	4.26	0.0083
14.0	0.015	20.47	0.0279
20.4	0.027	78.18	0.2137
78.0	0.215		

Meissner and Voigt	
Temp. °K	ρ/ρ_{273}
1.26	0.0446
4.21	0.0450
20.4	0.0670
78.0	0.2843
85.7	0.3149

RDM/RS Issued: 1/23/61

17.121e


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO, ρ/ρ273
.3
.2
.08
.06
.04
.02
.01
.008
.006
Meissner and Voigt
ρ273 = 60 x 10⁻⁶ ohm cm
Justi and Kramer
ρ273 = 36 x 10⁻⁶ ohm cm
Meissner, Franz and Westerhoff
ρ273 = 36 x 10⁻⁶ ohm cm
ELECTRICAL RESISTIVITY RATIO
FOR BARIUM
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of ZINC, Zn

(Atomic Number 30)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil., Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Holborn, L.; Ann. Physik 59, 145 (1919)

Jaeger, W. and Diesselhorst, H.; Wiss. Abhandl. physik tech. Reichsanstalt 3, 269 (1900)

Tuyn, W. and Onnes, K. H.; Proc. Acad. Sci. Amsterdam 26, 504 (1923)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for zinc to be used in calculating values of electrical resistivity (ρ_T) is 5.65×10^{-6} ohm-cm. The curves on this graph should not be extrapolated to lower temperatures as zinc becomes a superconductor at 0.93°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Holborn; and Jaeger and Diesselhorst; while those values listed in the International Critical Tables are from Tuyn and Onnes. These primary sources are listed above under "Other References". The original authors are used in labeling the two curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the two references are not available so a datum value reported by Jaeger and Diesselhorst ($\rho_{273} = 5.65 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The samples used by the investigators appearing in Landolt-Börnstein are reported as polycrystalline with a small amount of impurities present. The sample used by Holborn is reported as being cast. No information as to the nature of the sample used by Tuyn and Onnes is available, and no information is available on the mechanical or heat treatment of any of the samples from any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of ZINC (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

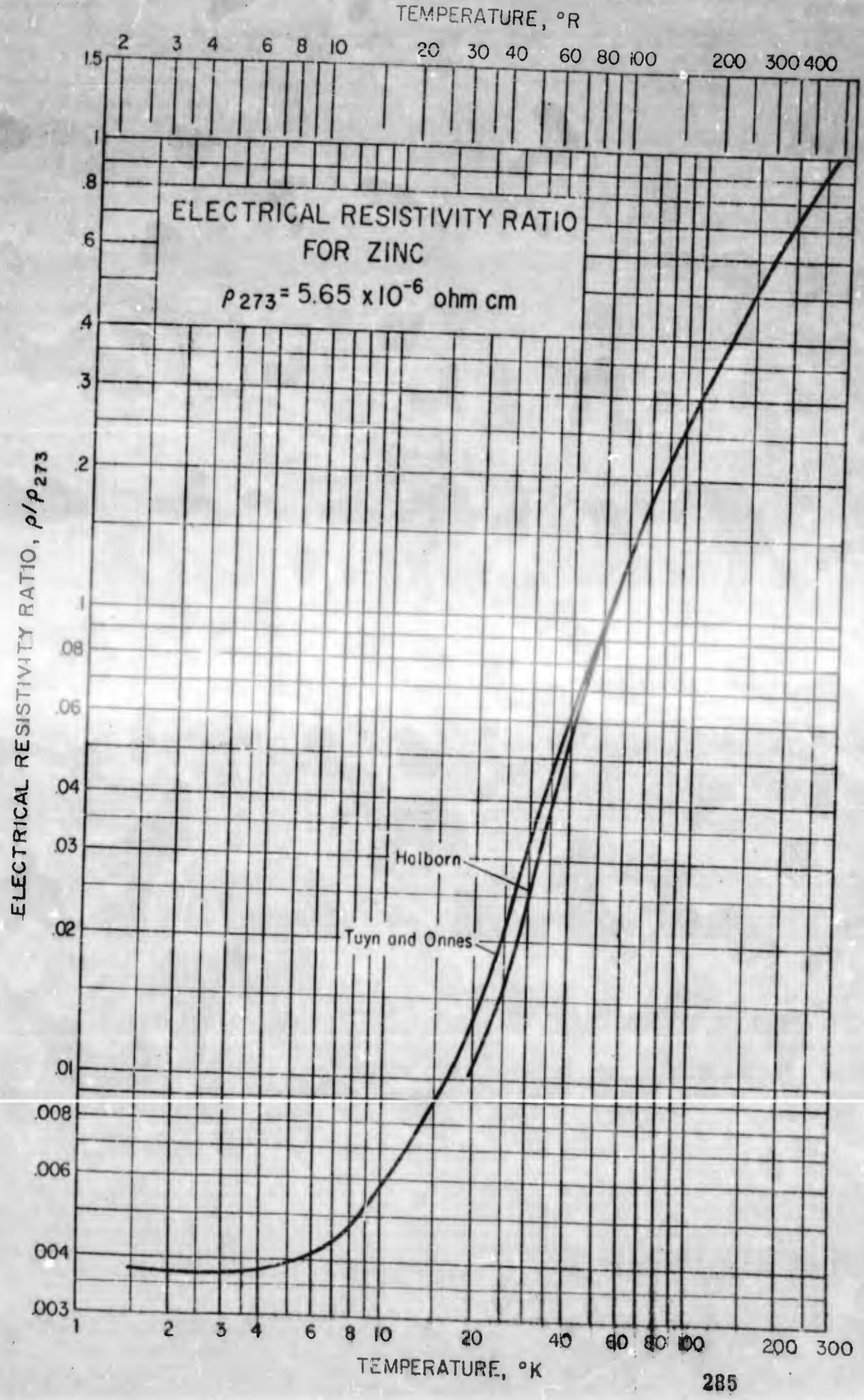
ρ_{273} = Resistivity at 273° K, (ohm-cm)

Tuyn and Onnes			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.2	68.62	-255.10	1.119
-184.37	25.367	-256.64	0.984
-192.05	22.136	-258.85	0.838
-200.38	18.643	-268.87	0.378
-206.99	15.901	-269.71	0.378
-215.26	12.552	-271.69	0.378
-252.60	1.383		

Holborn	
Temp. °K	ρ/ρ_{273}
20	0.0104
81	0.2200
195	0.6862

RDM/RS Issued: 2/2/61

17.122a


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR ZINC
$\rho_{273} = 5.65 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
Holborn
Tuyn and Onnes
1 2 3 4 6 8 10 20 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of CADMIUM, Cd
(Atomic Number 48)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Holborn, L.; Ann. Physik 59, 145 (1919)

Jaeger, W. and Diesselhorst, H.; Wiss. Abhandl. physik tech. Reichsanstalt 3, 269 (1900)

Meissner, W.; Physik Z. 27, 725 (1926)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for cadmium to be used in calculating electrical resistivity is 7.07×10^{-6} ohm-cm. The curves on this graph should not be extrapolated to lower temperatures since cadmium becomes a superconductor between 0.56 and 0.65°K.

The data for this graph were taken from the references cited under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Jaeger and Diesselhorst; and by Meissner; while those values listed in the International Critical Tables are from Holborn. These primary sources are listed above under "Other References". The original authors are used in labeling the two curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the electrical resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Jaeger and Diesselhorst ($\rho_{273} = 7.07 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The sample used by Meissner; and Jaeger and Diesselhorst are reported in the Landolt-Börnstein tables as polycrystalline with 0.05% impurities of unknown composition present in the Jaeger and Diesselhorst sample. No mention is made on the nature of the sample used by Holborn and no information is given on the mechanical or heat treatment of any of the samples in any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of CADMIUM (Cont.)

Tables of Values of Electrical Resistivity

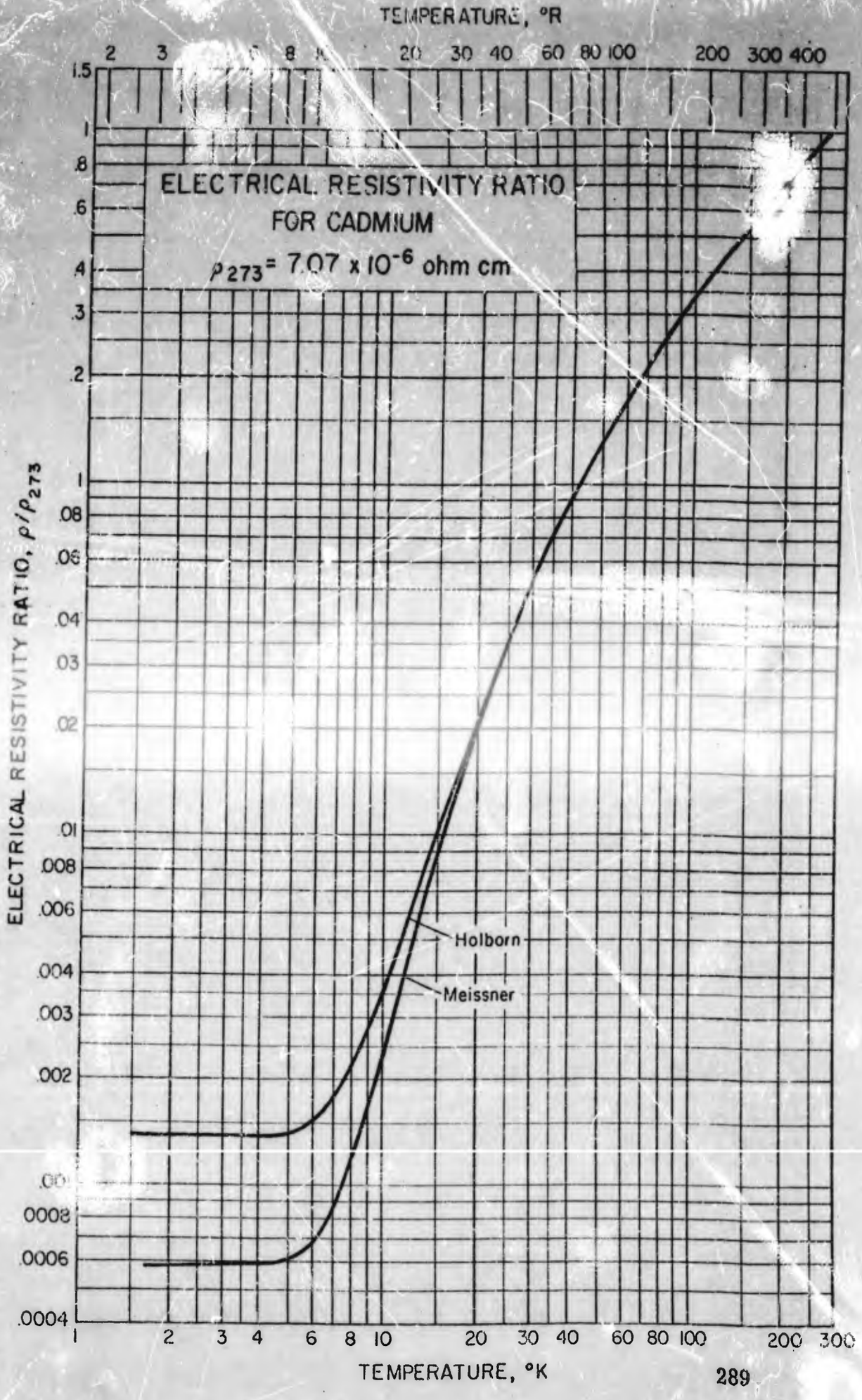
ρ = Resistivity, (ohm-cm)

ρ_{273} - Resistivity at 273°K, (ohm-cm)

Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.3	69.08	-256.56	1.331
-182.68	28.820	-258.87	0.907
-192.08	25.125	-268.87	0.143
-200.03	21.967	-269.63	0.141
-207.10	19.158	-269.70	0.141
-216.32	15.475	-271.22	0.140
-252.58	2.267	-271.69	0.140
-255.03	1.666		

Meissner	
Temp. °K	ρ/ρ_{273}
1.68	0.000594
4.2	0.000614
20.4	0.0209
82.5	0.2579

RDM/RS Issued: 2/3/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR CADMIUM
$\rho_{273} = 7.07 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.0008
.0006
.0004
Holborn
Meissner
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of MERCURY, Hg (solid)

(Atomic Number 80)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Dewar, J. and Fleming, J. A.; Proc. Roy. Soc. (London) 60, 76 (1897)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Onnes, H. K. and Holst, G.; Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 142a (1914)

Comments:

Reference should be made to the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for mercury to be used in calculating values of electrical resistivity (ρ_T) is 26.6×10^{-6} ohm-cm. The curves on this graph should not be extrapolated to lower temperatures as mercury becomes a superconductor at 4.160°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; and Onnes and Holst; while those values listed in the International Critical Tables are from Dewar and Fleming. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to a datum temperature of 273°K. Mercury has a phase change at 234°K which results in a discontinuity in the electrical resistivity curve. The ρ_{273} used here for these ratios is an extrapolation from the values for solid phase at temperatures below 234°K, rather than the resistivity of the liquid at 273°K. Values of specific resistivity of solid mercury for the samples used by the original investigators are not available so a value reported by Dewar and Fleming ($\rho = 21.30 \times 10^{-6}$ ohm-cm at 223°K) and the slope of the resistivity ratio curve from 100 to 200°K as determined by Onnes and Holst was used to determine ρ_{273}. The resulting datum value ($\rho_{273} = 26.6 \times 10^{-6}$ ohm-cm) is suggested here for calculating values of electrical resistivity from these ratios.

(Continued on following page)

ELECTRICAL RESISTIVITY of MERCURY (Cont.)

Comments: (cont.)

The Landolt-Börnstein tables report the sample used by Meissner and Voigt as polycrystalline with no mention made of impurities. No other pertinent information is available for any of the samples from any of the sources of data.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

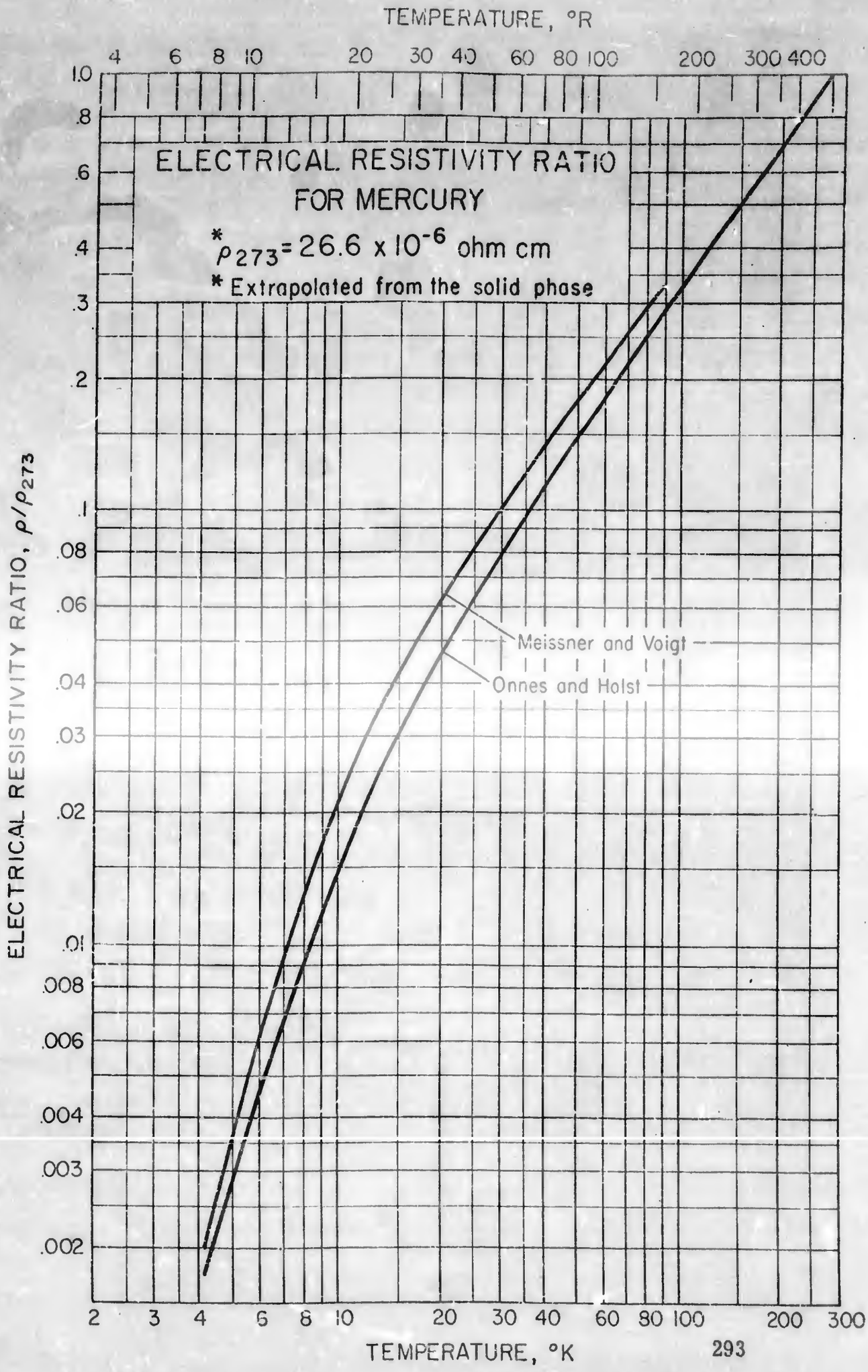
ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt	
Temp.* °K	ρ/ρ_{273}
4.20	0.0020
20.46	0.0642
77.8	0.2820
88.9	0.3259

Onnes and Holst	
Temp.* °K	ρ/ρ_{273}
4.15	0.0017
4.33	0.0020
14.6	0.0295
20.4	0.0490
90.1	0.2851
122.8	0.3982
165.8	0.5586

* The second decimal place of temperature values is somewhat in doubt.

RDM/RS Issued: 2/14/61


TEMPERATURE, °R
4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR MERCURY
*ρ_{273} = 26.6 x 10^{-6} ohm cm
* Extrapolated from the solid phase
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0 .8 .6 .4 .3 .2 .1 .08 .06 .04 .03 .02 .01 .008 .006 .004 .003 .002
Meissner and Voigt
Onnes and Holst
2 3 4 5 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of LANTHANUM, La

(Atomic Number 57)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

James, N. R., Legvold, S. and Spedding, F. H.; Phys. Rev. 88, 1092 (1952)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for lanthanum to be used in calculating electrical resistivity is 63.0×10^{-6} ohm-cm. The curve should not be extrapolated to lower temperatures since lanthanum becomes a superconductor between 4.8°K and 5.8°K.

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of ρ_{273} determined by James, et al., and suggested as a datum value here is $\rho_{273} = 63.0 \times 10^{-6}$ ohm-cm.

The samples used by James, et al., were of the cast polycrystalline type with less than 1.1% impurities. The impurities are further listed as being < 1% Mg; < 0.025% Ca; < 0.01% other rare earths, and 0.0085% Fe. No information was listed in Landolt-Börnstein on mechanical strain or heat treatment for any of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

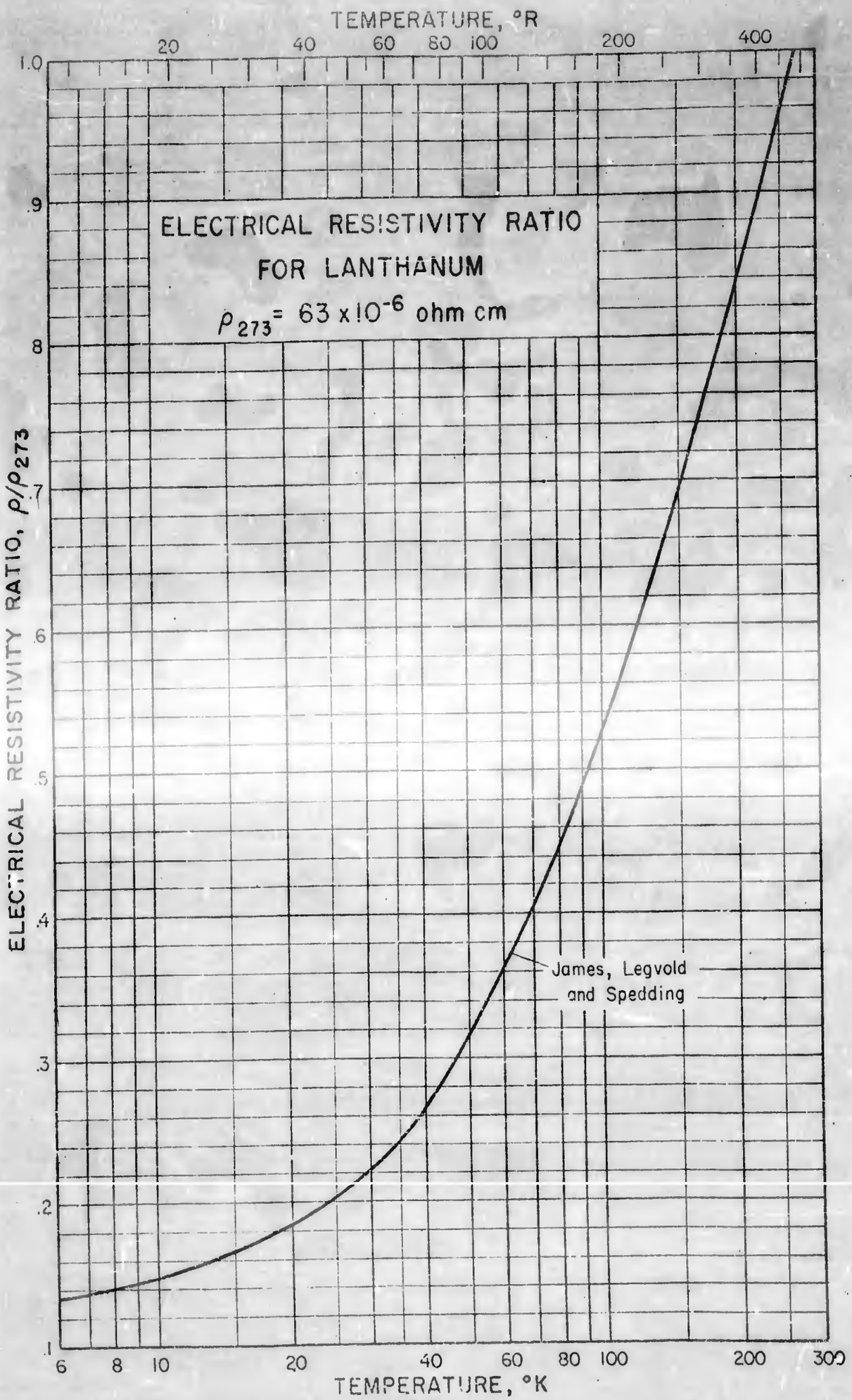
ρ_{273} = Resistivity at 273°K (ohm-cm)

James, et al.

Temp. °K	ρ/ρ_{273}*
6	0.133
40	0.267
80	0.450
160	0.729

*The third decimal place of the electrical resistivity values is somewhat in doubt.

RDM/RS Issued: 12/21/60


TEMPERATURE, °R
20
40
60
80
100
200
400
ELECTRICAL RESISTIVITY RATIO
FOR LANTHANUM
$\rho_{273} = 63 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
James, Legvold
and Spedding
6
8
10
20
40
60
80
100
200
300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of CERIUM, Ce

(Atomic Number 58)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

James, N. R., Legvold, S. and Spedding, F. H.; Phys. Rev. 88, 1092 (1952)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for cerium to be used in calculating electrical resistivity is 81.0×10^{-6} ohm-cm.

The data for this graph were taken from references cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by James, et al., cited under "Other Reference".

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of ρ_{273} determined by James, et al., and suggested as a datum value here is $\rho_{273} = 81.0 \times 10^{-6}$ ohm-cm.

The samples used by James, et al., were of the cast polycrystalline type with less than 1.1% impurities. The impurities are further listed as being < 1% Mg; < 0.025% Ca; < 0.01% other rare earths, and 0.029% Fe. No information was listed in Landolt-Börnstein on mechanical strain or heat treatment for any of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K (ohm-cm)

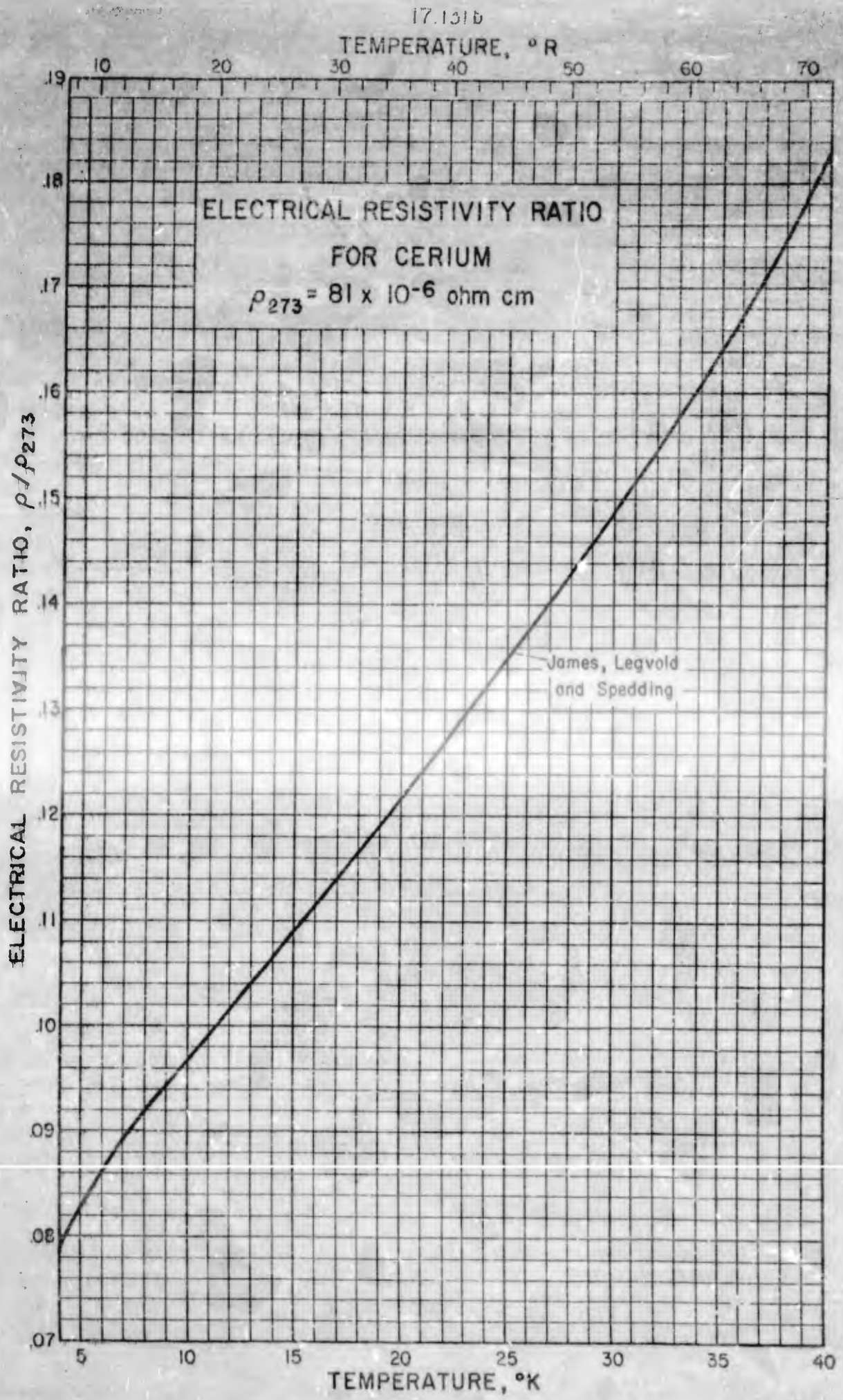
James, et al.

Temp. °K	ρ/ρ_{273}*
4	0.079
8	0.092
24	0.132
40	0.183

* The third decimal place of the electrical resistivity values is somewhat in doubt.

RDM/RS Issued: 12/22/60

17.131b


TEMPERATURE, °R
10
20
30
40
50
60
70
ELECTRICAL RESISTIVITY RATIO
FOR CERIUM
ρ_{273} = 81 x 10-6 ohm cm
James, Legvold
and Spedding
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.19
.18
.17
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
5
10
15
20
25
30
35
40
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of PRASEODYMIUM, Pr

(Atomic Number 59)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

James, N. R., Legvold, S. and Spedding, F. H.; Phys. Rev. 88, 1092, (1952)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for praseodymium to be used in calculating electrical resistivity (ρ_T) is 76.0 x 10^{-6} ohm-cm.

The data for this graph were taken from references cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by James, et al., cited under "Other Reference".

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of ρ_{273} determined by James, et al., and suggested as a datum value here is ρ_{273} = 76.0 x 10^{-6} ohm-cm.

The samples used by James, et al., were of the cast polycrystalline type with less than 1.1% impurities. The impurities are further listed as being < 1% Mg; < 0.025% Ca; < 0.01% other rare earths, and 0.0315% Fe. No information was listed in Landolt-Börnstein on mechanical strain or heat treatment for any of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

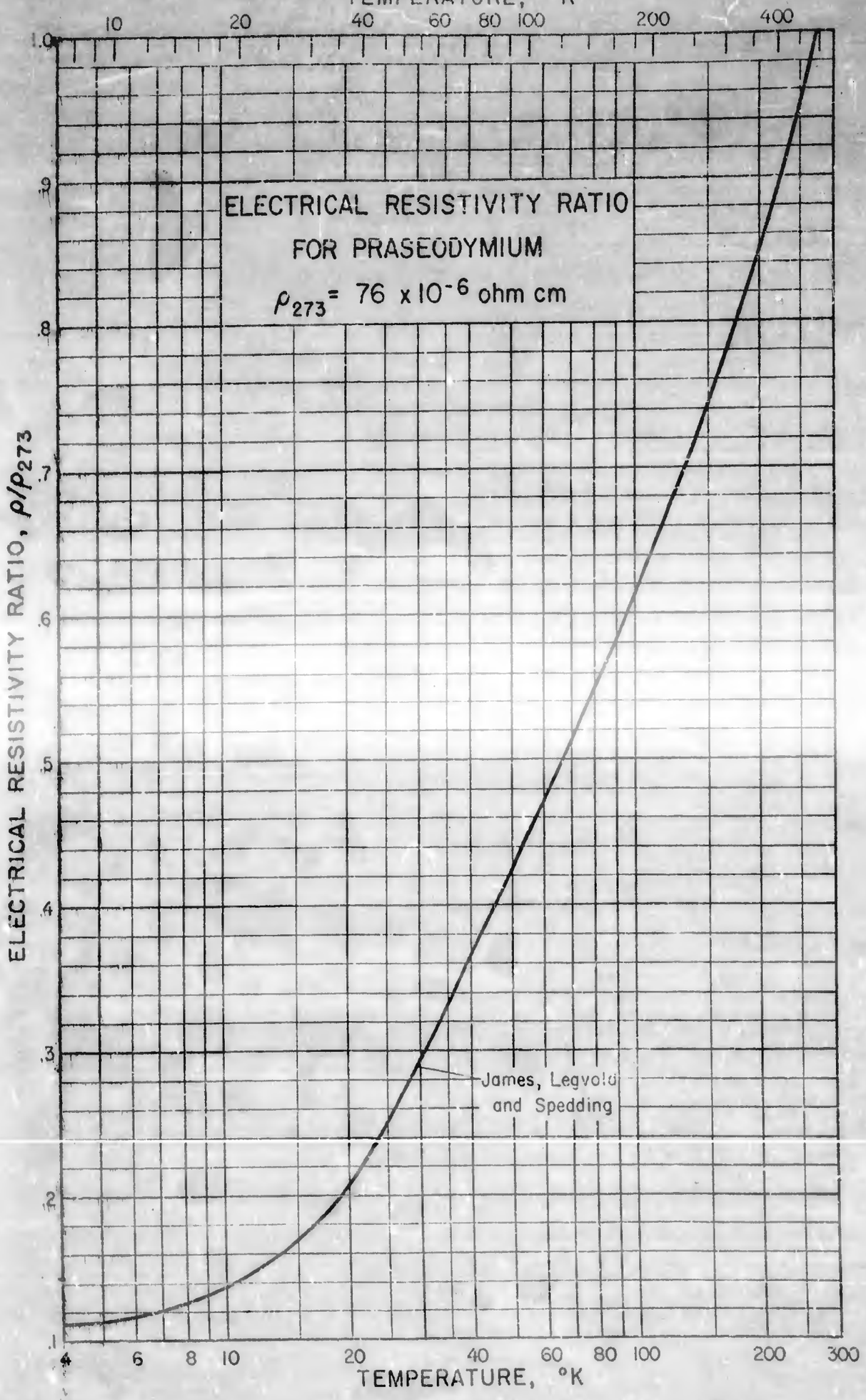
ρ_{273} = Resistivity at 273°K, (ohm-cm)

James, et al.	
Temp. °K	ρ/ρ_{273}*
4	0.112
20	0.209
80	0.550
160	0.768

* The third decimal place of the electrical resistivity is somewhat in doubt.

RDM/RS Issued: 12/23/60

17.131c


TEMPERATURE, °R
10
20
40
60
80
100
200
400
ELECTRICAL RESISTIVITY RATIO
FOR PRASEODYMIUM
ρ_{273} = 76 x 10⁻⁶ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
James, Legvold
and Spedding
4
6
8
10
20
40
60
80
100
200
300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of NEODYMIUM, Nd

(Atomic Number 60)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

James, N. R., Legvold, S. and Spedding, F. H.; Phys. Rev. 88, 1092 (1952)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for neodymium to be used in calculating electrical resistivity is 71.0×10^{-6} ohm-cm.

The data for this graph were taken from references cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by James, et al., cited under "Other Reference".

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of ρ_{273} determined by James, et al., and suggested as a datum value here is $\rho_{273} = 71.0 \times 10^{-6}$ ohm-cm.

The samples used by James, et al., were of the cast polycrystalline type with less than 1.1% impurities. The impurities are further listed as being < 1% Mg; < 0.025% Ca; < 0.01% other rare earths, and 0.017% Fe. No information was listed in Landolt-Börnstein on mechanical strain or heat treatment for any of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

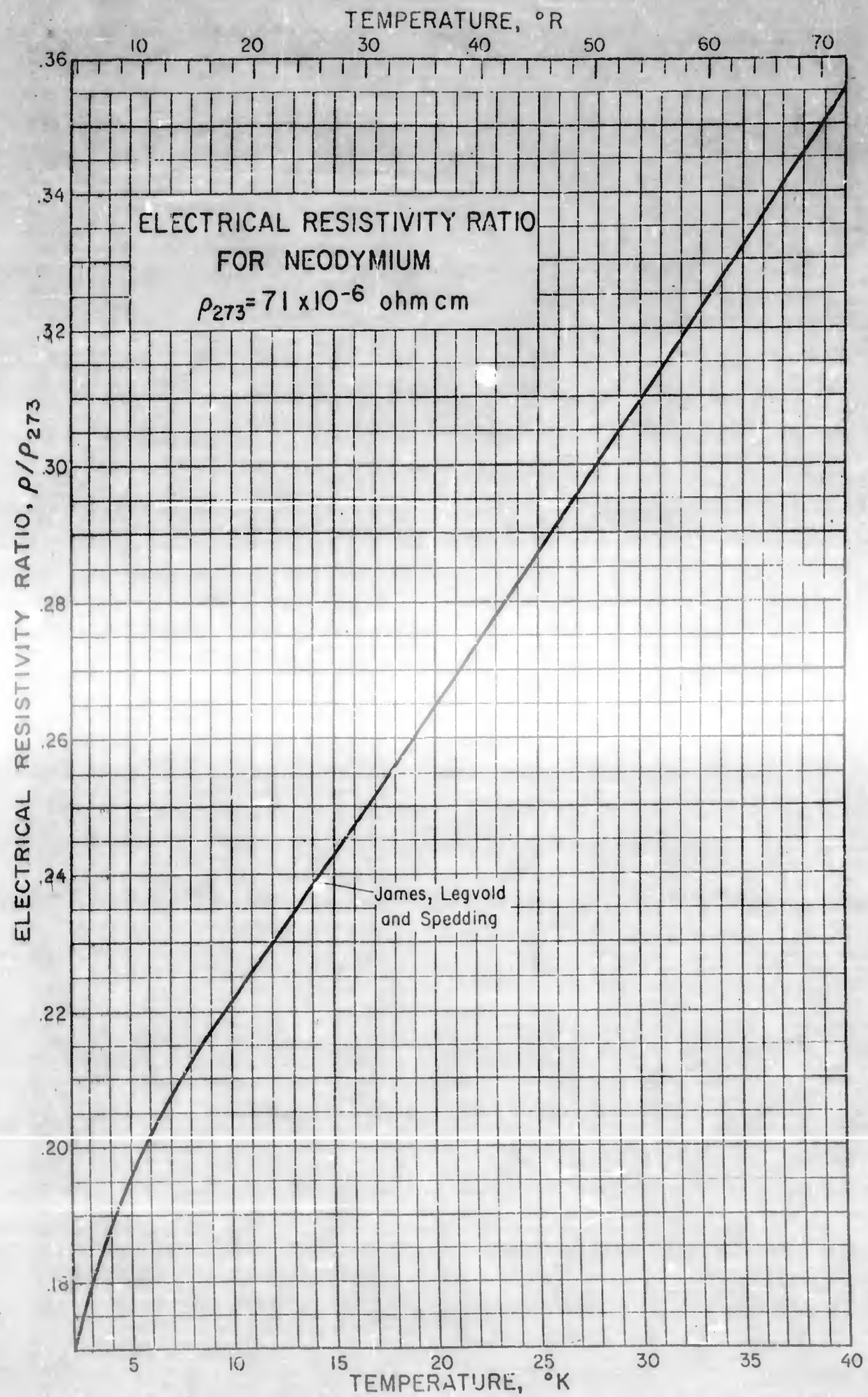
ρ_{273} = Resistivity at 273°K (ohm-cm)

James, et al.

Temp. °K	ρ/ρ_{273}*
2	0.170
8	0.213
24	0.283
40	0.356

* The third decimal place place of the electrical resistivity values is somewhat in doubt.

RDM/RS Issued: 12/23/60


TEMPERATURE, °R
10
20
30
40
50
60
70
.36
.34
.32
.30
.28
.26
.24
.22
.20
.18
ELECTRICAL RESISTIVITY RATIO FOR NEODYMIUM
$\rho_{273} = 71 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
James, Legvold and Spedding
5
10
15
20
25
30
35
40
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of GADOLINIUM, Gd

(Atomic Number 64)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

Legvold, S., Spedding, F. H., Borson, F. and Elliott, J. F.; Revs. Modern Phys. 25, 129 (1953)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for gadolinium to be used in calculating electrical resistivity (ρ_T) is 140×10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Legvold, et al., cited under "Other Reference".

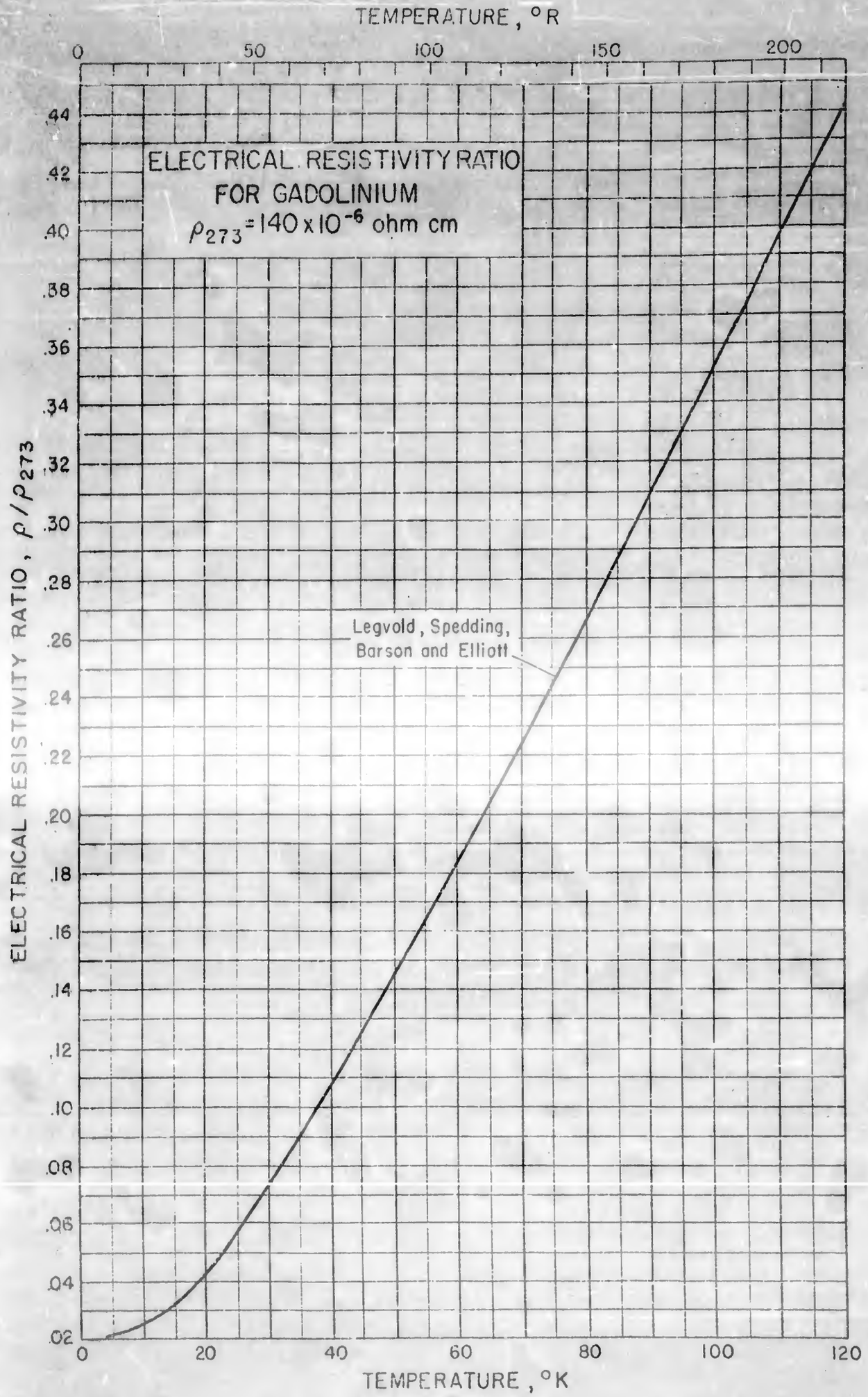
The data reported in Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of the datum (ρ_{273}) determined by Legvold, et al., is 140×10^{-6} ohm-cm. This value is suggested for calculating the resistivity from the ratios given here.

The Landolt-Börnstein tables list the samples used by the authors as being of a polycrystalline nature cast in a vacuum and annealed at 550°C with impurities of 0.25% consisting of Mg, Ca, Fe, and Sm.

Table of Values of Electrical Resistivity	
ρ = Resistivity, (ohm-cm) ρ_{273} = Resistivity at 273°K, (ohm-cm)	
Legvold, Spedding, Borson and Elliott	
Temp. °K	ρ/ρ_{273}*
4	0.021
20	0.043
40	0.108
120	0.443

* The third decimal place of the electrical resistivity values is somewhat in doubt.

RDM/RS Issued: 3/3/61


TEMPERATURE, °R
0
50
100
150
200
ELECTRICAL RESISTIVITY RATIO
FOR GADOLINIUM
$\rho_{273} = 140 \times 10^{-6}$ ohm cm
Legvold, Spedding,
Barson and Elliott
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.44
.42
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
20
40
60
80
100
120
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of DYSPROSIUM, Dy

(Atomic Number 66)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

Legvold, S., Spedding, F. H., Borson, F. and Elliott, J. F.; Revs. Modern Phys. 25, 129 (1953)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for dysprosium to be used in calculating electrical resistivity (ρ_T) is 135 x 10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Legvold et al. cited under "Other Reference".

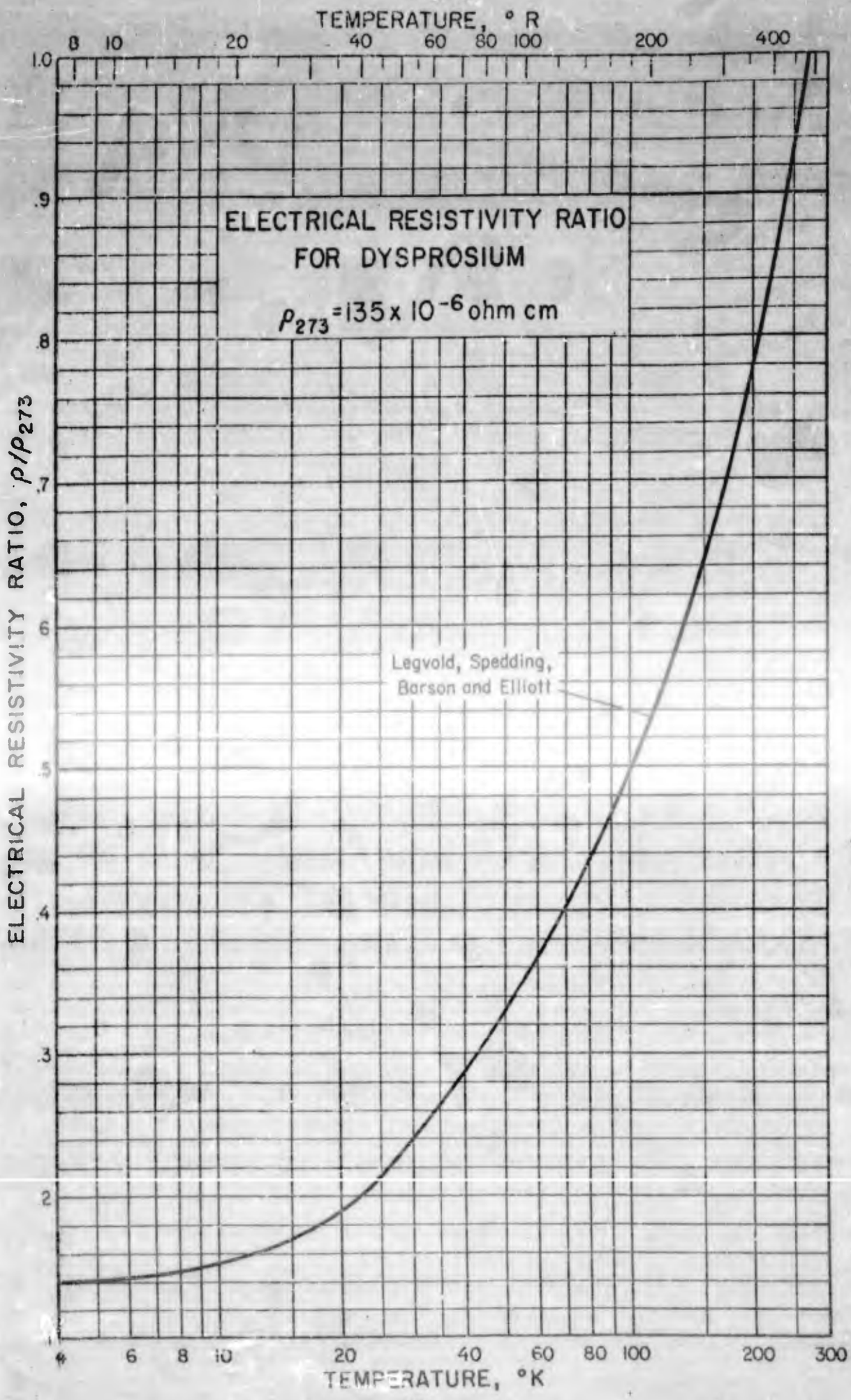
The data reported in Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of the datum (ρ_{273}) determined by Legvold, et al. is 135 x 10^{-6} ohm-cm. This value is suggested for calculating the resistivity from the ratios given here.

The Landolt-Börnstein tables list the samples used by the authors as polycrystalline. The samples were cast and later annealed at 500°C. The impurities in the samples are approximately 0.1% Ho and 0.07% Y.

Table of Values of Electrical Resistivity	
ρ = Resistivity, (ohm-cm) ρ_{273} = Resistivity at 273°K, (ohm-cm)	
Legvold, Spedding, Borson and Elliott	
Temp. °K	ρ/ρ_{273}
4	0.14
20	0.19
40	0.29
160	0.67

RDM/RS Issued: 12/23/60

17.131g


TEMPERATURE, ° R
8 10 20 40 60 80 100 200 400
ELECTRICAL RESISTIVITY RATIO
FOR DYSPROSIUM
$\rho_{273} = 135 \times 10^{-6}$ ohm cm
Legvold, Spedding,
Barson and Elliott
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
4 6 8 10 20 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of ERBIUM, Er

(Atomic Number 68)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

Legvold, S., Spedding, F. H., Borson, F. and Elliott, J. F.; Revs. Modern Phys. 25, 129 (1953)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for erbium to be used in calculating electrical resistivity (ρ_T) is 176.0 x 10-6 ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Legvold, et al., cited under "Other Reference".

The data reported in Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of the datum (ρ_{273}) determined by Legvold, et al., is 176.0 x 10-6 ohm-cm. This value is suggested for calculating the resistivity from the ratios given here.

The Landolt-Börnstein tables list the samples used as being cast in a vacuum and of the polycrystalline type. Impurities in the sample are reported as being of less than 0.1% in total composed of Ca and Fe. No information is listed on the mechanical and heat treatment of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

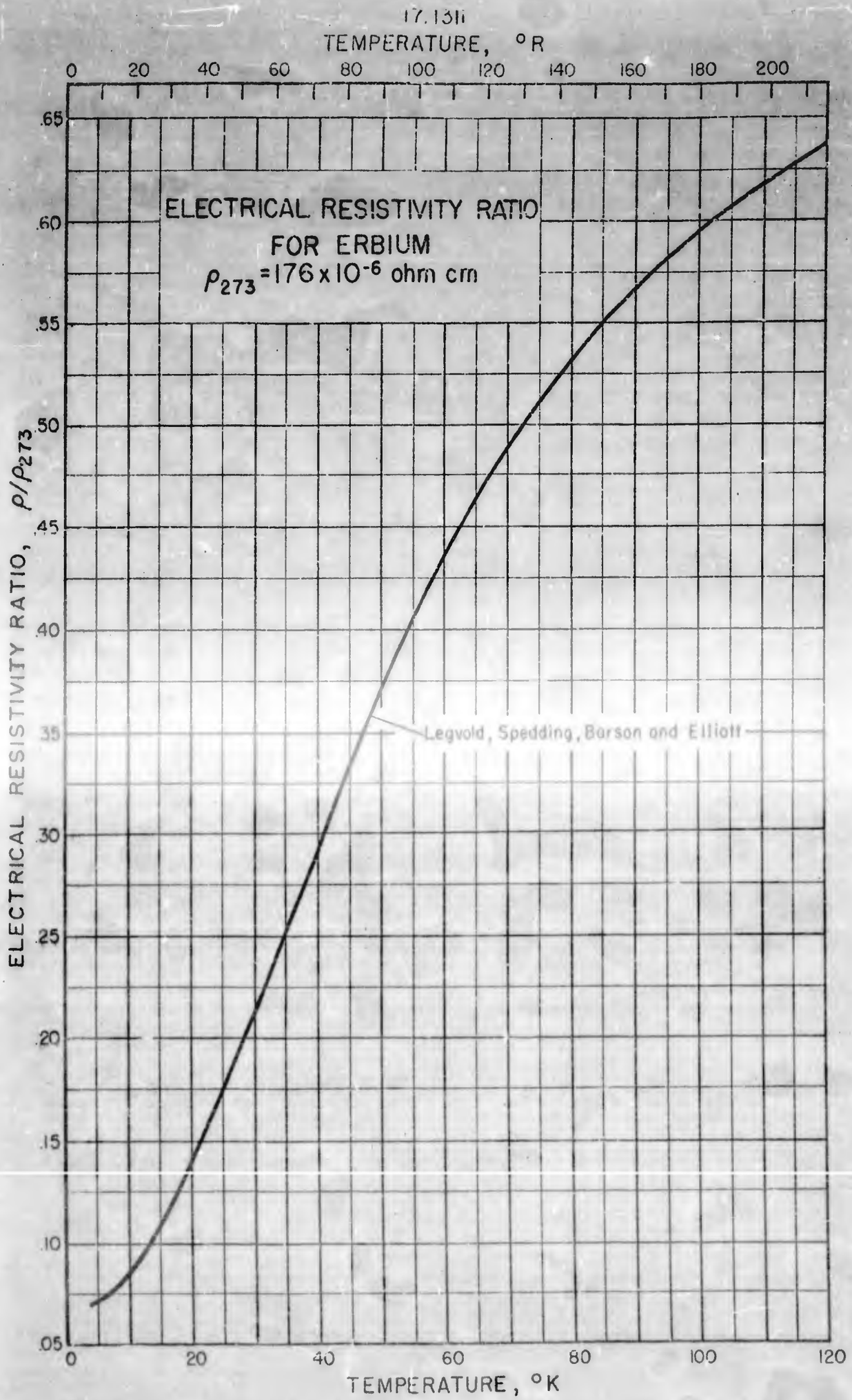
Legvold, Spedding, Borson and Elliott

Temp. °K	ρ/ρ_{273}*
4	0.071
20	0.142
40	0.292
120	0.637

*The third decimal place of the electrical resistivity values is somewhat in doubt.

RDM/RS Issued: 2/21/60

17.131i


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
180
200
ELECTRICAL RESISTIVITY RATIO
FOR ERBIUM
$\rho_{273} = 176 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
Legvold, Spedding, Barson and Elliott
0
20
40
60
80
100
120
TEMPERATURE, °K

17.131L

ELECTRICAL RESISTIVITY of THORIUM, Th

(Atomic Number 90)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Meissner, W. and Voigt, F.; Ann. Physik. (5) I, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for thorium to be used in calculating values of electrical resistivity (ρ_T) is 13 x 10^{-6} ohm-cm. The curve should not be extrapolated to lower temperatures since thorium becomes a superconductor between 1.388 and 1.40°K.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt cited under "Other Reference".

The data reported in Landolt-Börnstein and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of the datum (ρ_{273}) determined by Meissner and Voigt and suggested for calculating values of electrical resistivity here is ρ_{273} = 13 x 10^{-6} ohm-cm.

The Landolt-Börnstein tables report the sample used by Meissner and Voigt as a single crystal specimen pulled from a melt with less than 0.1% Fe impurity present. No information on the mechanical or heat treatment of the sample is given.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

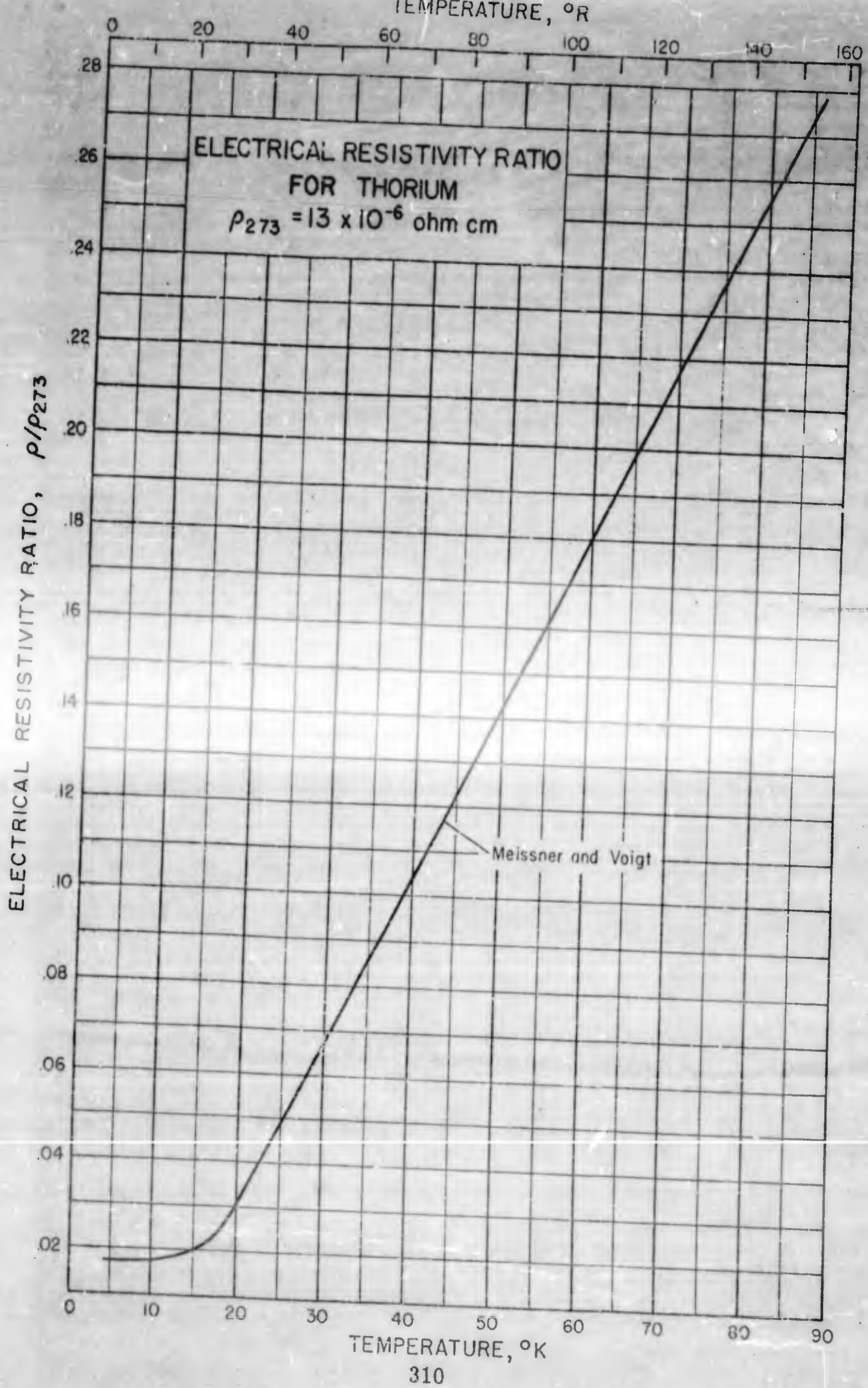
Meissner and Voigt

Temp., °K*	ρ/ρ_{273}**
1.49	0.0136
4.21	0.0171
20.4	0.0308
77.9	0.2454
86.1	0.2785

*The second decimal place is in doubt.
**The fourth decimal place is in doubt.

RDM/RS Issued: 3/14/61

17.131 L.


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO
FOR THORIUM
ρ_{273} = 13 x 10⁻⁶ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
Meissner and Voigt
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of URANIUM, U

(Atomic Number 92)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Dahl, A. I. and Van Dusen, M. S.; J. Research Natl. Bur. Standards 39, 53 (1947)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for uranium to be used in calculating electrical resistivity (ρ_T) is 21.0 X 10-6 ohm-cm. The curve should not be extrapolated to lower temperatures since uranium becomes a superconductor at 1.1°K.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by A. I. Dahl and M. S. Van Dusen; and W. Meissner and B. Voigt. These primary sources are listed above under "Other References".

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of ρ_{273} is not available for the samples used by Meissner and Voigt, so a datum value reported by Dahl and Van Dusen (ρ_{273} = 21.0 x 10^{-6} ohm-cm) is suggested for calculating values of resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by Meissner and Voigt as polycrystalline with approximately 2% impurities of unknown composition. No information is available in the mechanical or heat treatment of the Meissner and Voigt samples. The samples used by Dahl and Van Dusen are listed in Landolt-Börnstein tables as polycrystalline with 0.06% impurities of unknown composition. The Dahl and Van Dusen samples were annealed in a helium atmosphere at 600°C.

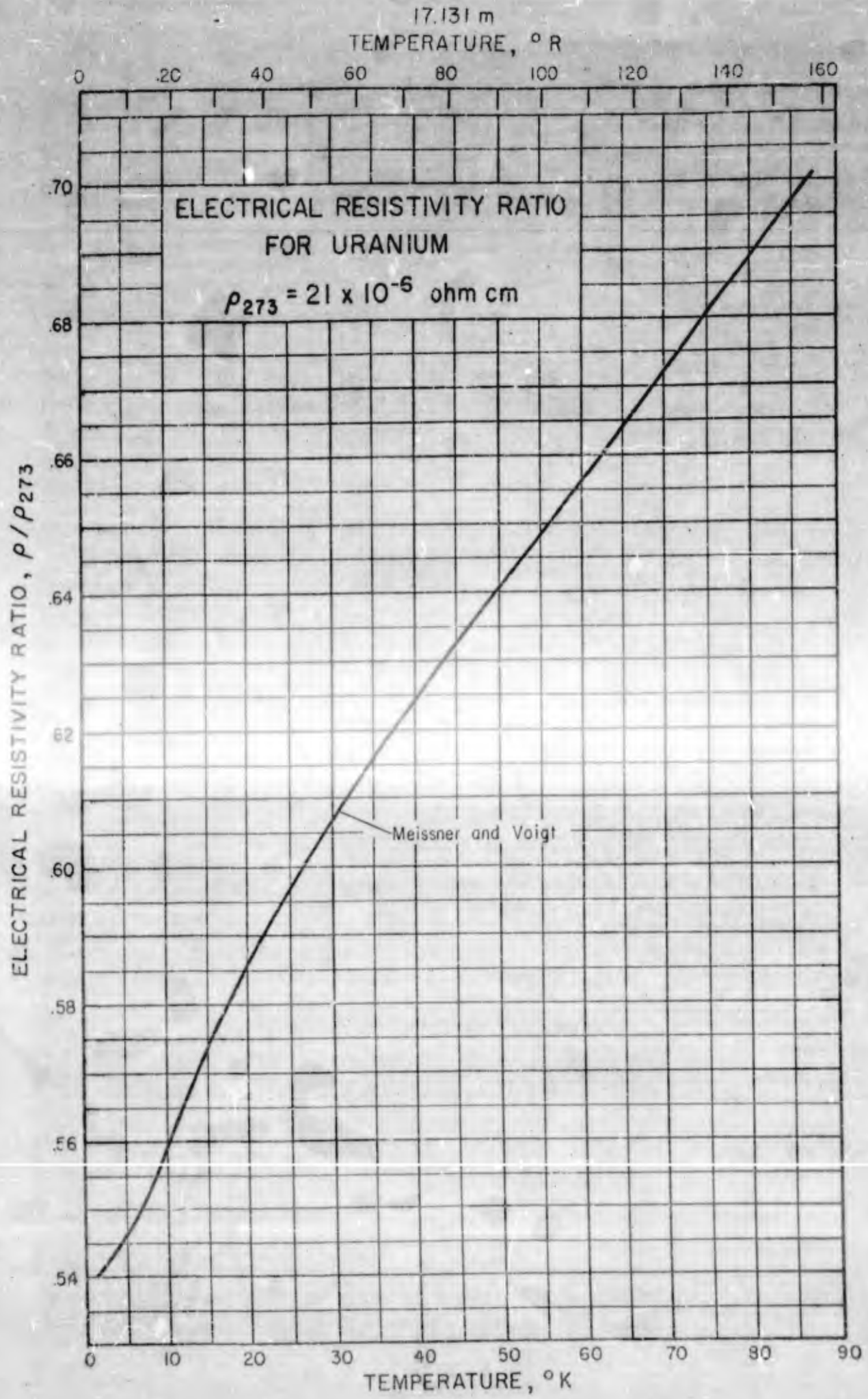
Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt	
Temp. °K*	ρ/ρ_{273}
1.41	0.5400
4.20	0.5445
20.4	0.5867
77.8	0.6844
86.8	0.7001

* The second decimal place is in doubt.


17.131 m
TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO
FOR URANIUM
$\rho_{273} = 21 \times 10^{-6}$ ohm cm
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.70
.68
.66
.64
.62
.60
.58
.56
.54
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of ALUMINUM, Al

(Atomic Number 13)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Other References:

Albert, P., Bull. inst. intern. froid, Annexe 1956-2, 41-49 (1956)

Alley, P. and Serin, B.; Phys. Rev. 116, No. 2, 334-338 (1959)

Boorse, H. A. and Niewodniczanski, H., Proc. Roy. Soc. (Loncon) A153, 463-475 (1936)

Caron, M., Bull. inst. intern froid, Annexe 1956-2, 51-62 (1956)

Caron, M., Compt. rend. 236, 1169 (1953)

Caron, M., Albert, P. and Chaudron, G., Compt. rend. 236, 686-688 (1954)

Chaudron, G., Nature 174, 923 (1954)

Grüneisen, E. and Goens, E.; Z. Physik. 44, 615 (1927)

Holborn, L.; Z. Instrumentenk. 22, 114 (1902)

Holborn, L., Ann. Physik. 59, 145 (1919)

Justi, F. and Scheffers, H.; Physik. Z. 39, 105 (1938)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Thomas, J. G. and Mendoza, E.; Phil. Mag. (7) 43, 900 (1952)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for aluminum to be used in calculating values of electrical resistivity (ρ_T) is listed below the authors' names labeling each individual curve on the graph. These curves should not be extrapolated to lower temperatures since aluminum becomes superconducting at 1.175°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Grüneisen and Goens; Holborn (1919); Justi and Scheffers; Meissner and Voigt; and Thomas and Mendoza, while those values listed by the International Critical Tables are from Holborn (1902 and 1919). These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

(Continued on following page)

ELECTRICAL RESISTIVITY of ALUMINUM, (Cont.)

Comments: (cont.)

The data reported in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of ρ_{273} to be used with the Holborn data in calculating values of electrical resistivity is $\rho_{273} = 2.53 \times 10^{-6}$ ohm-cm. The actual values of ρ_{273} are not available for the samples used by the other investigators so a datum value reported by Grüneisen and Goens ($\rho_{273} = 2.50 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from the remaining ratios.

The samples used by Holborn are reported in Landolt-Börnstein as polycrystalline with 0.4% impurities of unknown composition. The Holborn sample was annealed at 250°C. Grüneisen and Goens are reported to have used a polycrystalline sample with a small amount of impurities present. The sample used by Meissner and Voigt is reported as an annealed polycrystalline sample with undetermined impurities.

A single crystal with a small amount of impurities present is reported as the sample used by Justi and Scheffers. The sample used by Thomas and Mendoza was an annealed polycrystalline sample with 0.005% impurities of unknown composition. No other pertinent information was presented about any of the samples from any of the sources of data.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

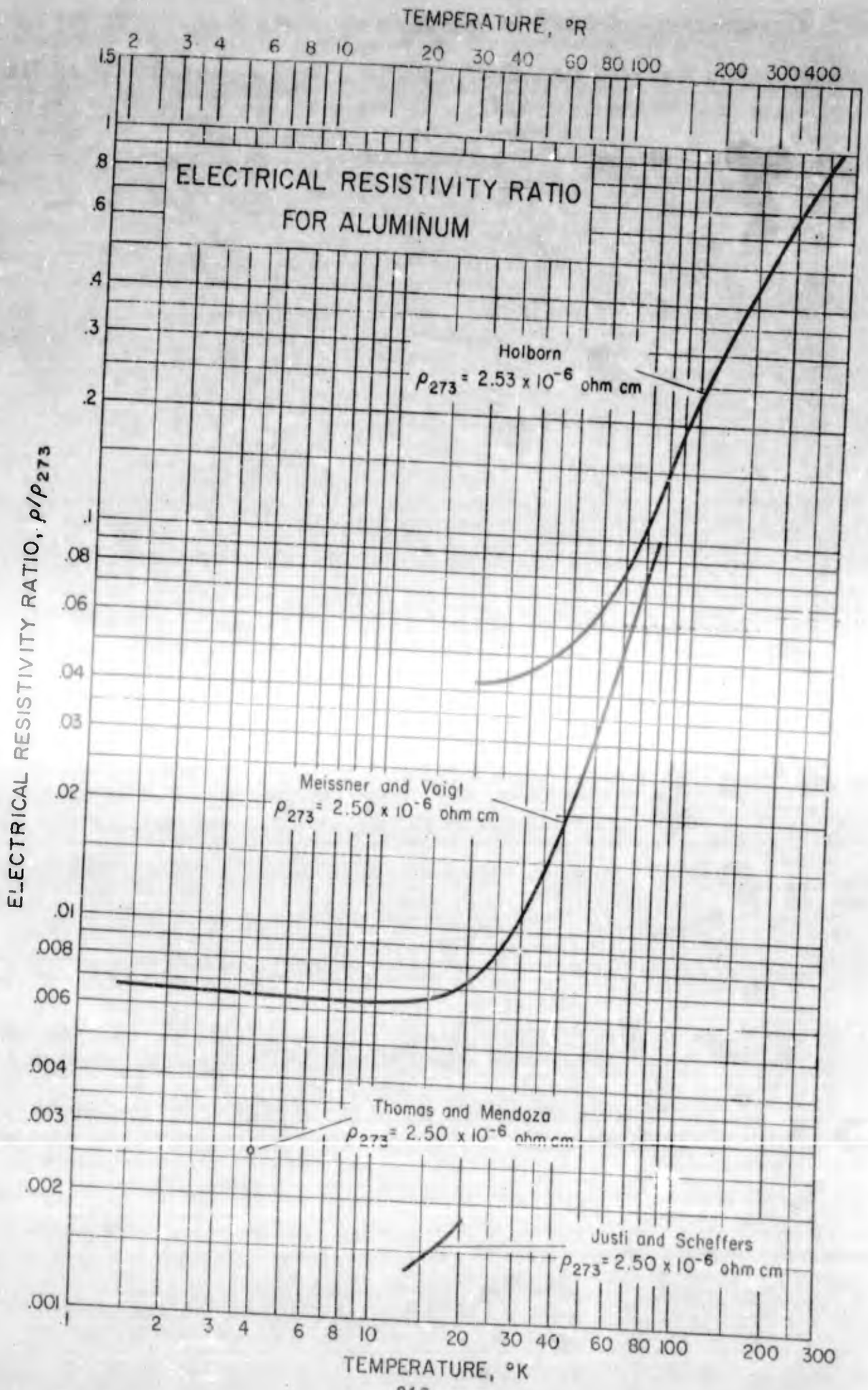
ρ_{273} = Resistivity at 273°K, (ohm-cm)

Holborn					
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.3*	64.80*	-140	37.7	-200	12.0
- 80	64.1	-160	28.9	-220	7.1
-100	55.2	-180	20.2	-240	4.9
-120	46.4	-191.9*	14.85*	-253*	4.27*
		-192.9*	14.49*		

* Observed values. All other values have been interpolated.

Justi and Scheffers		Meissner and Voigt		Thomas and Mendoza	
Temp. °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
14	0.0014	1.35	0.0067	4	0.0026
20	0.0018	4.21	0.0065		
		20.44	0.0075		
		77.7	0.1008		

* The second decimal place of the temperature values is somewhat in doubt.


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
ELECTRICAL RESISTIVITY RATIO FOR ALUMINUM
ELECTRICAL RESISTIVITY RATIO, ρ/ρ273
Holborn
ρ273 = 2.53 x 10-6 ohm cm
Meissner and Voigt
ρ273 = 2.50 x 10-6 ohm cm
Thomas and Mendoza
ρ273 = 2.50 x 10-6 ohm cm
Justi and Scheffers
ρ273 = 2.50 x 10-6 ohm cm
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of GALLIUM, Ga

(Atomic Number 31)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Bridgman, P. W.; Proc. Am. Acad. Arts Sci 56, 61 (1921)

de Haas, W. J. and Voogd, J.; Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 193b (1928)

Comments:

Reference should be made to the beginning of the Electrical Resistivity section for an explanation of the data. The value of the electrical resistivity at 273°K (ρ_{273}) for Gallium to be used in calculating values of electrical resistivity (ρ_T) is 40 x 10^{-6} ohm-cm.

The data presented here were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by de Haas and Voogd, cited above under "Other References".

The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of ρ_{273} is not available for the sample used by de Haas and Voogd so a datum value reported by Bridgman (ρ_{273} = 40 x 10^{-6} ohm-cm) is suggested for calculating values of resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by both investigators as polycrystalline with 0.3% impurities present in the de Haas and Voogd sample. No other pertinent information is given for either of the two samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

de Haas and Voogd	
Temp. °K	ρ/ρ_{273}*
1.1	0.00182
3.00	0.00254
4.20	0.00255
293.2	1.0693
* The fifth decimal place is in doubt.	

ELECTRICAL RESISTIVITY of INDIUM, In
(Atomic Number 49)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Meissner, W.; Franz, H. and Westerhoff, H.; Ann. Physik (5) 13, 555 (1932)

Meissner, W.; Franz, H. and Westerhoff, H.; Ann. Physik (5) 13, 505 (1932)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Tuyn, W. and Onnes, K. H.; Proc. Acad. Sci. Amsterdam 26, 504 (1923)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for indium to be used in calculating values of electrical resistivity (ρ_T) is 8.19×10^{-6} ohm-cm. The curves should not be extrapolated to lower temperatures since indium becomes a superconductor between 3.374 and 3.432°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner, Franz and Westerhoff; and Meissner and Voigt; while those values appearing in the International Critical Tables are from Tuyn and Onnes. These primary sources are listed above under "Other References". The original authors are used in labeling the three curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} were not available for the samples used by Meissner and Voigt; and Tuyn and Onnes so a datum value reported by Meissner, Franz and Westerhoff ($\rho_{273} = 8.19 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

(Continued on following page)

ELECTRICAL RESISTIVITY of INDIUM, (Cont.)

Comments: (cont.)

The Landolt-Börnstein tables list the samples of both references as polycrystalline with 0.1% impurities in the sample used by Meissner and Voigt and a very small amount of impurity in the samples used by Meissner, Franz and Westerhoff. No mention is made of the amount of impurities in the sample used by Tuyn and Onnes, and no information was given on the mechanical strain or heat treatment for any of the samples from any of the authors.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

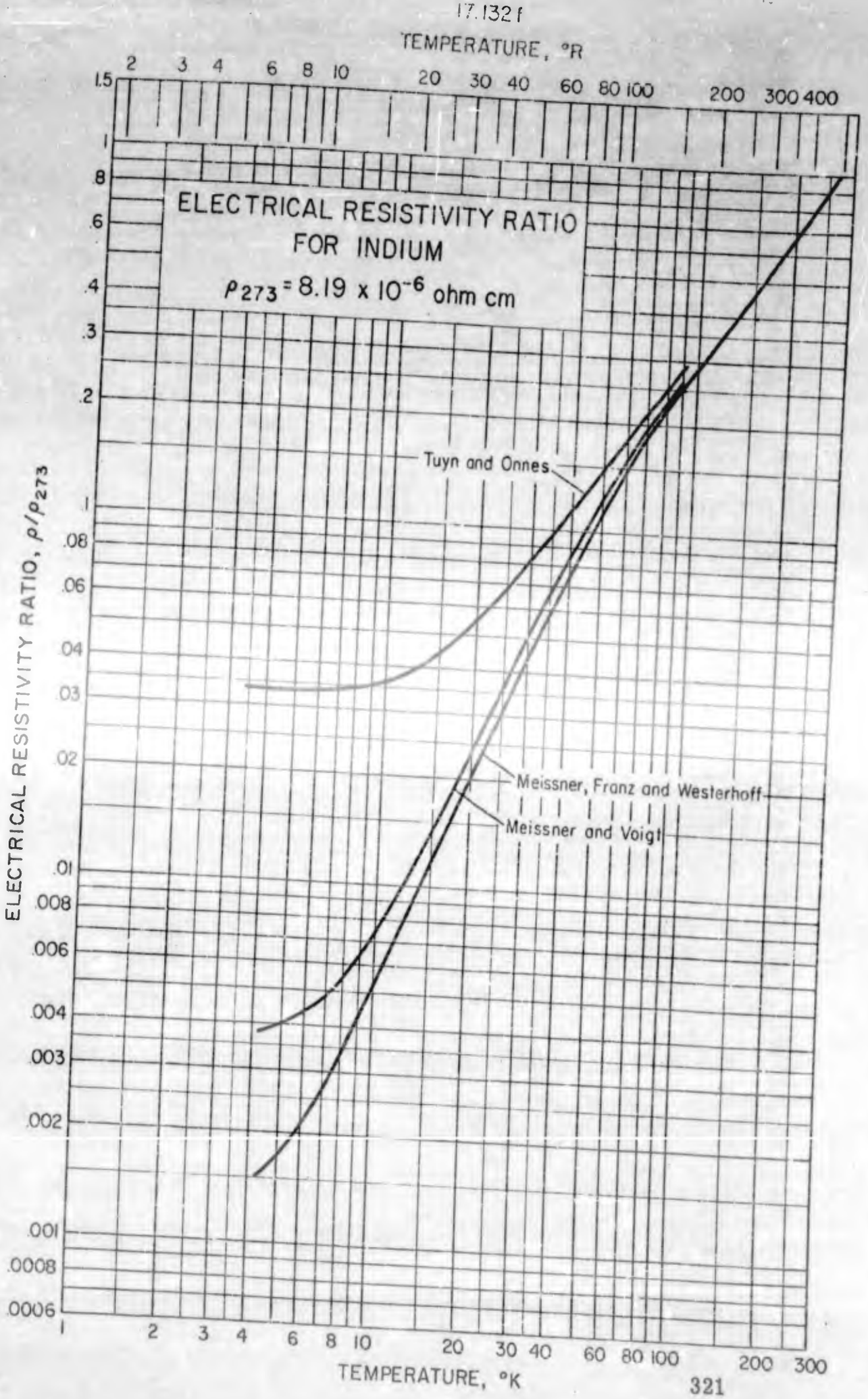
Meissner and Voigt	
Temp. °K	ρ/ρ_{273}
4.21	0.0038
20.5	0.0256
77.8	0.2177
88.9	0.2567

Meissner, Franz and Westerhoff	
Temp. °K	ρ/ρ_{273}
4.23	0.0015
20.4	0.0216
77.8	0.212

Tuyn and Onnes			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
-182.79	28.75	-254.95	5.173
-194.06	24.92	-256.61	4.796
-202.07	22.20	-258.89	4.317
-209.98	19.52	-268.87	3.394
-218.30	16.71	-269.49	3.392
-252.65	5.739	-269.61	3.387

RDM/RS Issued: 2/8/61

17.132 f


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
.0008
.0006
ELECTRICAL RESISTIVITY RATIO FOR INDIUM
$\rho_{273} = 8.19 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
Tuyn and Onnes
Meissner, Franz and Westerhoff
Meissner and Voigt
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of THALLIUM, Tl

(Atomic Number 81)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

de Haas, W. J.; de Boer, J. H. and Van den Berg, G. J.; Physica 2, 453 (1935)

Meissner, W., Franz, H. and Westerhoff, H.; Ann. Physik (5) 13, 555 (1932)

Meissner, W., Franz, H. and Westerhoff, H.; Ann. Physik (5) 13, 505 (1932)

Onnes, K. H. and Tuyn, W.; Proc. Acad. Sci. Amsterdam 25, 443 (1923)

Rosenbohm, E.; Physica 6, 337 (1939)

Comments:

Reference should be made to the preface at the beginning of the Electrical resistivity section for an explanation of the graph. The value of the electrical resistivity at 273°K (ρ_{273}) for thallium to be used in calculating values of electrical resistivity (ρ_T) is listed below the authors' names labeling each individual curve on the graph. These curves should not be extrapolated to lower temperatures as thallium becomes a superconductor at 2.392°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by de Haas, de Boer and Van den Berg; Meissner, Franz and Westerhoff; Onnes and Tuyn; and Rosenbohm. The values appearing in the International Critical Tables are also from Onnes and Tuyn. These primary sources are listed above under "Other References".

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of ρ_{273} for the sample used by Meissner, Franz and Westerhoff and suggested for calculating values of electrical resistivity from the Meissner, Franz and Westerhoff data is $\rho_{273} = 17.5 \times 10^{-6}$ ohm-cm. The actual values of ρ_{273} for the samples used by the remaining authors are not available, so a datum value ($\rho_{273} = 16.2 \times 10^{-6}$ ohm-cm) reported by Rosenbohm is suggested for calculating values of electrical resistivity from the remaining ratios. Rosenbohm reports a small amount of

(Continued on following page)

ELECTRICAL RESISTIVITY of THALLIUM, (Cont.)

Comments: (cont.)

impurities present in the polycrystalline sample used in the determination of ρ_{273}.

The Landolt-Börnstein tables list the samples of all four authors as polycrystalline with 0.005% impurities in the sample used by de Haas, de Boer and Van den Berg and a small amount of impurities in the samples used by the other authors. No other pertinent information was given for any of the samples used by any of the authors.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

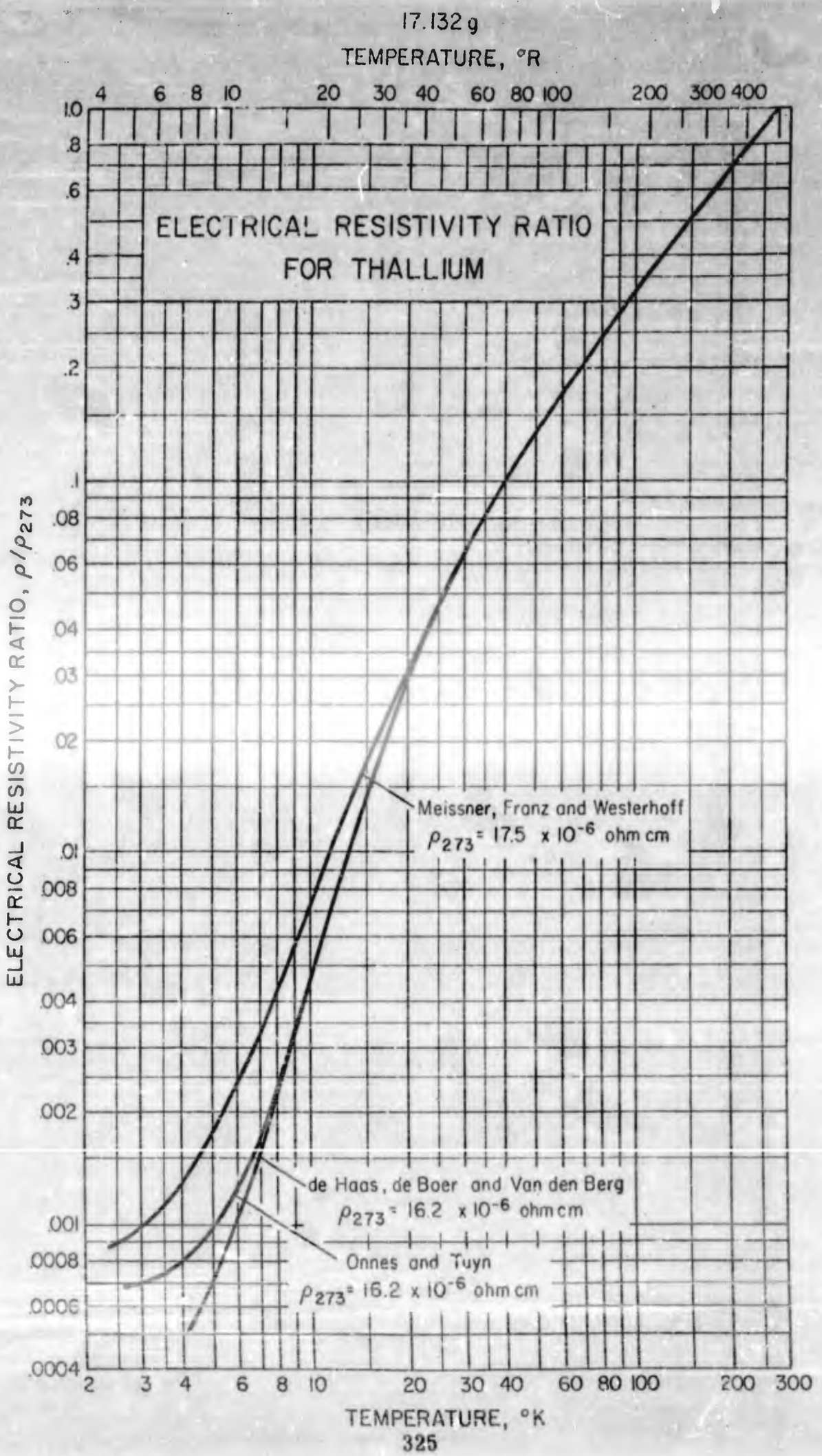
de Haas, de Boer and Van den Berg		Meissner, Franz and Westerhoff	
Temp.* °K	ρ/ρ_{273}*	Temp. °K	ρ/ρ_{273}
4.22	0.00053	4.2	0.0014
5.54	0.00086	20.4	0.0314
9.24	0.00356	77.9	0.2350
14.21	0.01297		
20.47	0.0317		

Onnes and Tuyn					
International Critical Tables				Landolt-Börnstein	
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp.	ρ/ρ_{273}
- 78.3	67.10	-252.62	3.023	4.2	0.0008
-184.52	27.20	-255.05	2.286	14.2	0.0126
-192.04	24.52	-256.62	1.841	20.5	0.0302
-200.03	21.69	-258.93	1.259	81.1	0.2453
-207.11	19.18	-268.86	0.084	194.8	0.6710
-216.33	15.92	-269.83	0.072		

* The second decimal place of the temperature values is somewhat in doubt.

\+ The fifth decimal place of values of electrical resistivity is somewhat in doubt.

17.132 g


TEMPERATURE, °R
4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR THALLIUM
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0 .8 .6 .4 .3 .2 .1 .08 .06 .04 .03 .02 .01 .008 .006 .004 .003 .002 .001 .0008 .0006 .0004
Meissner, Franz and Westerhoff
$\rho_{273} = 17.5 \times 10^{-6}$ ohm cm
de Haas, de Boer and Van den Berg
$\rho_{273} = 16.2 \times 10^{-6}$ ohm cm
Onnes and Tuyn
$\rho_{273} = 16.2 \times 10^{-6}$ ohm cm
2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of TITANIUM, Ti

(Atomic Number 22)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Clausing, P. and Moubis, G.; Physica 7, 245 (1927)

Fast, J. D.; Z. anorg. u allgem. Chem. 241, 42 (1939)

Meissner, W., Franz, H. and Westerhoff, H.; Ann. Physik (5) 13, 555 (1932)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for titanium to be used in calculating electrical resistivity is listed below the authors' names labeling each individual curve on the graph. These curves should not be extrapolated to lower temperatures since titanium becomes a superconductor at 0.39°K.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from the Landolt-Börnstein tables are those reported by the authors listed above under "Other References". The original authors are used in labeling the three curves on the graph.

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature, as listed in the following tabular data. The actual value of ρ_{273} is not available for the Meissner, Franz and Westerhoff data so a datum value reported by Fast ($\rho_{273} = 42.0 \times 10^{-6}$ ohm-cm) is suggested for calculating values of resistivity from these ratios. Fast reports very small impurities in the single crystal sample used in determining ρ_{273}.

The Landolt-Börnstein tables list the sample used by Clausing and Maubis as polycrystalline with 0.16% tungsten impurity. The sample used by Meissner and Voigt is also reported as of a polycrystalline nature drawn from a melt with 0.25% impurities of unknown type. The sample used by Meissner, Franz and Westerhoff is reported as being drawn from a melt with very small impurities. No comments were made on the mechanical working or heat treatment of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY OF TITANIUM (cont.)

Tables of Values of Electrical Resistivity

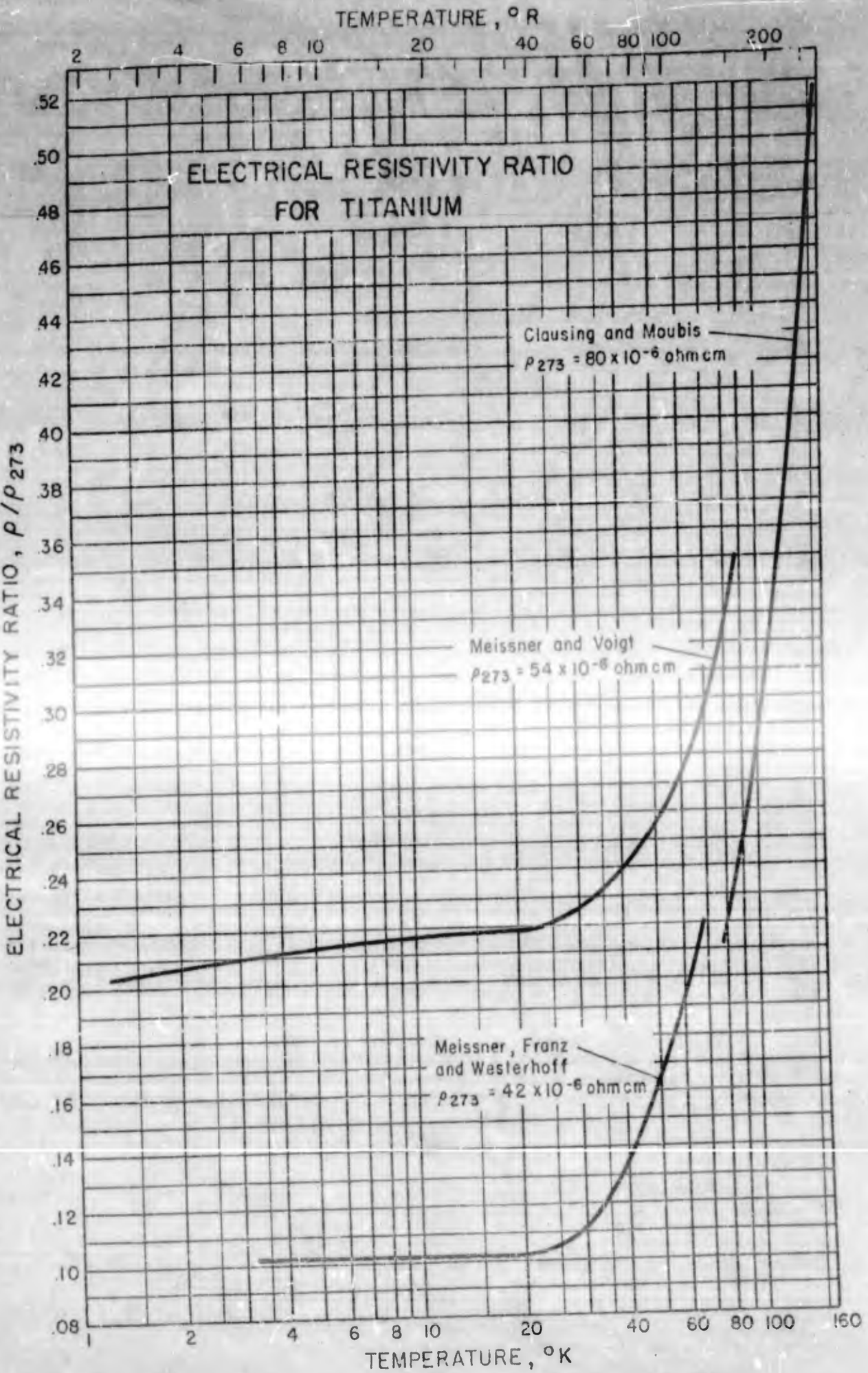
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Clausing & Moubis		Meissner, Franz & Westerhoff	
Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
78.5	0.2150	3.24	0.102
90.2	0.2547	20.4	0.1015
158.5	0.5178	79.1	0.211

Meissner & Voigt	
Temp. °K	ρ/ρ_{273}
1.26	0.203
4.21	0.215
20.5	0.2180
88.2	0.3505

RDM/RS Issued: 1/18/61


TEMPERATURE, °R
2
4
6
8
10
20
40
60
80
100
200
ELECTRICAL RESISTIVITY RATIO FOR TITANIUM
Clausing and Moubis
$\rho_{273} = 80 \times 10^{-6}$ ohm cm
Meissner and Voigt
$\rho_{273} = 54 \times 10^{-6}$ ohm cm
Meissner, Franz and Westerhoff
$\rho_{273} = 42 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.52
.50
.48
.46
.44
.42
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
1
2
4
6
8
10
20
40
60
80
100
160
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of ZIRCONIUM, Zr

(Atomic Number 40)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Other References:

de Boer, J. H. and Fast, J. D.; Z. anorg. allgem. Chem. 187, 193 (1930)

Clausing, P.; Physica 4, 372 (1924)

de Haas, W. J. and Voogd, J.; Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 194c (1928)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for zirconium to be used in calculating values of electrical resistivity (ρ_T) is listed below the authors' names labeling each individual curve on the graph. These curves should not be extrapolated to lower temperatures since zirconium becomes a superconductor at 0.55°K.

The data for this graph were taken from the references cited above under "sources of Data". The values listed in the Landolt-Börnstein tables are those reported by de Boer and Fast; de Haas and Voogd; and Meissner and Voigt; while those listed by the International Critical Tables are from Clausing. These primary sources are listed under "Other References". The original authors are used in labeling the several curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables, and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The value of ρ_{273} reported by Meissner and Voigt and suggested for calculating values of electrical resistivity from the Meissner and Voigt data is $\rho_{273} = 49 \times 10^{-6}$ ohm-cm. The actual values of ρ_{273} are not available for the samples used by the other authors so a datum value reported by de Boer and Fast ($\rho_{273} = 41 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from the remaining ratios. de Boer and Fast report a very small amount of impurities in the sample used in determining ρ_{273}.

The sample used by Meissner and Voigt is reported in Landolt-Börnstein as polycrystalline in nature having been pulled from a melt with less than 0.35% impurities of unknown composition. The sample used by de Haas and Voogd is reported as polycrystalline with a very small amount of impurities present. No other pertinent information was given for any of the samples in any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of ZIRCONIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

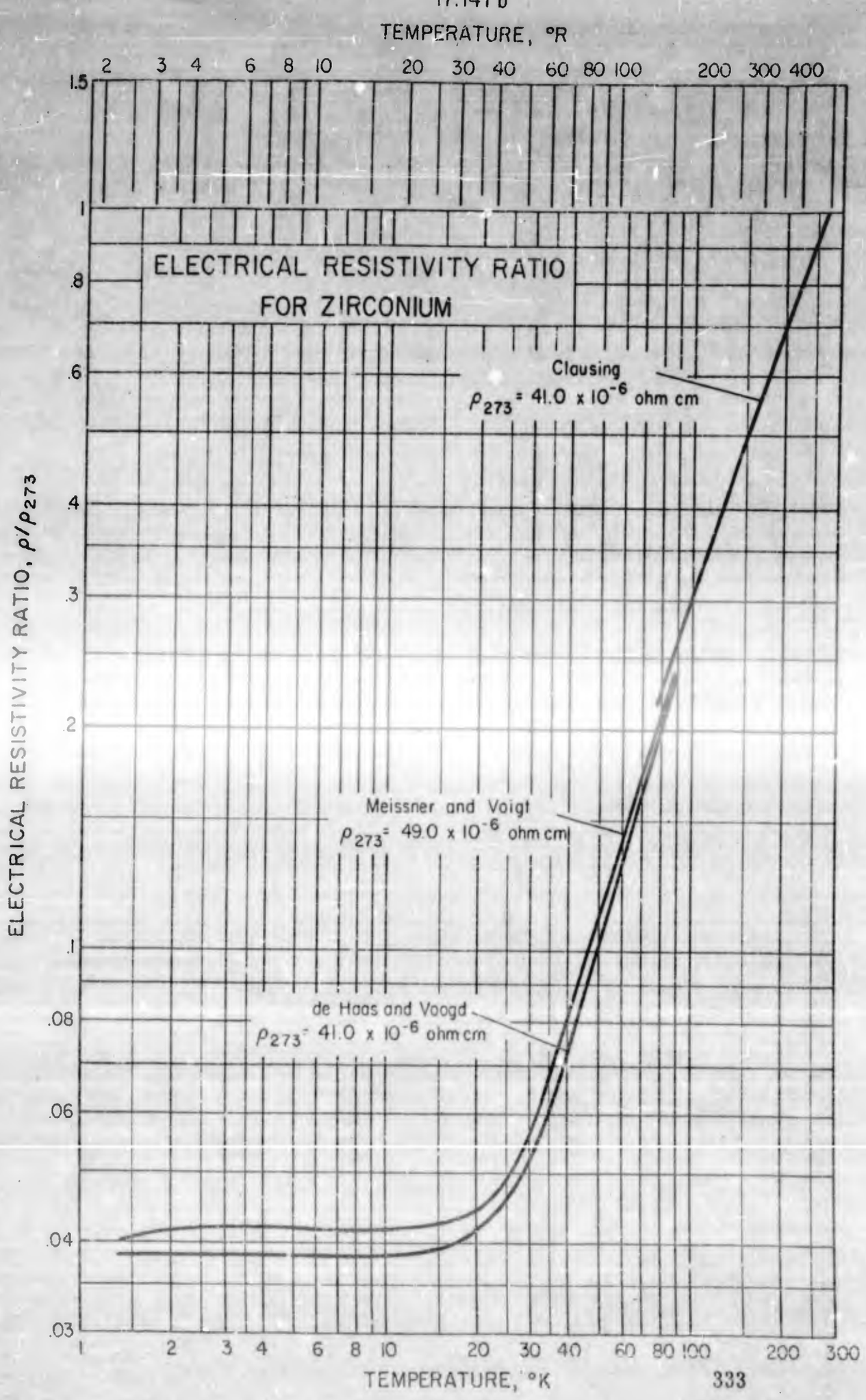
Meissner and Voigt		de Haas and Voogd	
Temp.* °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}
1.13	0.0388	1.35	0.0383
1.36	0.0403	4.21	0.0383
4.22	0.0421	14.2	0.0393
20.5	0.0444	18.0	0.0404
77.7	0.1971	20.3	0.0417
88.2	0.2380	78.2	0.1926
		90.0	0.2379

* The second decimal place of the temperature values is somewhat in doubt.

Clausing	
Temp. °C	$100\rho/\rho_{273}$
- 80	66.4
-100	58.4
-120	50.5
-140	42.7
-160	35.0
-180	27.4
-182.87*	26.26*
-194.93*	21.85*

* Results of actual observations. All other values from interpolations.

RDM/RS Issued: 2/10/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR ZIRCONIUM
Clausing
ρ_{273} = 41.0 x 10^{-6} ohm cm
Meissner and Voigt
ρ_{273} = 49.0 x 10^{-6} ohm cm
de Haas and Voogd
ρ_{273} = 41.0 x 10^{-6} ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of HAFNIUM, Hf

(Atomic Number 72)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

de Boer, J. H. and Fast, J. D.; Z. anorg. u allgem. Chem. 187, 193 (1930)

de Haas, W. J. and Voogd, J.; Communs. Phys. Lab. Univ. Leiden Commun. No. 194c, (1928)

Hein, R. A.; Phys. Rev. 102, 1511 (1956)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for hafnium to be used in calculating values of electrical resistivity (ρ_T) is 30×10^{-6} ohm-cm. The curves should not be extrapolated to lower temperatures since hafnium becomes a superconductor at 0.37°K.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from the Landolt-Börnstein tables are those reported by the authors listed above under "Other References". The original authors are used in labeling the two curves on the graph.

The data reported in the Landolt-Börnstein and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of ρ_{273} is not available for the several authors' data so a datum value reported by de Boer and Fast ($\rho_{273} = 30 \times 10^{-6}$ ohm-cm) is suggested for calculating values of resistivity from these ratios. de Boer and Fast report a very small amount of impurities in the polycrystalline sample used in determining ρ_{273}.

The samples used by de Haas and Voogd as reported in Landolt-Börnstein were drawn from a melt and of the polycrystalline type. No mention was made of the impurities present in the samples. The samples used by Hein were also of the polycrystalline type. Hein reports impurities of 1.08% of which 0.9% was Zr. No mention is made of the composition of the remainder of the impurities. The Hein samples were annealed several times, but no other mention is made of mechanical or heat treatment of any of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY of HAFNIUM (Cont.)

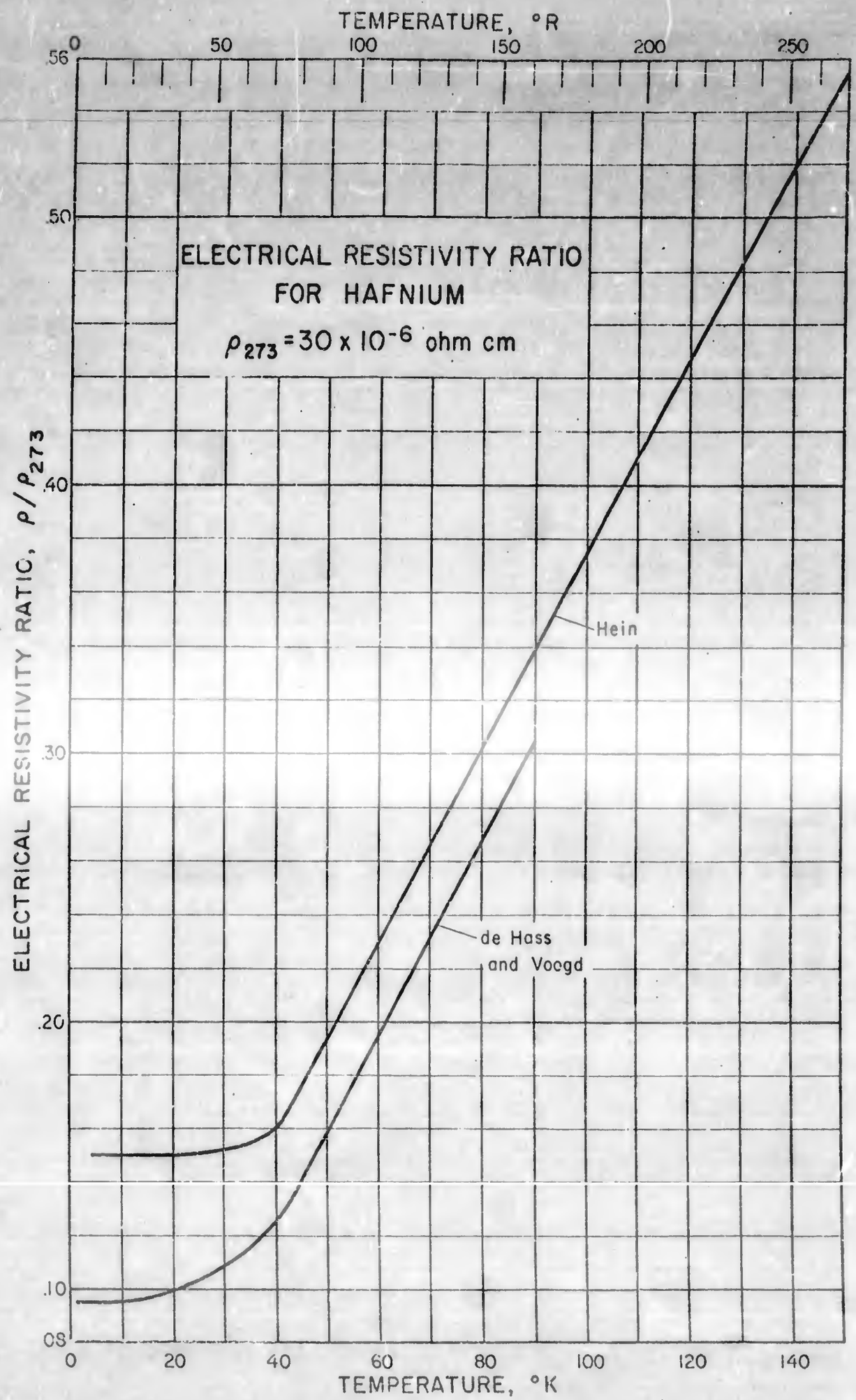
Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

de Haas and Voogd	
Temp. °K	ρ/ρ_{273}
1.3	0.0947
4.2	0.0947
14.2	0.0963
18.0	0.0982
20.3	0.1000
78.2	0.2626
90.0	0.3045

Hein	
Temp. °K	ρ/ρ_{273}
4.2	0.15
20.0	0.15
40.0	0.16
50.0	0.19
150.0	0.55


TEMPERATURE, °R
0
50
100
150
200
250
.56
.50
.40
.30
.20
.10
.05
ELECTRICAL RESISTIVITY RATIO
FOR HAFNIUM
$\rho_{273} = 30 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
Hein
de Hass
and Voogd
0
20
40
60
80
100
120
140
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of TIN, Sn
(Atomic Number 50)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Jaeger, W. and Diesselhorst, H.; Wiss. Abhandl. physik. tech. Reichsanstalt, 3, 269 (1900)

Meissner, W.; Physik. Z. 26, 689 (1925)

Onnes, K. H. and Tuyn, W.; Proc. Roy. Acad. Sci. Amsterdam 25, 443 (1923)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of the electrical resistivity at 273°K (ρ_{273}) for tin to be used in calculating values of electrical resistivity (ρ_T) is 11.15×10^{-6} ohm-cm. The curves should not be extrapolated to lower temperatures as tin becomes a superconductor at 3.74°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Jaeger and Diesselhorst; and Meissner; while those values appearing in the International Critical Tables are from Onnes and Tuyn. These primary sources are listed above under "Other References".

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the electrical resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by both the investigators are not available so a datum value reported by Jaeger and Diesselhorst ($\rho_{273} = 11.15 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios. Jaeger and Diesselhorst report less than 0.03% Pb impurity in the polycrystalline sample used in the determination of ρ_{273}.

The Landolt-Börnstein tables list the samples of Meissner as polycrystalline with no mention of impurities present. The sample used by Onnes and Tuyn is reported as polycrystalline with less than 0.01% impurities of unknown composition. No information was given on the mechanical or heat treatment of any of the samples from any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of TIN (Cont.)

Tables of Values of Electrical Resistivity

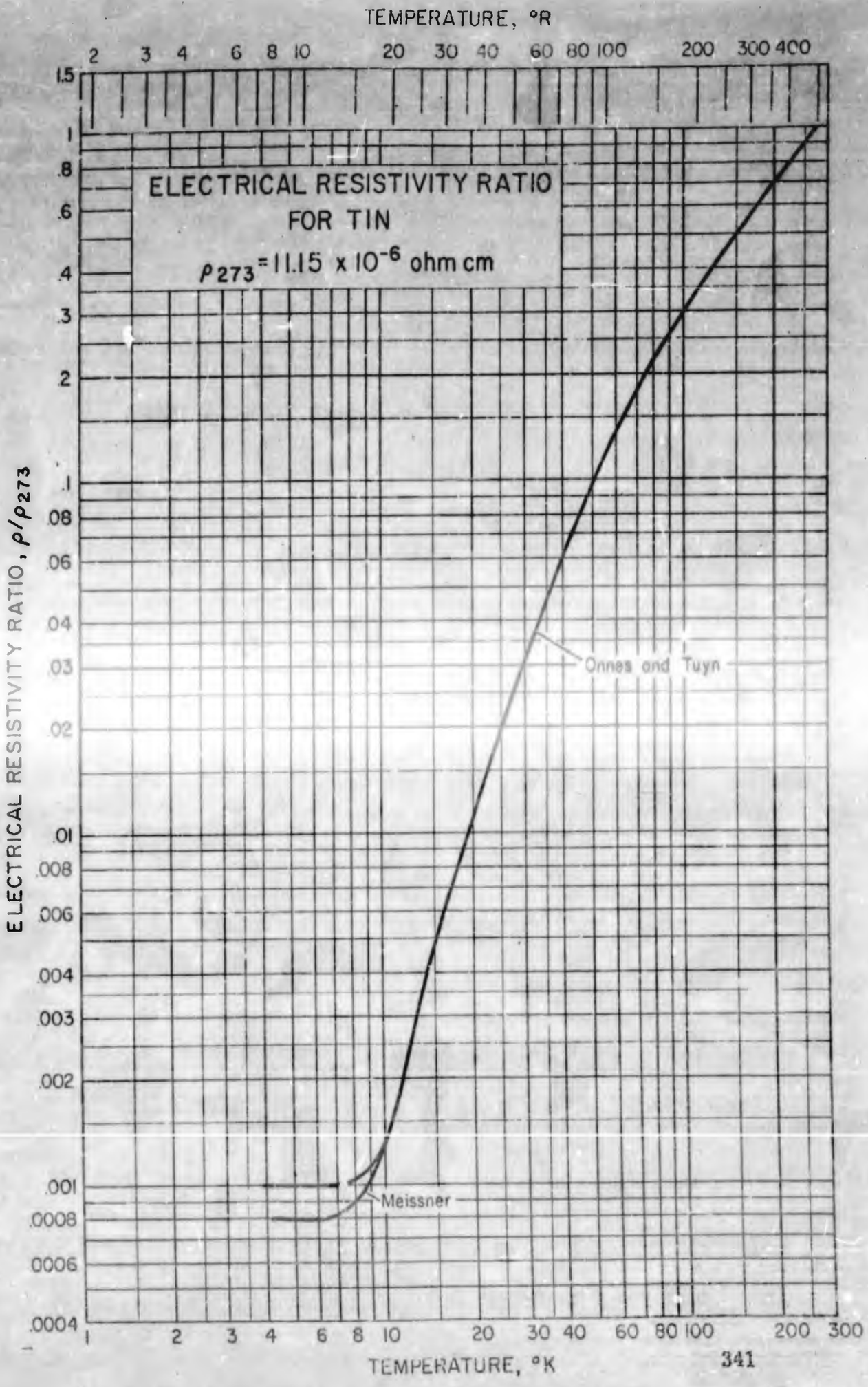
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Onnes and Tuyn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
-102.13	57.36	-209.98	14.67
-115.14	52.16	-218.30	11.45
-127.50	47.25	-252.65	1.162
-141.06	41.90	-254.95	0.836
-158.74	34.91	-256.61	0.637
-182.80	25.44	-258.89	0.409
-194.07	20.98	-269.33	0.099
-202.07	17.79		

Meissner	
Temp. °K	ρ/ρ_{273}
4.2	0.00078
20.4	0.0120
88.2	0.2457

RDM/RS Issued: 2/2/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR TIN
$\rho_{273} = 11.15 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5 1 .8 .6 .4 .3 .2 .1 .08 .06 .04 .03 .02 .01 .008 .006 .004 .003 .002 .001 .0008 .0006 .0004
Onnes and Tuyn
Meissner
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

17.142-3b

ELECTRICAL RESISTIVITY of LEAD, Pb

(Atomic Number 82)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Berlag, Berlin (1959) pp. 1-46

Other References:

Jaeger, W. and Diesselhorst, H.; Wiss. Abhandl. physik. tech. Reichsanstalt 3, 269 (1900)

Meissner, W. and Franz, H.; Z. Physik. 65, 30 (1930)

Meissner, W.; Ann. Physik. (5) 13, 641 (1932)

Onnes, H. K. and Tuyn, W.; Communs. Kamerlingh Onnes Lab. Univ. Leiden Suppl. No. 58 (1926)

Van den Berg, G. J.; Physica 14, 111 (1948)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for lead to be used in calculating values of electrical resistivity (ρ_T) is 19.2×10^{-6} ohm-cm. The curves on the graph should not be extrapolated to lower temperatures as lead becomes a superconductor at 7.22°K.

It will be noted, however, that the data of Van den Berg extend into the superconducting region. These data below the transition temperature were based on observations of the electrical resistance with the lead subjected to a super critical magnetic field to maintain electrical resistance.

The data for this graph were taken from the reference cited above under "Source of Data". The data listed in the Landolt-Börnstein tables are those reported by the authors listed above under "Other References". The original authors are used in labeling the curves on the graph.

The data reported in Landolt-Börnstein and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the original investigators so a datum value reported by Jaeger and Diesselhorst ($\rho_{273} = 19.2 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios. Jaeger and Diesselhorst report the sample used in determining ρ_{273} as polycrystalline with less than 0.05% impurities.

The Landolt-Börnstein tables report the samples used by all of the investigators as polycrystalline with a very small amount of impurities present. No other pertinent information is given about any of the samples used by any of the investigators.

(Continued on the following page)

ELECTRICAL RESISTIVITY of LEAD (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

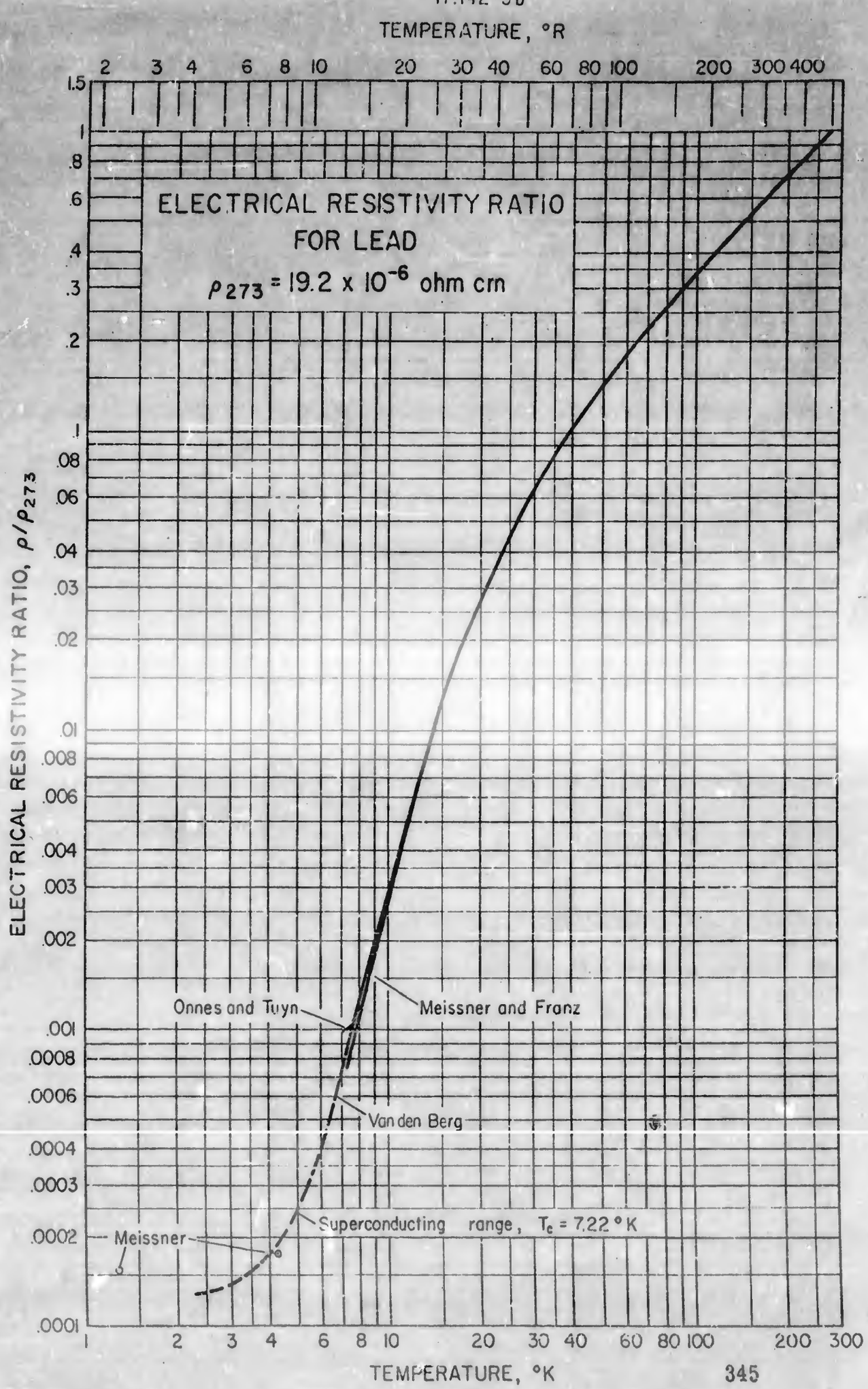
Meissner and Franz		Meissner	
Temp.* °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
7.26	0.0007	1.3	1.55×10^{-4}+
14.02	0.0104	4.2	1.75×10^{-4}+
20.32	0.0292		

Onnes and Tuyn		Van den Berg	
Temp.* °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}***
7.26	0.0010	2.30	0.00013+
14.32	0.0113	3.22	0.00015+
20.52	0.0301	4.24	0.00019+
73.11	0.2321	7.22	0.00083
88.56	0.2895	9.38	0.0025
		20.32	0.0301

* The second decimal place of the temperature values is somewhat in doubt.

** The fifth decimal place of the electrical resistivity ratio values is somewhat in doubt.

\+ These measurements were made with the aid of a supercritical magnetic field at temperatures at which lead is normally a superconductor. (For a more detailed explanation see the preface of the electrical resistivity section.)


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR LEAD
$\rho_{273} = 19.2 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5 1 .8 .6 .4 .3 .2 .1 .08 .06 .04 .03 .02 .01 .008 .006 .004 .003 .002 .001 .0008 .0006 .0004 .0003 .0002 .0001
Onnes and Tuyn
Meissner and Franz
Van den Berg
Meissner
Superconducting range, $T_c = 7.22$ °K
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of NIOBIUM, Nb

(Atomic Number 41)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Meissner, W., Franz, H. and Westerhoff, H.; Ann Physik (5) 17, 593 (1933)

Reimann, A. L. and Grant, K.; Phil. Mag. (7) 22, 34 (1936)

Comments:

Reference should be made to the beginning of the Electrical Resistivity section for an explanation of the data. The value of the electrical resistivity at 273°K (ρ_{273}) for Niobium to be used in calculating values of electrical resistivity (ρ_T) is 16.1×10^{-6} ohm-cm. This data should not be extrapolated to lower temperatures as Niobium becomes a superconductor between 8.7 and 8.9°K.

The data presented here were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner, Franz and Westerhoff; and Reimann and Grant, cited above under "Other References".

The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of ρ_{273} is not available for the sample used by Meissner, et al. so a datum value reported by Reimann and Grant ($\rho_{273} = 16.1 \times 10^{-6}$ ohm-cm) is suggested for calculating values of resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by Meissner, et al. as polycrystalline with 0.08% O_2 and 0.02% Ta impurities present. No other pertinent information is given about either of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner, Franz and Westerhoff	
Temp. °K	ρ/ρ_{273}
9.33	0.035
20.4	0.0617
78	0.2416

ELECTRICAL RESISTIVITY of TANTALUM, Ta
(Atomic Number 73)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Burgers, W. G. and Basart, J. C. M.; Z. Anorg. Allgem. Chem. 216, 223 (1934)

Holborn, L.; Ann. Physik 59, 145 (1919)

McLennan, J. C., Howlett, L. E. and Wilhelm, J. O.; Trans. Roy. Soc. Can. 23, III, 287 (1930)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for tantalum to be used in calculating values of electrical resistivity (ρ_T) is 12.4 x 10^{-6} ohm-cm. The curves on this graph should not be extrapolated to lower temperatures as tantalum becomes a superconductor at 4.38 degrees.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Burgers and Basart; McLennan, Howlett and Wilhelm; and Meissner and Voigt; while those values appearing in the International Critical Tables are from Holborn. These primary sources are cited above under "Other References". The names of the original authors are used in labeling the curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Burgers and Basart (ρ_{273} = 12.4 x 10^{-6} ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The samples used by the investigators appearing in Landolt-Börnstein are reported as polycrystalline with no mention made of impurities. No other pertinent information is given about any of the samples from any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of TANTALUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

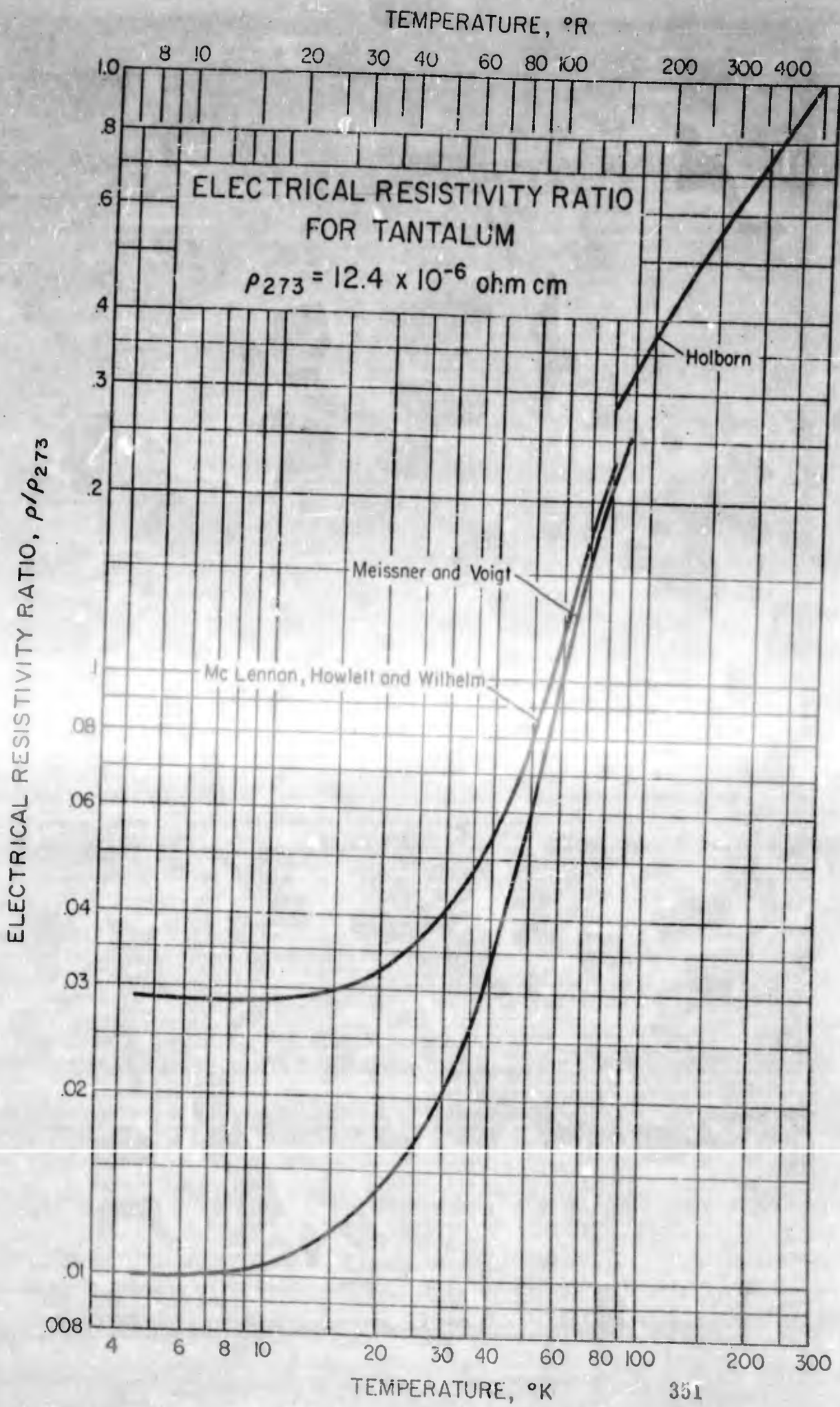
Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.2	72.98	-140 +	49.6
- 80 +	72.4	-160 +	41.9
-100 +	64.9	-180 +	34.3
-120 +	57.3	-192.6	29.55

Meissner and Voigt		McLennan, Howlett and Wilhelm	
Temp.* °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
4.29	0.00019	4.3	0.029
4.49	0.0099	20.6	0.033
20.44	0.0140	80.0	0.230
77.61	0.2037		
88.30	0.2511		

* The second decimal place of the temperature values is somewhat in doubt.

\+ Values from interpolation.

RDM/RS Issued: 2/15/61


TEMPERATURE, °R
8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR TANTALUM
$\rho_{273} = 12.4 \times 10^{-6}$ ohm cm
Holborn
Meissner and Voigt
Mc Lennan, Howlett and Wilhelm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of VANADIUM, V

(Atomic Number 23)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Meissner, W. and Westerhoff, H.; Z. Physik 87, 206 (1933)

Potter, H. H.; Proc. Phys. Soc. (London) 53, 695 (1941)

Comments:

Reference should be made to the beginning of the Electrical Resistivity section for an explanation of the data. The value of the electrical resistivity at 273°K (ρ_{273}) for vanadium to be used in calculating values of electrical resistivity (ρ_T) is 18.2×10^{-6} ohm-cm. This data should not be extrapolated to lower temperatures as vanadium becomes a superconductor at 4.89°K.

The data presented here were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Potter; and Meissner and Westerhoff, cited above under "Other References".

The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of ρ_{273} is not available for the sample used by Meissner and Westerhoff so a datum value reported by Potter ($\rho_{273} = 18.2 \times 10^{-6}$ ohm-cm) is suggested for calculating values of resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by all of the investigators as polycrystalline. The sample used by Potter is reported as having 0.2% Fe impurities present. The sample used by Meissner and Westerhoff is reported as having 0.5% Fe, 0.06% Zn, and 0.08% Pt present. The Meissner and Westerhoff sample was pulled from a melt. No further pertinent information is given about any of the samples.

Table of Values of Electrical Resistivity

ρ = Resistivity (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner and Westerhoff	
Temp. °K	ρ/ρ_{273}
4.3*	0.0017
20.4	0.0031
77.5	0.1625

* Superconducting Range

RDM/RS Issued: 2/28/61

ELECTRICAL RESISTIVITY of ARSENIC, As

(Atomic Number 33)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other Reference:

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for arsenic to be used in calculating values of electrical resistivity (ρ_T) is 26×10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt, cited under "Other Reference".

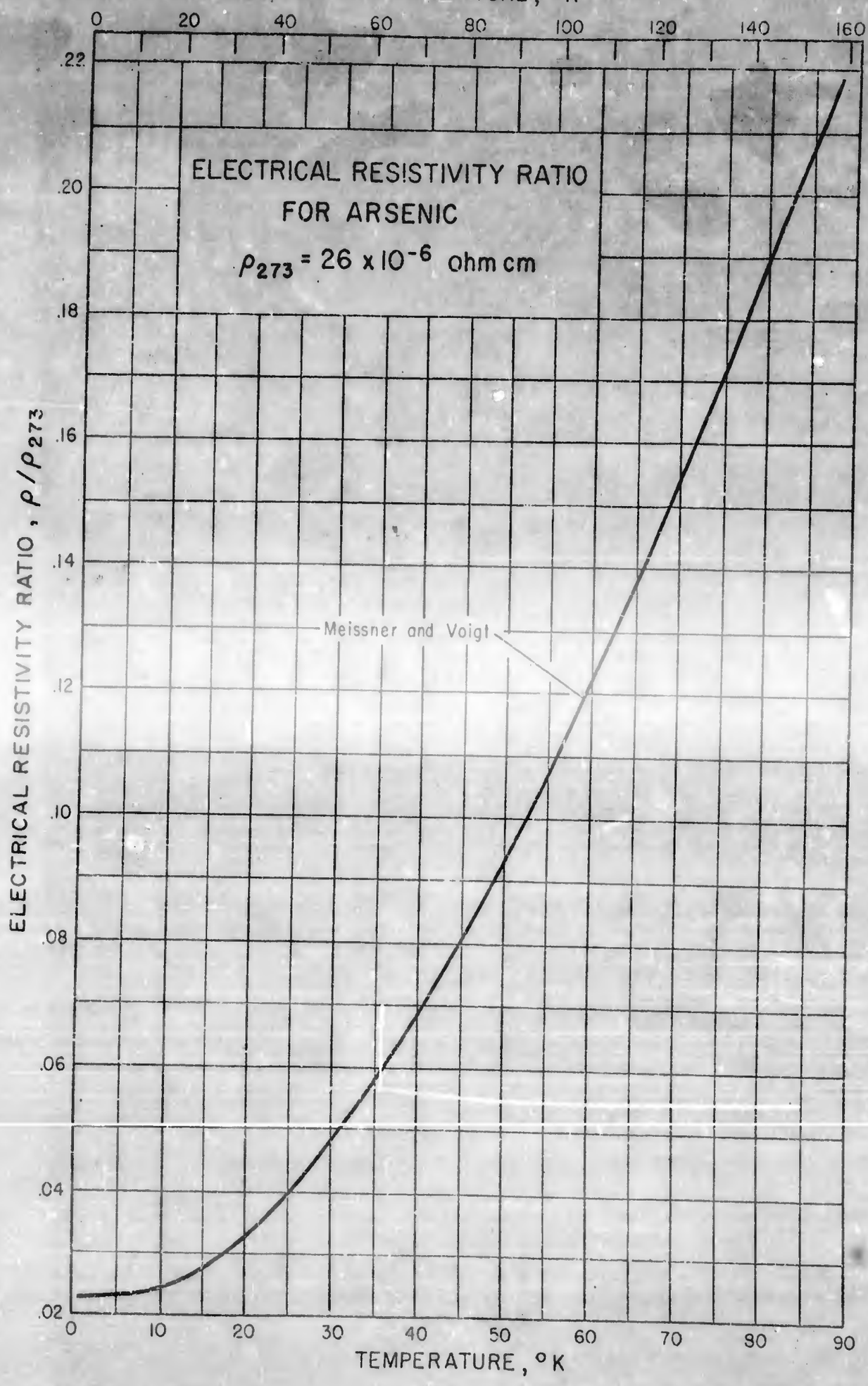
The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of ρ_{273} determined by Meissner and Voigt and suggested as a datum value here is $\rho_{273} = 26 \times 10^{-6}$ ohm-cm.

The sample used by Meissner and Voigt was of a polycrystalline nature with a reported 0.01% Zn impurity present. No information is given in Landolt-Börnstein on the mechanical or heat treatment of the sample.

Table of Values of Electrical Resistivity	
ρ = Resistivity, (ohm-cm)	
ρ_{273} = Resistivity at 273°K, (ohm-cm)	
Meissner and Voigt	
Temp.* °K	ρ/ρ_{273}
1.13	0.0211
1.36	0.0213
4.20	0.0228
20.45	0.0322
78.3	0.1825
88.2	0.2184
*The second decimal place is somewhat in doubt.	

RDM/RS Issued: 1/11/61

17.152 a


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO FOR ARSENIC
$\rho_{273} = 26 \times 10^{-6}$ ohm cm
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of ANTIMONY, Sb

(Atomic Number 51)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc. (1929) pp. 124-135

Other References:

Eucken, A. and Gehlhoff, G.; Verhandl. deut. physik. Ges. 14, 169-182 (1912)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Gehlhoff, G. and Neumeier, F.; Verhandl. deut. physik. Ges. 15, 876 (1913)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for antimony to be used in calculating values of electrical resistivity (ρ_T) is 39 x 10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; and Eucken and Gehlhoff, while those values listed by the International Critical Tables are from Gehlhoff and Neumeier. These primary sources are listed above under "Other References". The original authors are used in labeling the two curves on the graph.

The data reported in the Landolt-Börnstein tables and in the International Critical Tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so that a datum value reported by Eucken and Gehlhoff (ρ_{273} = 39 x 10^{-6} ohm-cm) is suggested for calculating values of resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by both references as being polycrystalline. The sample used by Meissner and Voigt is reported to have less than 0.1% impurities of unknown composition while the sample used by Eucken and Gehlhoff is reported to have 0.05% impurities of unknown composition. No mention is made of the nature of the sample used by Gehlhoff and Neumeier, and no information is given on mechanical or heat treatment for any of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY of ANTIMONY (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt	
Temp.* °K	ρ/ρ_{273}
1.16	0.0180
1.30	0.0192
4.20	0.0195
20.42	0.0319
77.7	0.2041
88.4	0.2441

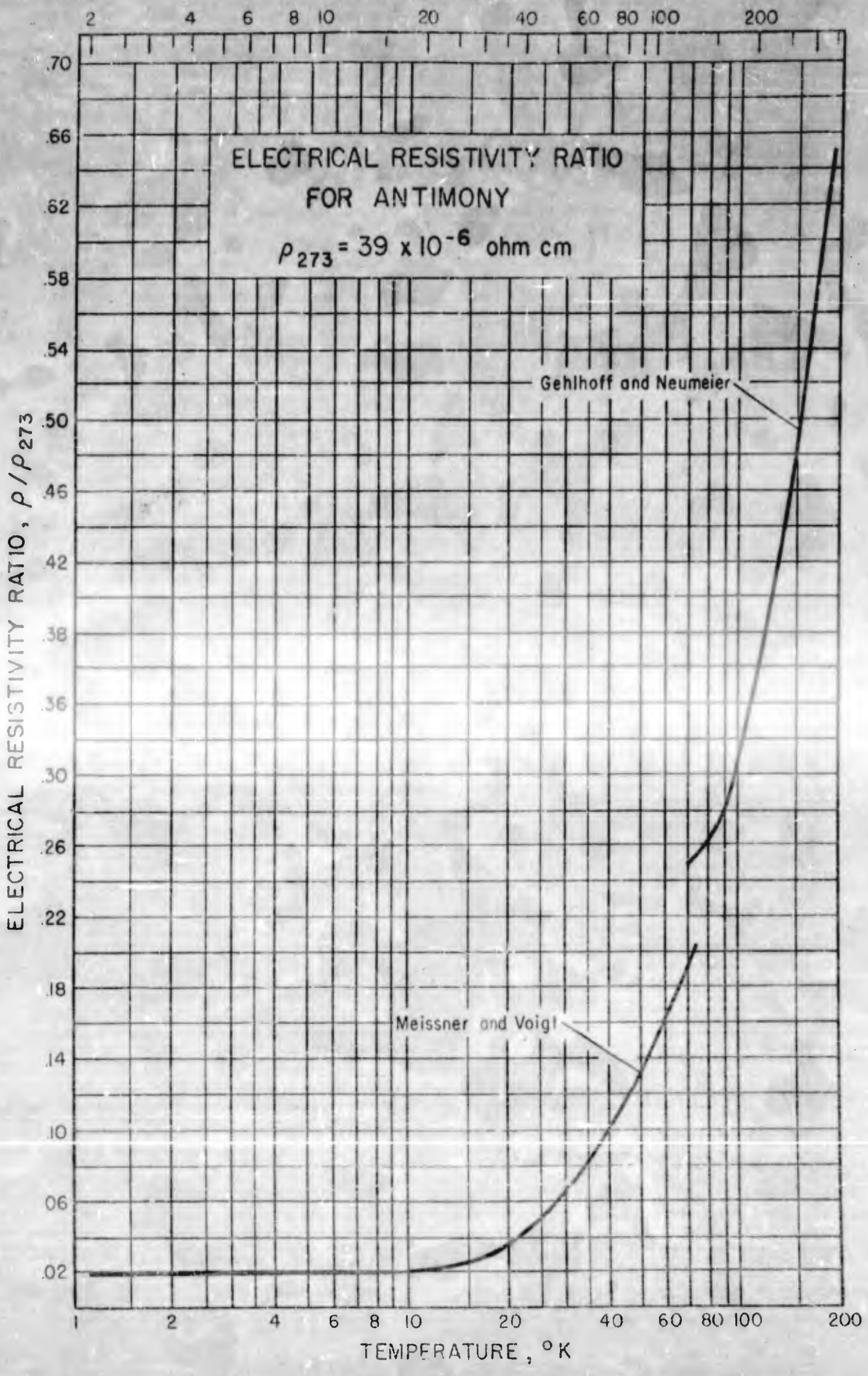
*The second decimal place of the temperature values is somewhat in doubt.

Gehlhoff and Neumeier	
Temp. °C	$100\rho/\rho_{273}$
- 77	65.73*
- 80	64.5
-100	56.7
-120	49.1
-140	41.7
-160	34.8
-180	28.3
-190	25.03*

* Observed points. Other points have been interpolated.

RDM/RS Issued: 1/12/61

17.152 b


TEMPERATURE °R
2
4
6
8
10
20
40
60
80
100
200
ELECTRICAL RESISTIVITY RATIO FOR ANTIMONY
$\rho_{273} = 39 \times 10^{-6}$ ohm cm
Gehlhoff and Neumeier
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.70
.66
.62
.58
.54
.50
.46
.42
.38
.36
.30
.26
.22
.18
.14
.10
.06
.02
1
2
4
6
8
10
20
40
60
80
100
200
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of BISMUTH, Bi

(Atomic Number 83)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Jaeger, W., and Diesselhorst, H.; Wiss. Abhandl. physik tech. Reichanstalt 3, 269 (1900)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Onnes, K. H. and Clay, J.; Proc. Acad Sci Amsterdam 10, 207 (1908)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for bismuth to be used in calculating electrical resistivity is 110.0 x 10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Jaeger and Diesselhorst; and Meissner and Voigt; while those values appearing in the International Critical Tables are from Onnes and Clay. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Jaeger and Diesselhorst (ρ_{273} = 110.0 x 10^{-6} ohm-cm) is suggested for calculating values of resistivity from these ratios.

The sample used by Meissner and Voigt is reported to be polycrystalline with a very small amount of impurities present of an unknown composition. The Jaeger and Diesselhorst sample is reported in Landolt-Börnstein as polycrystalline with 0.03% impurities of unknown composition. No information is available on the sample used by Onnes and Clay, and no mention is made of the mechanical or heat treatment of any of the samples in any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of BISMUTH (Cont.)

Tables of Values of Electrical Resistivity

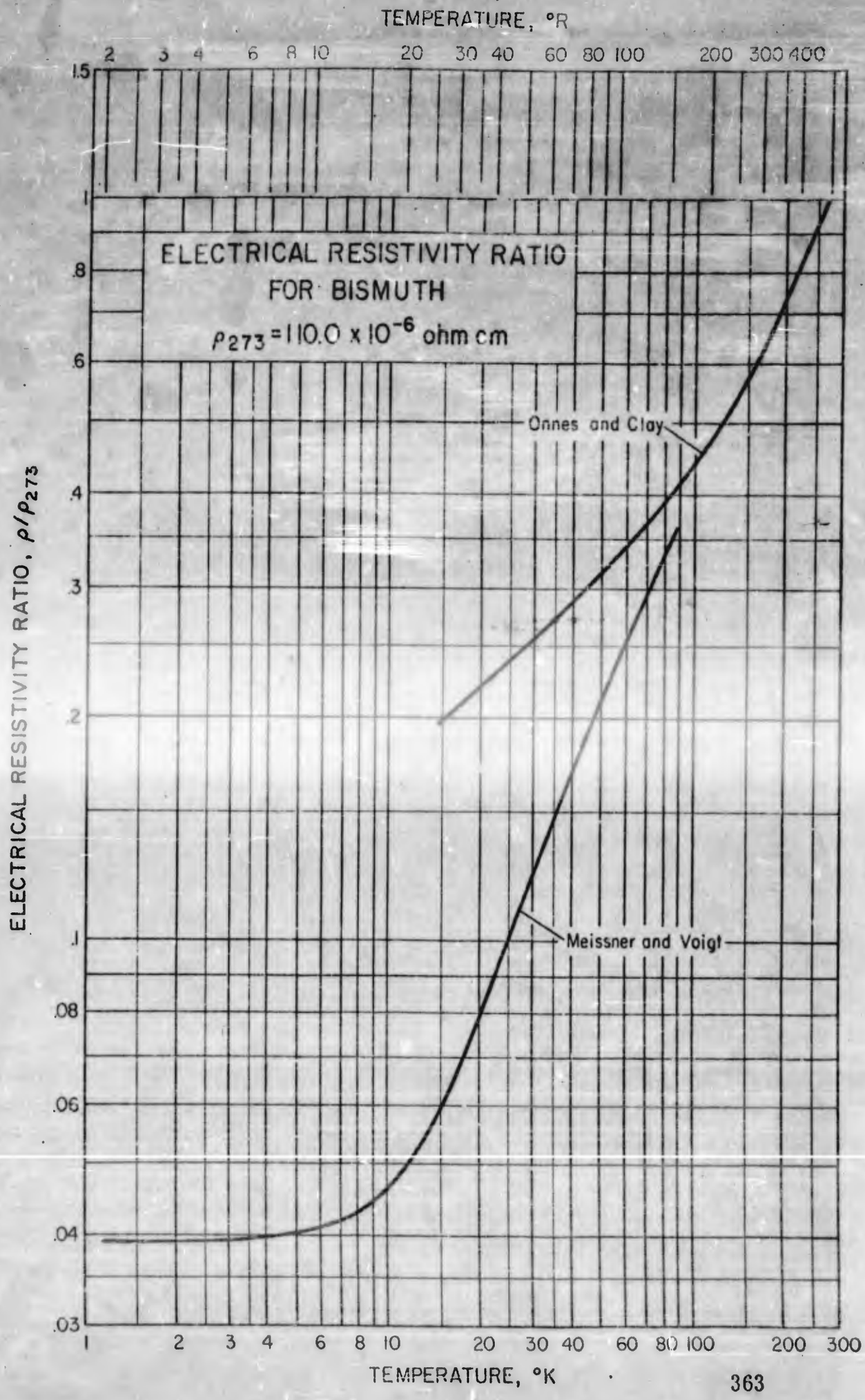
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Onnes and Clay			
Temp.* °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 80 *	71.3	-195.17	38.478
-100 *	64.8	-204.68	36.064
-103.71	63.649	-216.01	33.014
-139.88	52.865	-253.01	22.329
-164.05	46.246	-255.34	21.388
-182.73	41.435	-258.86	19.574
* Values by interpolation			

Meissner and Voigt	
Temp.* °K	ρ/ρ_{273}
1.17	0.0392
1.39	0.0392
4.21	0.0402
20.4	0.0810
77.8	0.3255
86.9	0.3582
* The second decimal place of the temperature values is somewhat in doubt.	

RDM/RS Issued: 2/1/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR BISMUTH
$\rho_{273} = 110.0 \times 10^{-6}$ ohm cm
Onnes and Clay
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of CHROMIUM, Cr

(Atomic Number 24)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

McLennan, J. C., Niven, C. D. and Wilhelm, J. O.; Phil. Mag. 6, 672 (1928)

Erfling, H. D.; Ann. Physik. (5) 34, 136 (1939)

Bridgman, P. W.; Proc. Am. Acad. Arts Sci. 79, 149 (1951)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for chromium to be used in calculating the electrical resistivity (ρ_T) is 18.2×10^{-6} ohm-cm.

The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by McLennan, et al., Erfling and Bridgman cited under "Other References".

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by McLennan, et al. or Erfling so a datum value ($\rho_{273} = 18.2 \times 10^{-6}$ ohm-cm) reported by Bridgman is suggested for calculating values of resistivity from these ratios.

The samples used by Bridgman were of a polycrystalline type with 0.7% impurities of unknown composition. No mention was made of the mechanical or heat treatment of the Bridgman samples. The samples used by McLennan et al. were of an annealed polycrystalline nature. No mention was made of the impurities present or of the mechanical treatment of the samples. The samples used by Erfling are also of a polycrystalline nature. These samples were pulled from a melt and later annealed. No mention is made of the mechanical treatment of the samples.

(Continued on following page.)

ELECTRICAL RESISTIVITY of CHROMIUM, Cr (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

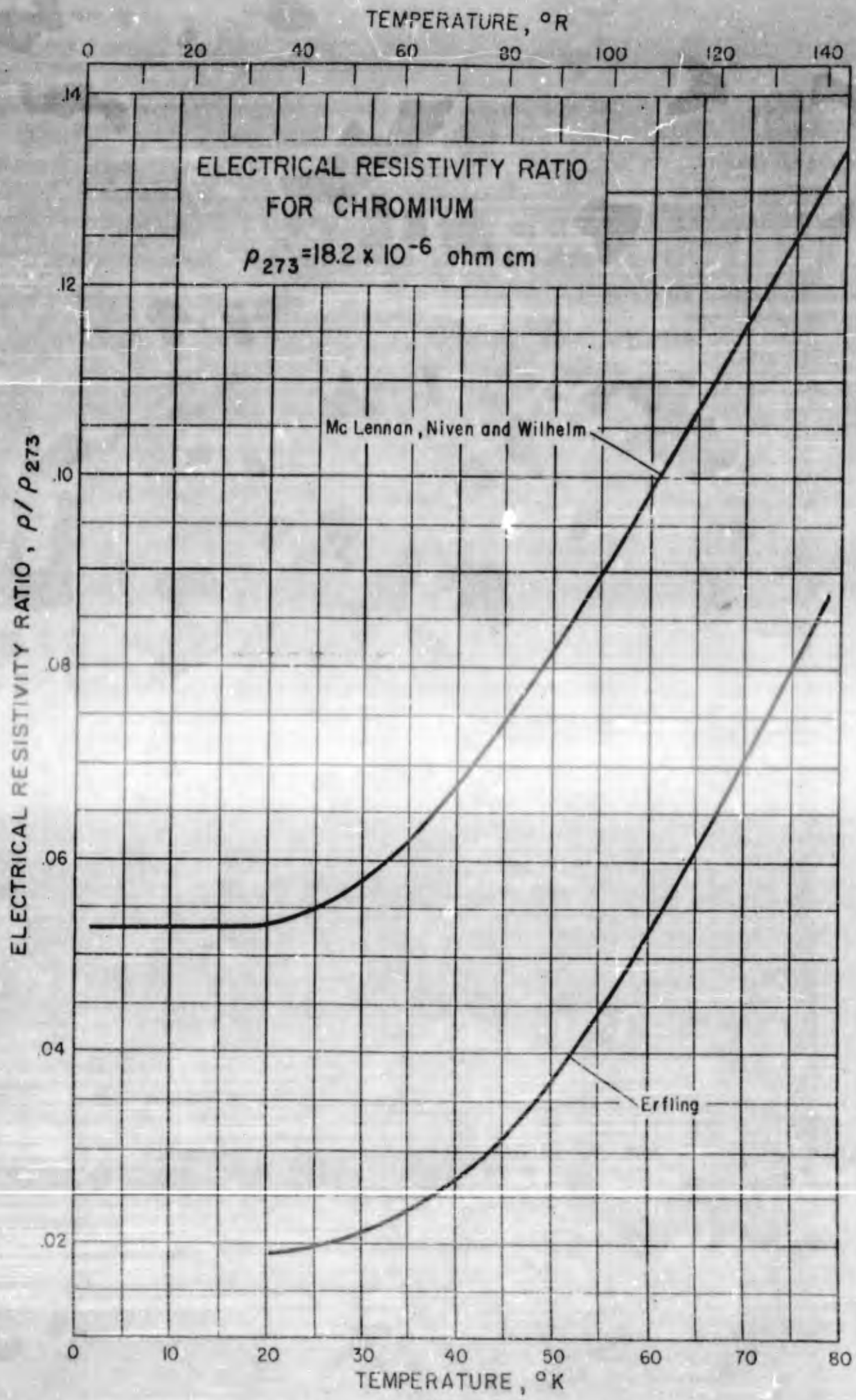
ρ_{273} = Resistivity at 273°K, (ohm-cm)

McLennan, Niven and Wilhelm	
Temp. °K	ρ/ρ_{273}*
2.2	0.0526
4.2	0.0526
20.6	0.0533
80.0	0.134

* The fourth decimal place of the electrical resistivity values is somewhat in doubt.

Erfling	
Temp. °K	ρ/ρ_{273}
20.4	0.0188
79.0	0.0874

RDM/RS Issued: 1/10/61


TEMPERATURE, °R
0
20
40
60
80
100
120
140
ELECTRICAL RESISTIVITY RATIO
FOR CHROMIUM
ρ_{273}=18.2 x 10^{-6} ohm cm
Mc Lennan, Niven and Wilhelm
Erfling
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.14
.12
.10
.08
.06
.04
.02
0
10
20
30
40
50
60
70
80
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of MOLYBDENUM, Mo

(Atomic Number 42)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc. (1929) pp. 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Blom, E. C.; Phys. Rev. 13, 308 (1919)

Holborn, L.; Ann. Physik. 59, 145 (1919)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for molybdenum to be used in calculating values of electrical resistivity (ρ_T) is 4.4 x 10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; and Blom; while those values listed by the International Critical Tables are from Holborn. These original authors are used in labeling the two curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the several investigators are not available so a datum value reported by Blom (ρ_{273} = 4.4 x 10^{-6} ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by both authors as polycrystalline with no mention made of impurities present. No reference is made as to the nature of the sample used by Holborn, and no information is available on mechanical strain or heat treatment for any of the samples from any of the sources of data.

(Continued on following page.)

ELECTRICAL RESISTIVITY of MOLYBDENUM (Cont.)

Tables of Values of Electrical Resistivity

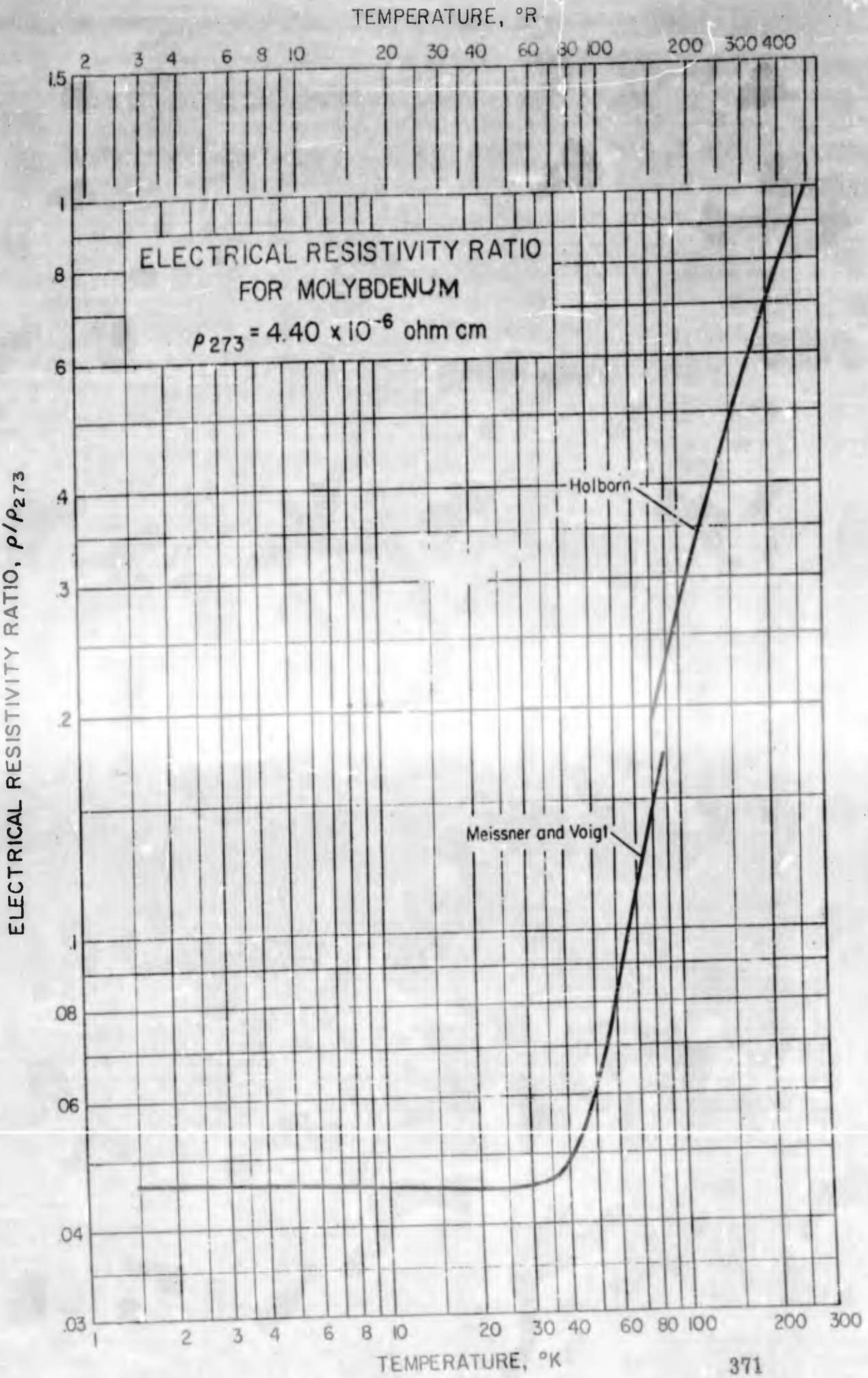
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Holborn	
Temp. °C	$100\rho/\rho_{273}$
- 78.2	66.60
- 80*	65.9
-100*	57.4
-120*	48.9
-140*	40.5
-160*	32.2
-180*	24.2
-192.5	19.11
* Values from interpolation	

Meissner and Voigt	
Temp. °K	ρ/ρ_{273}
1.5	0.0462
4.2	0.0455
20.4	0.0448
77.8	0.1370
86.9	0.1701

RDM/RS Issued: 2/2/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
8
6
4
3
2
.1
.08
.06
.04
.03
ELECTRICAL RESISTIVITY RATIO FOR MOLYBDENUM
$\rho_{273} = 4.40 \times 10^{-6}$ ohm cm
Holborn
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of TUNGSTEN, W

(Atomic Number 74)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Other References:

de Haas, W. J.; and de Nobel, J.; Physica 5, 449 (1938)

Holborn, L., Ann. Physik. 59, 145-169 (1919)

Grüneisen, E. and Adenstedt, A.; Ann. Physik (5) 31, 714 (1938)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Van den Berg, G. J.; Physica 14, 111 (1948)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for tungsten to be used in calculating values of electrical resistivity (ρ_T) is 4.86×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Van den Berg; de Haas and de Nobel; Meissner and Voigt; and Grüneisen and Adenstedt; while those values listed by the International Critical Tables are from Holborn. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data reported in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Grüneisen and Adenstedt ($\rho_{273} = 4.86 \times 10^{-6}$ ohm-cm) is suggested for calculating values of resistivity from these ratios.

The samples used by the authors referenced in the Landolt-Börnstein tables are reported as single crystals with very small amounts of impurities of unknown composition. Since the lattice structure of tungsten is body centered cubic the crystal axis orientation has no effect on the electrical resistivity; therefore these values should be representative of the electrical resistivity for the polycrystalline form. The International Critical tables make no mention as to the physical nature of the samples used by Holborn. Information was not given on the mechanical or heat treatment of any of the samples.

(Continued on following page)

ELECTRICAL RESISTIVITY of TUNGSTEN, (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

de Haas and de Nobel	
Temp. °K	ρ/ρ_{273}*
1.57	0.00033
4.21	0.00035
14.14	0.00048
20.42	0.00086
50.55	0.0291
90.15	0.1650

Holborn	
Temp. °C	$100\rho/\rho_{273}$
- 78.3+	65.09+
- 80	64.4
-100	55.7
-120	46.9
-140	38.2
-160	29.5
-180	20.8
192.8+	15.29+

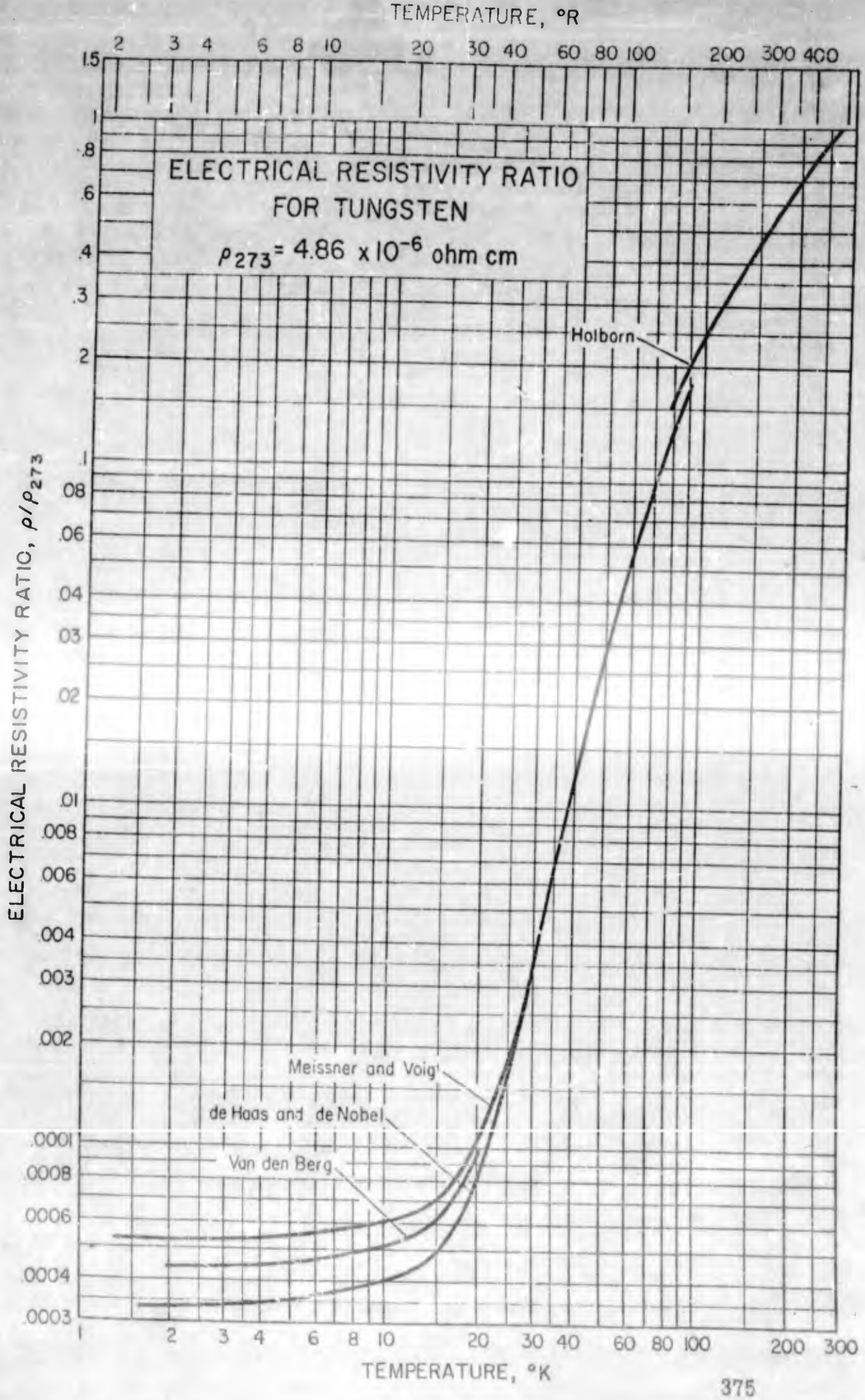
Meissner and Voigt	
Temp.** °K	ρ/ρ_{273}*
1.31	0.00053
4.21	0.00054
20.4	0.0011
77.6	0.1156
87.4	0.1565

Van den Berg	
Temp. °K	ρ/ρ_{273}
2.01	0.00044
4.40	0.00046
20.41	0.00097

* The fifth decimal place of the electrical resistivity ratio values is somewhat in doubt.

** The second decimal place of the temperature values is somewhat in doubt.

\+ Observed values. Other values have been interpolated.


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
2
.1
08
.06
04
03
02
.01
.008
.006
.004
.003
.002
.0001
.0008
.0006
.0004
.0003
ELECTRICAL RESISTIVITY RATIO FOR TUNGSTEN
$\rho_{273} = 4.86 \times 10^{-6}$ ohm cm
Holborn
Meissner and Voigt
de Haas and de Nobel
Van den Berg
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of MANGANESE, Mn

(Atomic Number 25)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik and Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Brunke, F.; Ann. Physik (5) 21, 139 (1934)

Erfling, H. D.; Ann. Physik 37, 162 (1940)

Erfling, H D.; Ann. Physik (5) 34, 136 (1939)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Reddemann, H.; Ann. Physik (5) 22, 28 (1935)

Comments:

Reference should be made to the beginning of the Electrical Resistivity section for an explanation of the data. The value of the electrical resistivity at 273°K (ρ_{273}) for manganese to be used in calculating values of electrical resistivity (ρ_T) from a particular set of tabulated ratios is listed with that set.

The data presented here were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by the authors cited above under "Other references".

The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by Meissner and Voigt; Brunke; and Erfling are listed in each group of data attributed to the above authors. The value of ρ_{273} reported by Brunke ($\rho_{273} = 91 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from the Reddemann ratios

Manganese is an allotropic metal and undergoes two phase changes at cryogenic temperatures. These phase changes are recognizable by changes in energy, crystal lattice structure and other physical properties

The data tabulated here are separated according to the phase of the sample. The popular phase designations in the literature, and followed here, are α, β, γ. The Meissner and Voigt data are reported as determined from a sample composed of a combination of the α and β phase. The Brunke sample is reported as being in the α phase. The Reddemann sample is reported as being in the β phase and the Erfling sample is reported as being in the γ phase.

The Landolt-Börnstein tables list all the samples considered here as polycrystalline with a small amount of impurities present No further pertinent information is given.

(Continued on following page)

ELECTRICAL RESISTIVITY of MANGANESE (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt (α + β)-Manganese ρ_{273} = 150 x 10^{-6} ohm-cm		Reddemann β-Manganese ρ_{273} = 91 x 10^{-6} ohm-cm	
Temp.* °K	ρ/ρ_{273}**	Temp. °K	ρ/ρ_{273}
1.41	0.9581	78.1	0.731
4.20	0.9765	90.1	0.750
20.5	1.0020	194.7	0.891
77.8	0.9807		
88.9	0.9776		

* The second decimal place of the temperature values is somewhat in doubt.

** The fourth decimal place of the electrical resistivity ratio values is somewhat in doubt.

Brunke α-Manganese ρ_{273} = 715 x 10^{-6} ohm-cm		Erfling γ-Manganese ρ_{273} = 39.2 x 10^{-6} ohm-cm	
Temp. °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
89.2	0.971	79.0	0.130

ELECTRICAL RESISTIVITY of RHENIUM, Re

(Atomic Number 75)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 5 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Aschermann, G. and Justi, E.; Physik. Z. 43, 207 (1942)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The values of electrical resistivity at 273°K (ρ_{273}) for rhenium to be used in calculating values of electrical resistivity (ρ_T) are listed below the authors' names labeling each individual curve on the graph. These curves should not be extrapolated to lower temperatures since rhenium becomes a superconductor at 1.70°K.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from the Landolt-Börnstein tables are those reported by the authors listed above under "Other References".

The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The values of ρ_{273} which appear on the graph below the authors' names are the values determined by those authors.

The samples used by Aschermann and Justi; and by Meissner and Voigt are reported in Landolt-Börnstein as being of the sintered polycrystalline type. The Aschermann and Justi sample contained 0.2% impurities of unknown composition but no mention is made of impurities in the Meissner and Voigt samples. No information is available as to the mechanical or heat treatment of the samples.

Table of Values of Electrical Resistivity

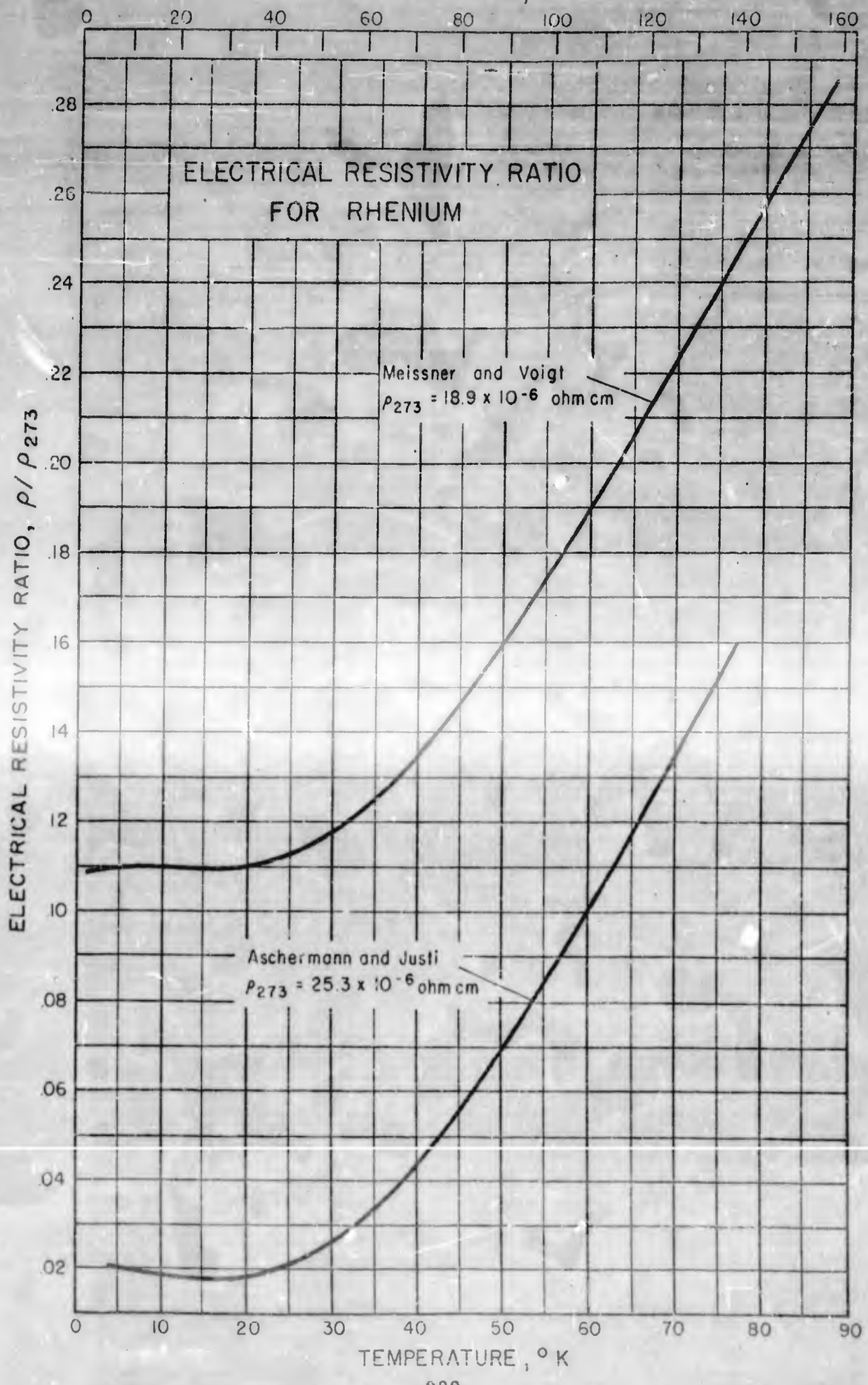
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Aschermann and Justi		Meissner and Voigt	
Temp. °K	ρ/ρ_{273}*	Temp.** °K	ρ/ρ_{273}
4.22	0.021	1.36	0.109
14.0	0.0183	4.22	0.110
20.4	0.0183	20.4	0.110
77.7	0.1609	38.2	0.2849

* The fourth decimal place is somewhat in doubt.
** The second decimal place is somewhat in doubt.

17.171 b


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO FOR RHENIUM
Meissner and Voigt
ρ_{273} = 18.9 x 10⁻⁶ ohm cm
Aschermann and Justi
ρ_{273} = 25.3 x 10⁻⁶ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of IRON, Fe

(Atomic Number 26)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Cleaves, H. E. and Hiegel, J. M.; J. Research Natl. Bur. Standards RP 1472 28, 643 (1942)

Holborn, L.; Ann. Physik 59, 145 (1919)

Meissner, W.; Physik. Z. 29, 897 (1928)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for iron to be used in calculating values of electrical resistivity (ρ_T) is 8.6×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner; and Cleaves and Hiegel; while those values appearing in the International Critical Tables are from Holborn. These primary sources are cited above under "Other References". The original authors are used in labeling the two curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the several investigators are not available so a datum value reported by Cleaves and Hiegel ($\rho_{273} = 8.6 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables list the sample used by Cleaves and Hiegel as an annealed polycrystalline specimen with less than 0.01% impurities. The sample used by Meissner is reported as an annealed polycrystalline specimen with a very small amount of impurities present. No other pertinent information is given on any of the samples in any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of IRON (Cont.)

Tables of Values of Electrical Resistivity

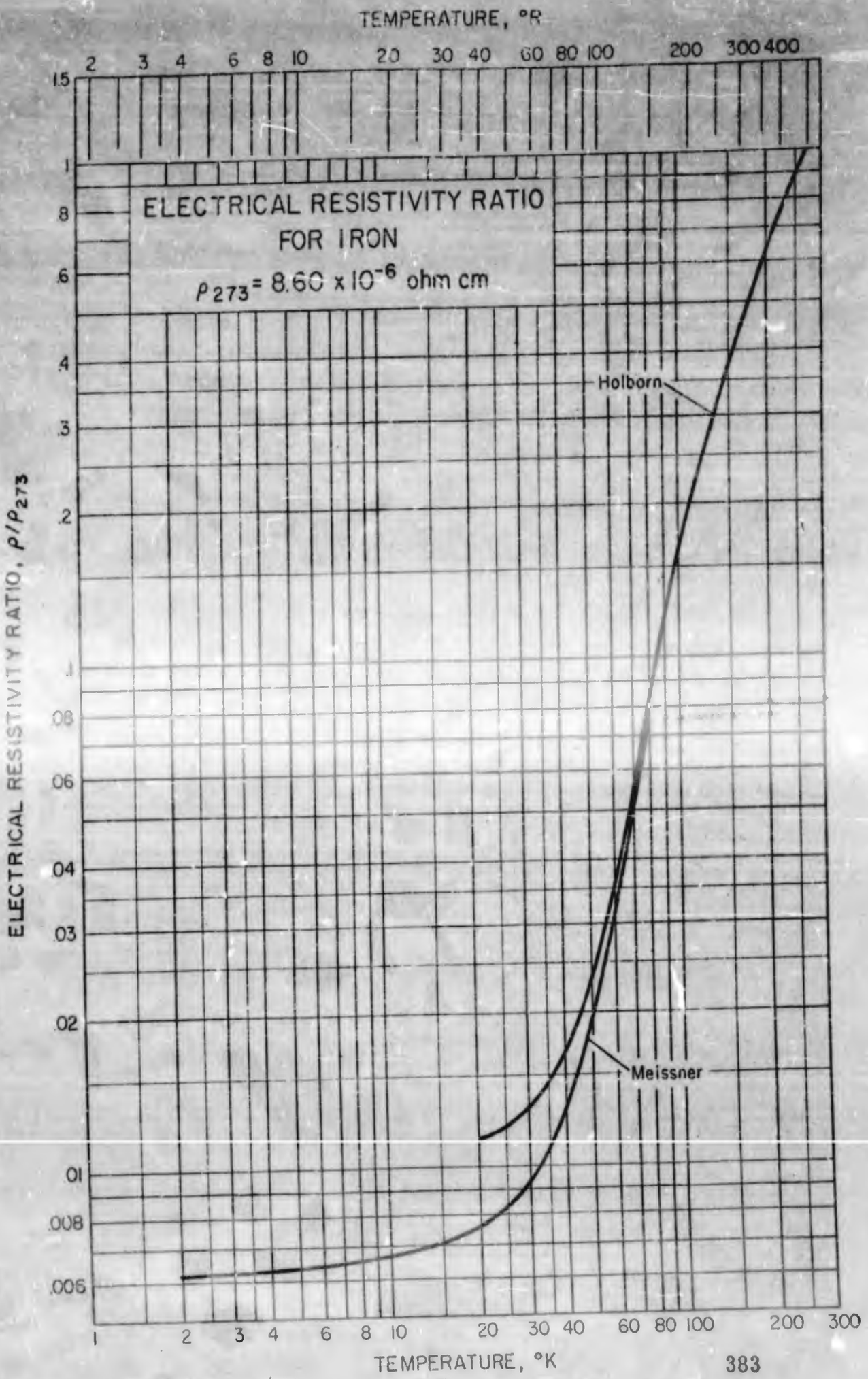
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.1	57.86	-192.7	8.48
- 80 *	55.9	-200 *	6.2
-100 *	47.3	-220 *	2.7
-120 *	38.1	-240 *	1.4
-140 *	29.2	-253	1.13
-160 *	20.7		
* Values from interpolation			

Meissner	
Temp.* °K	ρ/ρ_{273}**
1.98	0.000618
4.21	0.000620
20.4	0.000761
78.2	0.0741
* The second decimal place is in doubt.	
**The fifth decimal place is in doubt.	

RDM/RS Issued: 1/31/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR IRON
$\rho_{273} = 8.60 \times 10^{-6}$ ohm cm
Holborn
Meissner
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.08
.06
.04
.03
.02
.01
.008
.006
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of NICKEL, Ni
(Atomic Number 28)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Fleming, J. A.; Proc. Roy. Soc. (London) 66, 50 (1900)

Dewar, J.; Proc. Roy. Soc. (London) 73, 244 (1904)

Meissner, W.; Physik. Z. 27, 725 (1926)

Wise, E. M.; Proc. Inst. Radio Engrs. 25, 714 (1937)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for nickel to be used in calculating electrical resistivity is 6.14×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Wise; while those values appearing in the International Critical Tables are from Dewar and Fleming. These primary references are cited above under "Other References". The original authors are used in labeling both curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the several investigators are not available so a datum value reported by Wise ($\rho_{273} = 6.14 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables list the sample used by Wise as polycrystalline with 0.01% impurities of unknown composition. The sample used by Meissner is reported as a polycrystalline and annealed in a hydrogen atmosphere. No further pertinent information is available on any of the samples from any of the sources of data.

(Continued on following page)

ELECTRICAL RESISTIVITY of NICKEL (Cont.)

Tables of Values of Electrical Resistivity

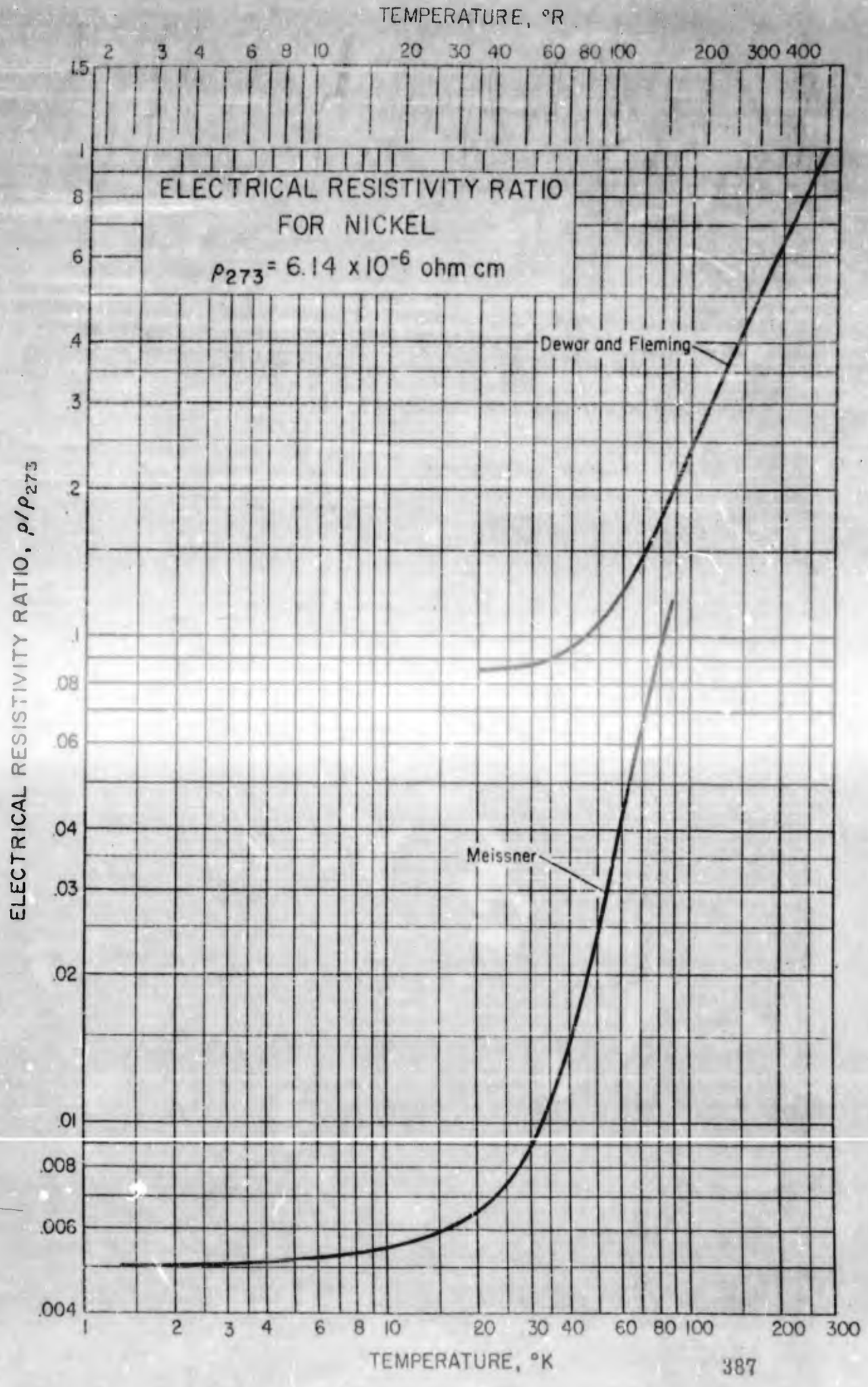
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Dewar and Fleming			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.3	61.3	-180 +	21.7
- 80 +	60.5	-182.9	20.8
-100 +	51.8	-200 +	15.6
-120 +	43.7	-220 +	11.2
-140 +	36.1	-240 +	8.9
-160 +	28.7	-252.7	8.5
+ Values are from interpolation			

Meissner	
Temp.** °K	ρ/ρ_{273}*
1.34	0.00503
4.21	0.00508
20.40	0.00662
78.8	0.0919
87.4	0.1179
** The second decimal place is in doubt.	
* The fifth decimal place is in doubt.	

RDM/RS Issued: 2/1/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR NICKEL
ρ_{273} = 6.14 x 10^{-6} ohm cm
Dewar and Fleming
Meissner
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of COBALT, Co
(Atomic Number 27)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Bridgman, P. W.; Proc. Am. Acad. Arts. Sci. 79, 149 (1940)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Schimank, H.; Ann. Physik 45, 706 (1914)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for cobalt to be used in calculating values of electrical resistivity (ρ_T) is 5.57×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; and Bridgman; while those values appearing in the International Critical Tables are from Schimank. These primary sources are cited above under "Other References". The original authors are used in labeling the two curves on the graph.

The data in Landolt-Börnstein tables; the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the several investigators are not available so a datum value reported by Bridgman ($\rho_{273} = 5.57 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables list the sample used by Meissner and Voigt as an annealed, sintered polycrystalline specimen with no mention made of impurities present. The sample used by Bridgman was reported as polycrystalline with a very small amount of impurities. No information is given on the amount of impurity or nature of the Schimank sample, and no further information is available on the mechanical strain or heat treatment for any of the samples from any of the sources of data.

(Continued on following page.)

ELECTRICAL RESISTIVITY of COBALT (Cont.)

Tables of Values of Electrical Resistivity

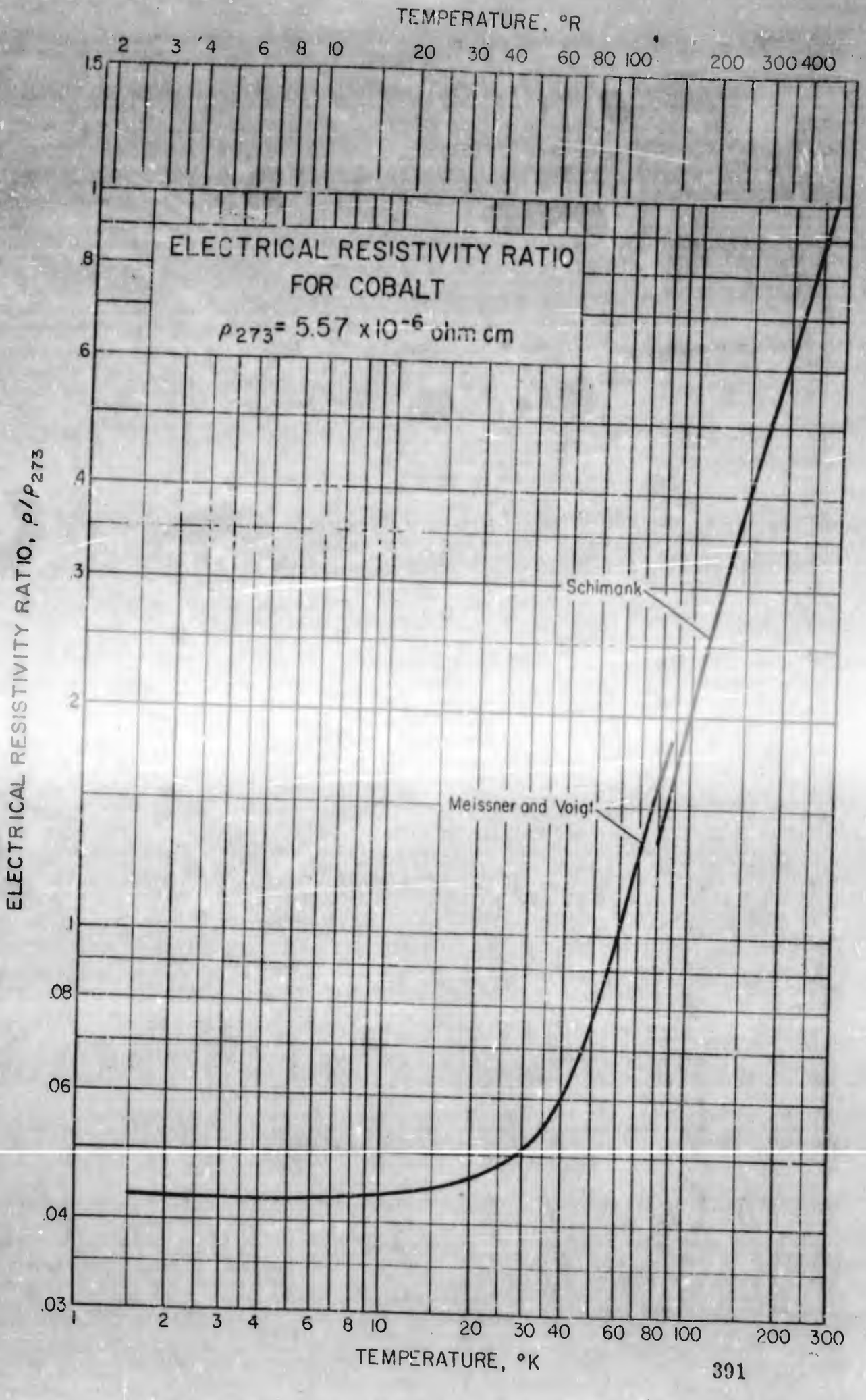
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt	
Temp. °K	ρ/ρ_{273}
1.5	0.0431
4.2	0.0426
20.4	0.0463
77.8	0.1516
86.9	0.1829

Schimark	
Temp. °C	$100\rho/\rho_{273}$
- 80*	57.4
-100*	48.2
-120*	32.3
-160*	24.8
-180*	17.4
-192	13.5
*Values from interpolation	

RDM/RS Issued: 2/2/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR COBALT
$\rho_{273} = 5.57 \times 10^{-6}$ ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
Schimank
Meissner and Voigt
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of RUTHENIUM, Ru

(Atomic Number 44)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Justi, E.; Z. Naturforsch. 4a, 472 (1949)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The values of electrical resistivity at 273°K (ρ_{273}) for ruthenium to be used in calculating values of electrical resistivity (ρ_T) are listed below the authors' names labeling each individual curve on the graph. These curves should not be extrapolated to lower temperatures since ruthenium becomes a superconductor at 0.47°K.

The data for this graph were taken from the reference cited above under "Source of Data". The values taken from the Landolt-Börnstein tables are those reported by the authors listed under "Other References".

The data reported in Landolt-Börnstein tables and tabulated here are listed as ratios of the electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The values of ρ_{273} which appear on the graph below the authors' names are the values determined by those authors.

The samples used by Meissner and Voigt; and Justi are reported in Landolt-Börnstein as being of the sintered polycrystalline type, with approximately 4.2% and 0.01% of unknown impurities respectively. No mention is made of the mechanical or heat treatment of any of the samples.

Table of Values of Electrical Resistivity

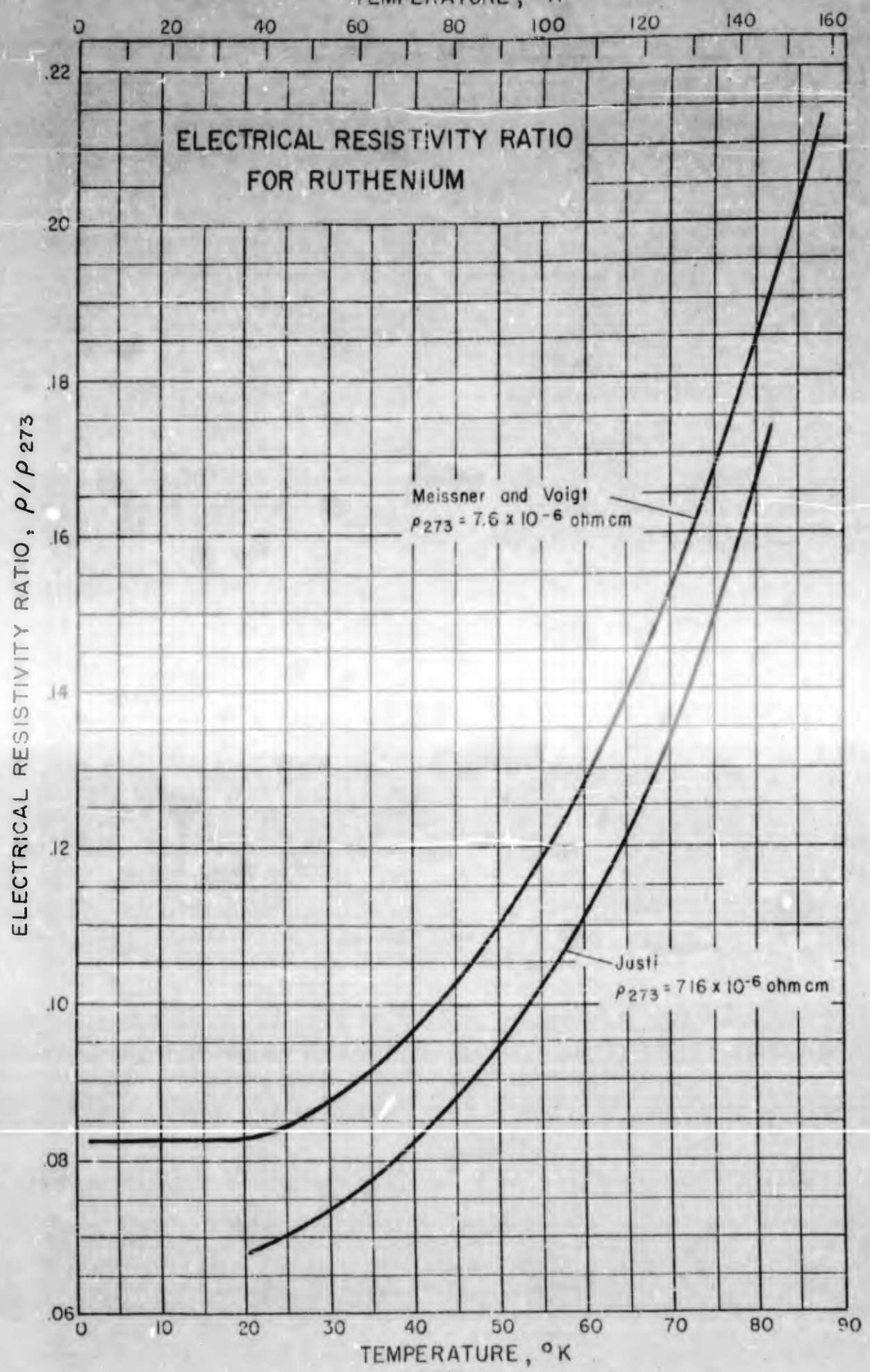
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Justi		Meissner and Voigt	
Temp.* °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}
20.38	0.0683	1.17	0.0827
81.7	0.1734	4.21	0.0827
		20.4	0.0830
		77.6	0.01755
		87.2	0.2106

* The second decimal place of the temperature values is somewhat in doubt.

17.182a


TEMPERATURE, °R
0
20
40
60
80
100
120
140
160
ELECTRICAL RESISTIVITY RATIO FOR RUTHENIUM
.22
.20
.18
.16
.14
.12
.10
.08
.06
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
Meissner and Voigt
$\rho_{273} = 7.6 \times 10^{-6}$ ohm cm
Justi
$\rho_{273} = 7.16 \times 10^{-6}$ ohm cm
0
10
20
30
40
50
60
70
80
90
TEMPERATURE, °K

17.182b

ELECTRICAL RESISTIVITY of RHODIUM, Rh

(Atomic Number 45)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp. 124-135

Other References:

Bridgman, P. W.; Proc. Am. Acad. Arts Sci. 68, 27 (1933)

Holborn, L.; Ann. Physik. 59, 145 (1919)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for rhodium to be used in calculating values of electrical resistivity (ρ_T) is 4.35×10^{-6} ohm-cm. The curves on this graph should not be extrapolated to lower temperatures as rhodium becomes a superconductor at 0.9°K.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Bridgman; and Meissner and Voigt. The values reported by Holborn appear both in the International Critical Tables and the Landolt-Börnstein tables. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data in Landolt-Börnstein, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Bridgman ($\rho_{273} = 4.35 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables report the samples used by both authors as polycrystalline with a very small amount of impurities in the sample used by Bridgman. The sample used by Meissner and Voigt is reported to have been annealed, but no mention is made of impurities present. No other pertinent information is given on any of the samples from any of the sources of data.

(Continued on following page.)

ELECTRICAL RESISTIVITY of RHODIUM (Cont.)

Tables of Values of Electrical Resistivity

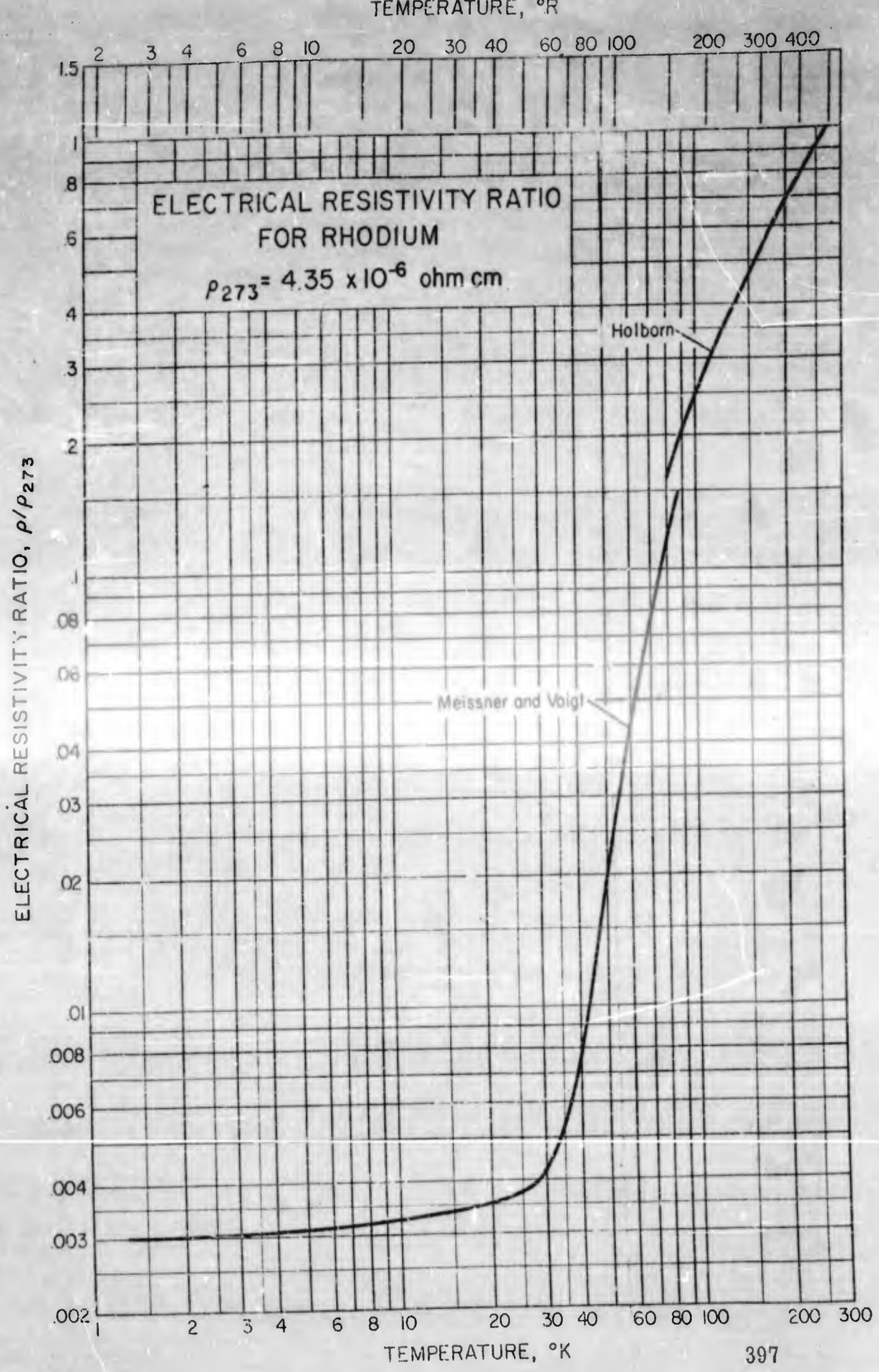
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.4	65.80	-140*	39.0
- 80*	65.1	-160*	30.2
-100*	56.4	-180*	21.4
-120*	47.7	-191.9	16.25
* Values from interpolation			

Meissner and Voigt	
Temp.* °K	ρ/ρ_{273}**
1.32	0.00300
4.22	0.00309
20.4	0.00353
77.6	0.1066
87.4	0.1466
*The second decimal place is in doubt. **The fifth decimal place is in doubt.	

RDM/RS Issued: 1/31/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
ELECTRICAL RESISTIVITY RATIO FOR RHODIUM
$\rho_{273} = 4.35 \times 10^{-6}$ ohm cm
Holborn
Meissner and Voigt
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of PALLADIUM, Pd

(Atomic Number 46)

Source of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp. 1-46

Other References:

Grüneisen, E. and Reddemann, H.; Ann. Physik. (5) 20, 848 (1934)

Holborn, L.; Ann. Physik. 59, 145 (1919)

Meissner, W. and Voigt, B.; Ann. Physik. (5) 7, 761, 892 (1930)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for palladium to be used in calculating values of electrical resistivity (ρ_T) is 9.77 x 10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Grüneisen and Reddemann; Holborn; and Meissner and Voigt; cited above under "Other References". The original authors are used in labeling the curves on the graph.

The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} are not available for the samples used by the several investigators so a datum value reported by Grüneisen and Reddemann (ρ_{273} = 9.77 x 10^{-6} ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables report all the samples used by the several investigators as annealed polycrystalline specimens with a very small amount of impurities present of unknown composition. No other pertinent information is given on any of the samples in any of the sources of data.

(Continued on following page.)

ELECTRICAL RESISTIVITY of PALLADIUM (Cont.)

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

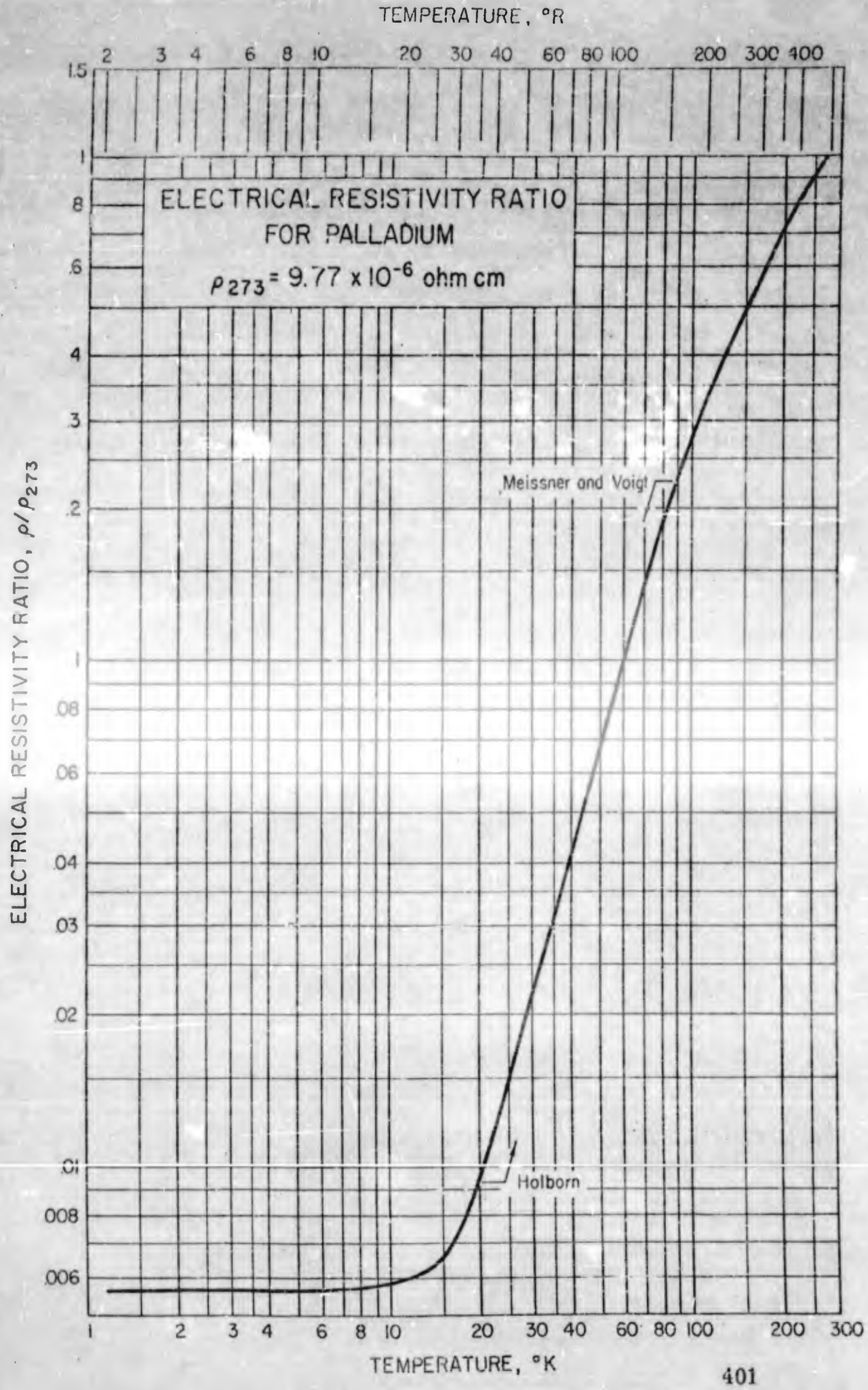
Meissner and Voigt			
Temp.* °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}**
1.17	0.00559	20.46	0.0096
1.45	0.00559	77.8	0.1730
3.16	0.00563	88.9	0.2220
4.20	0.00566		

* The second decimal place of the temperature values is somewhat in doubt.

** The fifth decimal place of the electrical resistivity ratio values is somewhat in doubt.

Holborn	
Temp. °K	ρ/ρ_{273}
20	0.0093
81	0.1874
195	0.6855

RDM/RS Issued: 2/8/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
ELECTRICAL RESISTIVITY RATIO FOR PALLADIUM
$\rho_{273} = 9.77 \times 10^{-6}$ ohm cm
Meissner and Voigt
Holborn
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of IRIDIUM, Ir
(Atomic Number 77)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Holborn, L.; Ann. Physik 59, 145 (1919)

Jaeger, W. and Diesselhorst, H.; Wiss. Abhandl. physik tech. Reichanstalt 3, 269 (1900)

Meissner, W. and Voigt, B.; Ann. Physik (5) 7, 761, 892 (1930)

Potter, H. H.; Proc. Phys. Soc. (London) 53, 695 (1941)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for iridium to be used in calculating values of electrical resistivity (ρ_T) is 4.93 x 10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Jaeger and Diesselhorst; Meissner and Voigt; Potter; and Holborn. The Holborn data also appear in the International Critical Tables. These primary sources are listed above under "Other References". The original authors are used in labeling the three curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the several investigators are not available so a datum value reported by Jaeger and Diesselhorst (ρ_{273} = 4.93 x 10^{-6} ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables report the samples of all the authors as polycrystalline. The Meissner and Voigt sample is reported as an annealed sample with a very small amount of impurities present. The sample used by Holborn was a cast specimen, but no mention is made of impurities present. The sample used by Potter is reported to have a

(Continued on following page)

ELECTRICAL RESISTIVITY of IRIDIUM, (Cont.)

Comments: (cont.)

very small amount of impurities present. No information is listed on the composition of the impurities for any of the samples. No further pertinent information is available for any of the samples from any of the sources of data.

Tables of Values of Electrical Resistivity

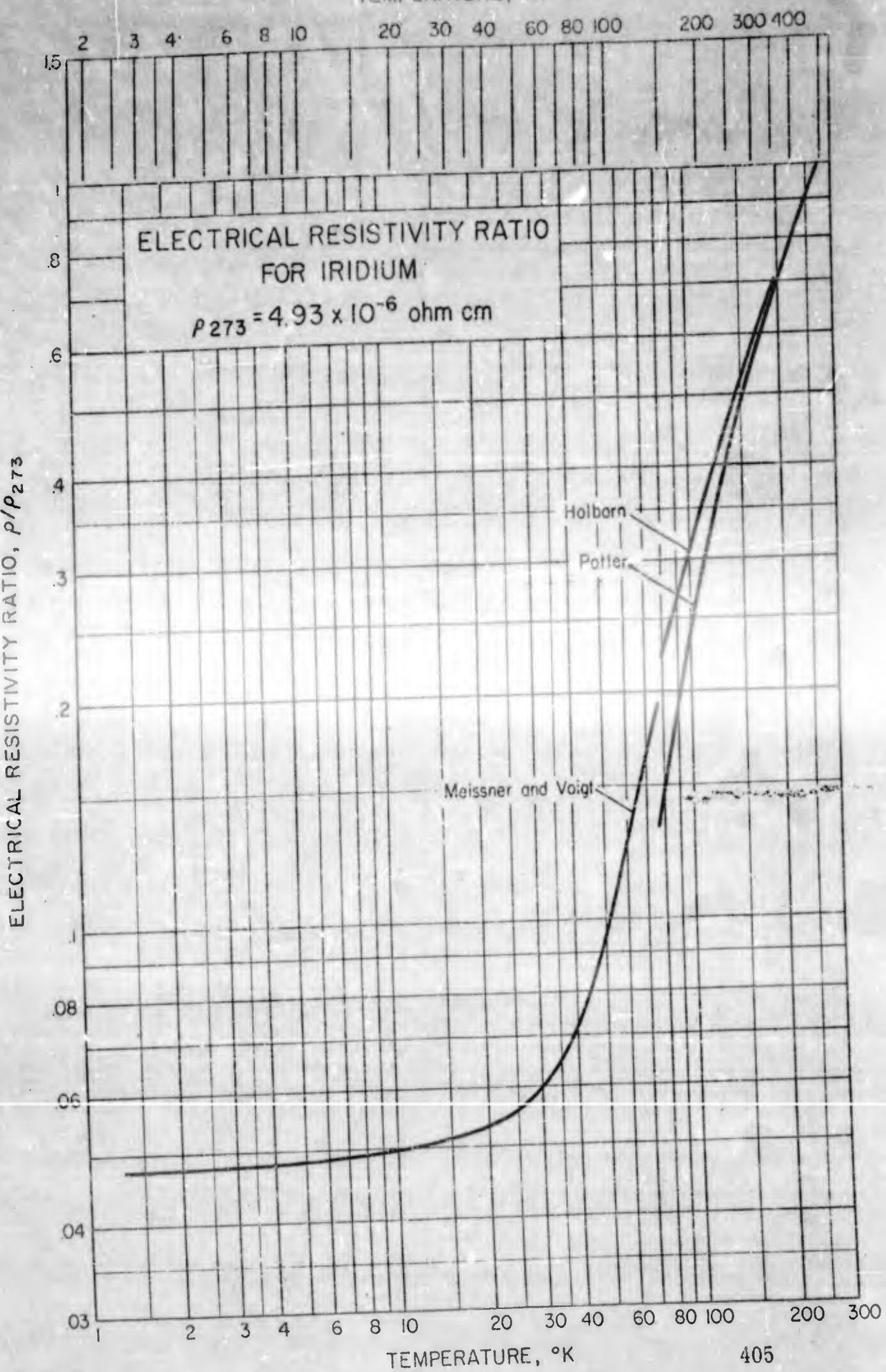
ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.4	69.22	-140 *	44.4
- 80 *	68.6	-160 *	36.0
-100 *	60.6	-180 *	27.5
-120 *	52.5	-191.9	22.57
* Values from interpolation.			

Meissner and Voigt		Potter	
Temp.* °K	ρ/ρ_{273}	Temp. °K	ρ/ρ_{273}
1.29	0.0478	77	0.135
4.22	0.0480	90	0.19
20.42	0.0536	173	0.58
77.7	0.1905		
* The second decimal place of the temperature values is somewhat in doubt.			

RDM/RS Issued: 2/7/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO FOR IRIDIUM
$\rho_{273} = 4.93 \times 10^{-6}$ ohm cm
Holborn
Potter
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

ELECTRICAL RESISTIVITY of PLATINUM, Pt

(Atomic Number 78)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. (1929) pp 124-135

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin (1959) pp 1-46

Other References:

Henning, F.; Handbuch der Physik IX, Berlin, Springer-Verlag (1926)

Holborn, L.; Ann. Physik. 59, 145 (1919)

Meissner, W.; Ann. Physik (4) 47, 1001 (1915)

Meissner, W.; Physik Z. 27, 725 (1926)

Meissner, W. and Grassmann, P.; Physik Z. 34, 516 (1933)

Onnes, H. K. and Tuyn, W.; Communs. Phys. Lab. Univ. Leiden Suppl. No. 58 (1926)

Van der Horst, H. D.; Tuyn, W. and Onnes, K. H.; Private communication with the editors of the International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, (1929)

Comments:

Reference should be made to the preface at the beginning of the Electrical Resistivity section for an explanation of the graph. The value of electrical resistivity at 273°K (ρ_{273}) for platinum to be used in calculating values of electrical resistivity (ρ_T) is 9.81×10^{-6} ohm-cm.

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Holborn; Meissner; and Meissner and Grassmann; while those values appearing in the International Critical Tables are from Henning; Tuyn and Onnes; and Van der Horst, Tuyn and Onnes. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph.

The data in the Landolt-Börnstein tables, the International Critical Tables and tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} for the samples used by the various investigators are not available so a datum value reported by Meissner ($\rho_{273} = 9.81 \times 10^{-6}$ ohm-cm) is suggested for calculating values of electrical resistivity from these ratios.

(Continued on following page)

ELECTRICAL RESISTIVITY of PLATINUM (Cont.)

Comments: (cont.)

The sample used by Holborn is reported in the Landolt-Börnstein tables as cast polycrystalline with a very small amount of impurities present. The samples used by Meissner are reported as polycrystalline with a very small amount of impurities present. The Meissner sample from the 1915 reference is reported to have been annealed. The sample used by Meissner and Grassmann is reported as an annealed polycrystalline sample with less than 0.001% of Cu and Pb impurities present. No other pertinent information is given on any of the samples fron any of the sources of data.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Holborn		Meissner		Meissner and Grassmann	
Temp. °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}**	Temp.* °K	ρ/ρ_{273}**
20	0.0060	1.35	0.00165	1.35	0.00031
81	0.2060	4.21	0.00168	4.2	0.00031
195	0.6860	20.40	0.00607	20.4	0.00425
		91.4	0.250		

* The second decimal place is in doubt.

** The fifth decimal place is in doubt.

(Continued on following page)

ELECTRICAL RESISTIVITY of PLATINUM (Cont.)

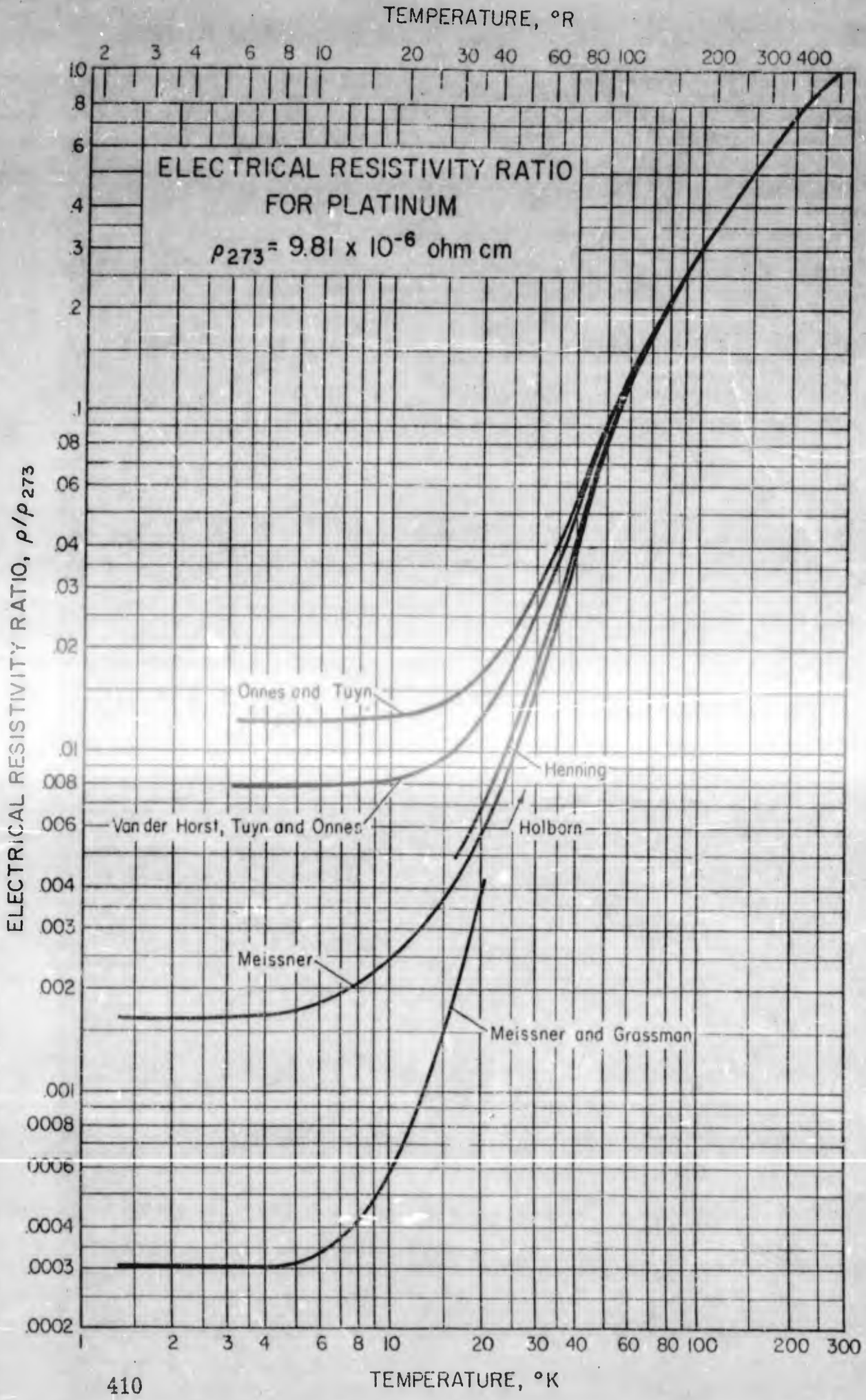
Table of Values of Electrical Resistivity

ρ = Resistivity, (ohm-cm)

ρ_{273} = Resistivity at 273°K, (ohm-cm)

Temp. °C	Tuyu and Onnes $100\rho/\rho_{273}$	Van der Horst et al. $100\rho/\rho_{273}$	Henning $100\rho/\rho_{273}$
- 80	68.158	68.017	67.782
- 90	64.113	63.955	63.688
-100	60.053	59.874	59.576
-120	51.863	51.650	51.295
-140	43.595	43.337	42.928
-160	35.213	34.904	34.463
-180	26.709	26.356	25.885
-200	18.176	17.750	17.268
-210	14.009	13.563	--
-220	--	9.587	--
-230	--	6.030	--
-240	--	3.252	--
-250	--	1.571	--
-255	1.5885	1.1263	0.5706
-260	1.335	0.894	--
-265	1.239	0.810	--
-270	1.225	0.7863	--

RDM/RS Issued: 2/15/61


TEMPERATURE, °R
2 3 4 6 8 10 20 30 40 60 80 100 200 300 400
ELECTRICAL RESISTIVITY RATIO
FOR PLATINUM
ρ_{273} = 9.81 x 10^{-6} ohm cm
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.0
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
.0008
.0006
.0004
.0003
.0002
Onnes and Tuyn
Henning
Holborn
Van der Horst, Tuyn and Onnes
Meissner
Meissner and Grassman
1 2 3 4 6 8 10 20 30 40 60 80 100 200 300
TEMPERATURE, °K

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The Vapor Pressure, Critical Point, Heat of Vaporization and Entropy of Liquid He^3
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Helium: Entropy

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COMPRESSIBILITY FACTOR (11.000)

(DENSITY, P-V-T, EQUATION OF STATE, ATOMIC WEIGHT, VIRIAL COEFFICIENT, MOLAL VOLUME, ETC.)

HELIUM.....11.001

45 64 95 198 241 242 243 244 279*
280 291 350+ 353 365 366 368 369 410
422 427 441 442 443 495 496 501 525
560 620 655+

HYDROGEN.....11.002

5 19 20 21 22 25 95 116 173+
198 232 237 240 241 242 243 260+ 262+
280 353 365 366 368 369 379 380 397
404 405 422 425 431 441 442 443 467
496 504 526* 532 533 552 560 564 590
594 628 629 631 648*

NEON.....11.003

95 97+ 209 241 242 243 270 280 353
366 430+ 441 442 443 455 496 532 533
650*

NITROGEN.....11.004

5 20 21 22 25 28* 37 43* 57
62 74 95 133 173 198 214 232+ 234
237 242 243 254 270 280 305 317 335
352 353 365 369 402 411 416 422 441
442 443 486 496 502 506 514 533 581
600 644 646 647

OXYGEN.....11.005

5 23 25 36 37 74 92 95 103
180 198 214 232 237 242 243 270 280
317 322 323 353 365 369 370 396 406
411 413 414 421 422 435 441 442 443
467 487 496 532 533 547 593 599 601
607 641 722 725

AIR.....11.006

25 30 74 92 125* 198 214 232+ 242
243 244 254 365 407+ 408+ 441 442 443
496 502 525 533

* REFERENCE USED AS SOURCE OF DATA
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COMPRESSIBILITY FACTOR (11.000)

(DENSITY, P-V-T, EQUATION OF STATE, ATOMIC WEIGHT, VIRIAL COEFFICIENT, MOLAL VOLUME, ETC.)

CARBON MONOXIDE.....11.007

25 124 144 198 209 232 353 371 403
414 442 486 504 533 552 590 641 644

FLUORINE.....11.008

630

ARGON.....11.009

5 22 24 37 57 95 128 132 198
232 234 242 244 270 280 305 335 336
353 365 366 369 398 409 422 429 441
442 443 455 466 496 506 509 594 626

METHANE.....11.010

8 25 29 209 270 324+ 353 371 372*
400 422 441 442 443 467 482+ 494 532
533 644

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PROPERTY AND MATERIAL INDEX OF REFERENCES

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ENTROPY (14.000)

HELIUM.....14.001

1	2	3	4	13	72	101	137	148
152	196	231	275	279	282	286	289	290
300	316	350	353	363	364	436	462	471
472	484	495	510	541	546	617	624	

HYDROGEN.....14.002

46	77	85	101	106	115	148	149	152
154	163	179	183	186	208	232	258	261
268	285	300	311	353	361	474	475	482
484	505	513	548	556	558	618	623	631
643	648							

NEON.....14.003

83	84	95	97+	137	209	300	312	353
430+	465	481*	484	650*	651*			

NITROGEN.....14.004

43	46	62	74	77	101	115	148	149
152	154	163	182	185	188	208	215	232
254	259	268	281	288	293	300	305	307
317	352	353	411	476	482	484	517	558
623	638	643	646	647				

OXYGEN.....14.005

58	74	77	101	148	149	152	154	163
172	182	187	215	232	262	268	284	293
300	317	338	353	411	476	482	483	484
517	540	618	623	643	645			

AIR.....14.006

30	58	66	74	77	125	215	232	254
268	499	512	656					

CARBON MONOXIDE.....14.007

46	79	80	101	115	124	148	149	154
163	182	188	208	209	232	259	268	284
300	353	401	482	517	540	558	618	623

FLUORINE.....14.008

65	90	172	177	179	189	247	248	274
417	418	484						

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ENTROPY (14.000)

ARGON.....14.009

26	83	85	86	101	137	148	151	152
189	209	232	255	271	299	300	305	343
353	398	399	463	464	466	484	517	548
623	626							

METHANE.....14.010

29	87	101	117	141	142	143	149	170
184	209	212	268	276	283	287	299	300
348	353	373	376	400	419	437	482	500
517	528	539	608	618	638			

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VELOCITY OF SOUND (15.000)

HELIUM.....15.001

11+	12+	13*	63+	64	70*	71+	164*	165*
200	202	236	294+	295*	308	347	365	422
440+	446+	495	501*	511	524	563+	565	572*
575+	576*	577*	578*	579*	585	586*	588	589*
591*	620	621	622					

HYDROGEN.....15.002

75+	94*	102+	127	138+	176*	201	206+	229
232+	236	246	278	351+	365	408+	422	447*+
456+	460	461	467	511	520	521	522	523
531+	544+	553	564+	565	580*	583+	584+	585
586	588+	589	590	591	592*	594+	596*	597+
605+	619	648+	654	658+	705*			

NEON.....15.003

294+	297*	511+	554	582+	585	586+

NITROGEN.....15.004

50	74	91+	126+	168+	176+	232*	235+	236+
246	298*	309	325	327	329	330	346+	352*
365	402+	422	503	507+	511	537	559	569*
574	581	583	584+	587*	588+	589	592+	604+
619	646	647	654	657	658			

OXYGEN.....15.005

15+	16+	50	74	92+	107*	127	138+	139+
153	176*	187	228	232*	246	296+	306	309
338	344*	345+	365	422	445+	447+	467	503+
507	511	520	537	542	554	566	568*	573
582	583+	584+	587*	589+	592	593*	598+	599

AIR.....15.006

6	38	52	67	68	74	91+	92	94+
99	122	126	127	146	168	169+	175	197
206	217	221	222	232*	233	236+	246	278
295+	306	310+	339	340	351	365	374	375
408*	412	415	423	438+	444	454+	456	457
485	503	507	511	519	523	527	531	536
543	553	573	580+	587	592+	609	610	611
612	613	614	615	616	649	654	658	

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EQUILIBRIUM CONCENTRATIONS IN BINARY MIXTURES (16.000)

NITROGEN-CARBON MONOXIDE MIXTURES.....16.004/7
131 162 313+ 488 491 492 497+ 518+ 549
606* 653*

NITROGEN-ARGON MIXTURES.....16.004/9
159* 245* 488 550+ 625+ 716+ 721+

NITROGEN-METHANE MIXTURES.....16.004/10
41* 42 43* 73* 158+ 199 508+ 529+ 551+
603 713+ 719

OXYGEN-CARBON MONOXIDE MIXTURES.....16.005/7
253

OXYGEN-ARGON MIXTURES.....16.005/9
60 76 123 137 150 160 452 488 602
625 714 717

OXYGEN-METHANE MIXTURES.....16.005/10
158

CARBON MONOXIDE-METHANE MIXTURES.....16.007/10
371

ARGON-METHANE MIXTURES.....16.009/10
602 714

* REFERENCE USED AS SOURCE OF DATA
\+ REFERENCE LISTED AS OTHER REFERENCE

LITHIUM.....17.111A
56 203 210+ 252* 266 332* 354 356 357+
360* 385+ 392+ 478

SODIUM.....17.111B
34 51 56 114 135 203 213+ 252* 266+
277 332* 354 355 356 357+ 360* 392+ 634
640+ 642

POTASSIUM.....17.111C
56 203 213+ 252* 266+ 332* 354 356 357+
360* 562+ 640+

RUBIDIUM.....17.111D
203 213+ 252* 266+ 321+ 332* 354 356 357+
360 392+

CESIUM.....17.111E
203 213+ 252* 266+ 332* 354 356 358+ 360
392+ 632

COPPER.....17.112-1A
14 33 39 89 93 110+ 119 120 134
203 204 205 218 226+ 239+ 252* 256 320
332* 355 382+ 384+ 395 439 450 477 498
562 567 633 634

SILVER.....17.112-1B
112+ 119 120+ 203 218 239+ 252* 256 332*
355 381+ 395 428+ 477 498 567 634

GOLD.....17.112-2
44 69+ 96 110 112 119 136 203 205
218 239+ 252* 256 264+ 266 272 332* 333
359 381+ 384+ 395 477 498 561 634

BERYLLIUM.....17.121A
53 54 118 203 204 332* 342+ 358+ 382
392+ 451+ 477 637

MAGNESIUM.....17.121B
120+ 203 224 252* 266 273 332* 349 377
392+ 420+ 477 479+ 516 545 652+

* REFERENCE USED AS SOURCE OF DATA
\+ REFERENCE LISTED AS OTHER REFERENCE

ELECTRICAL RESISTIVITY (17.000)

CALCIUM.....17.121C
56 203 332* 355 358+ 392+ 470+

STRONTIUM.....17.121D
56+ 203 332* 358 392+

BARIUM.....17.121E
54 203 267+ 332* 390+ 392+ 469+

ZINC.....17.122A
59 114 120 203 239+ 252* 256+ 272 332*
355 498 555+

CADMIUM.....17.122B
109 203 239+ 252* 256+ 266 332* 355 381+
432 477 498

MERCURY.....17.122C
56 [illegible] 121+ 203 219 252* 332* 355 377
392+ 432+

LANTHANUM.....17.131A
54 56 257+ 332* 477

CERIUM.....17.131B
54 257+ 332* 477

PRASEODYMIUM.....17.131C
54 257+ 332*

NEODYMIUM.....17.131D
56 257+ 332*

GADOLINIUM.....17.131F
332* 337+

DYSPROSIUM.....17.131G
204 332* 337+

ERBIUM.....17.131I
252 332* 337+ 715

THORIUM.....17.131L
32 54 203 332* 377 392+

* REFERENCE USED AS SOURCE OF DATA
\+ REFERENCE LISTED AS OTHER REFERENCE

PROPERTY AND MATERIAL INDEX OF REFERENCES
(NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

ELECTRICAL RESISTIVITY (17.000)

URANIUM.....17.131M
32 100+ 332* 377 392+ 477

ALUMINUM.....17.132B
44 59 89 120 203 205+ 238+ 239+ 252*
256 266 269+ 320 332* 355 382 392+ 449
477 515 538 545+ 700+ 701+ 704+ 708+ 709+
710+ 711+

GALLIUM.....17.132D
56+ 114+ 203 332* 377 477

INDIUM.....17.132F
47 48 114 203 219 252* 332* 355 377
388+ 390+ 392+ 535 555+

THALLIUM.....17.132G
59 109+ 145 203 219 252* 332* 355 377
388+ 390+ 434+ 480+

TITANIUM.....17.141A
32 56 81+ 301 332* 377 390+ 392+ 477
634

ZIRCONIUM.....17.141B
32 56 78+ 108+ 113 145 252* 301 332*
377 392+ 477 634

HAFNIUM.....17.141C
108+ 113 223+ 332* 377 378+ 634 636

CARBON.....17.142-1
56 355 459

GERMANIUM.....17.142-2B
35+ 140 174 181 250 252 637

TIN.....17.142-3A
44 47 48 59 109 120 203 218 219
252* 256+ 273 319 332* 377 382 386+ 432
434+ 562

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ELECTRICAL RESISTIVITY (17.000)

URANIUM.....17.131M
32 100+ 332* 377 392+ 477

ALUMINUM.....17.132B
44 59 89 120 203 205+ 238+ 239+ 252*
256 266 269+ 320 332* 355 382 392+ 449
477 515 538 545+ 700+ 701+ 704+ 708+ 709+
710+ 711+

GALLIUM.....17.132D
56+ 114+ 203 332* 377 477

INDIUM.....17.132F
47 48 114 203 219 252* 332* 355 377
388+ 390+ 392+ 535 555+

THALLIUM.....17.132G
59 109+ 145 203 219 252* 332* 355 377
388+ 390+ 434+ 480+

TITANIUM.....17.141A
32 56 81+ 301 332* 377 390+ 392+ 477
634

ZIRCONIUM.....17.141B
32 56 78+ 108+ 113 145 252* 301 332*
377 392+ 477 634

HAFNIUM.....17.141C
108+ 113 223+ 332* 377 378+ 634 636

CARBON.....17.142-1
56 355 459

GERMANIUM.....17.142-2B
35+ 140 174 181 250 252 637

TIN.....17.142-3A
44 47 48 59 109 120 203 218 219
252* 256+ 273 319 332* 377 382 386+ 432
434+ 562

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VELOCITY OF SOUND (15.000)

CARBON MONOXIDE.....15.007

27 138+ 232+ 503+ 511 583+ 589+ 590* 619
649+ 658

ARGON.....15.009

7 15+ 17 18 26 50 125 126+ 128
176+ 201+ 211 225 232* 309 326 329 330
346+ 365 398 422 530+ 583 591 594* 595*
604+ 619

METHANE.....15.010

126 325+ 328+ 329 367+ 422 424+ 454* 467
569+ 595* 718+

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EQUILIBRIUM CONCENTRATIONS IN BINARY MIXTURES (16.000)

HELIUM 3-HELIUM 4 MIXTURES.....16.001/1
104 105

HELIUM-HYDROGEN MIXTURES.....16.001/2
292 723*

HELIUM-NEON MIXTURES.....16.001/3
292

HELIUM-NITROGEN MIXTURES.....16.001/4
161 193+ 279 292 304* 489+

HELIUM-OXYGEN MIXTURES.....16.001/5
292

HELIUM-METHANE MIXTURES.....16.001/10
192* 279 372*

HYDROGEN--NITROGEN MIXTURES.....16.002/4
131+ 147+ 190 191+ 194* 199 362+ 492+ 508+
606+

HYDROGEN-OXYGEN MIXTURES.....16.002/5
129 717

HYDROGEN-CARBON MONOXIDE MIXTURES.....16.002/7
131 147* 166+ 190 253 492+ 518+ 552 606*
653+

HYDROGEN--ARGON MIXTURES.....16.002/9
714

HYDROGEN-METHANE MIXTURES.....16.002/10
31* 41* 147 156+ 171* 190 191 199 241+
508 606 702+ 703+ 706

NEON-NITROGEN MIXTURES.....16.003/4
96

NITROGEN-OXYGEN MIXTURES.....16.004/5
9* 88* 130* 162 232* 251+ 313+ 317+ 318+
452+ 453 488+ 491+ 493 625+ 721*

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PROPERTY AND MATERIAL INDEX OF REFERENCES

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ELECTRICAL RESISTIVITY (17.000)

LEAD.....17.142-3B
44 59 110 114 203 256+ 266 272 332*
355 383+ 384+ 387+ 394 433+ 498 562+

NIOBIUM.....17.151A
32 53 264 332* 377 389+ 458+ 477 634
636

TANTALUM.....17.151B
61+ 203 219 239+ 252* 264 332* 377+ 382
392+ 477 634

VANADIUM.....17.151C
332* 393+ 448+ 634 636

ARSENIC.....17.152A
53 56 218 332* 392+

ANTIMONY.....17.152B
145 150+ 178+ 203 252* 332* 382 392+ 477

BISMUTH.....17.152C
56 145 203 204 216 218 252* 256+ 272
332* 392+ 428+ 637

CHROMIUM.....17.161A
53 55+ 145+ 203 332* 378+ 634

MOLYBDENUM.....17.161B
40+ 145 203 239+ 252* 332* 377 382 392+
477 545 634

TUNGSTEN.....17.161C
56 111+ 203 204+ 205 239+ 252* 332* 334
377 382 392+ 477 545 562+ 634

TELLURIUM.....17.162D
203 252 426

MANGANESE.....17.171A
145+ 203 332* 477 634 707+ 712+ 720+

RHENIUM.....17.171B
10+ 249 332* 392+ 634

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(NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

ELECTRICAL RESISTIVITY (17.000)

IRON.....17.181A

82+ 120 195 203 205 239+ 252* 301 314
315 332* 355 382+ 477 498 534 571 634

NICKEL.....17.181B

119+ 120 167+ 195 203 252* 256 301 314
315 332* 381+ 477 498 534 570 634 639+

COBALT.....17.181C

55+ 203 204 252* 332* 378 382 392+ 477
498+ 545 634

RUTHENIUM.....17.182A

53 249 265+ 332* 392+ 634 635

RHODIUM.....17.182B

53+ 145 203 239+ 252* 332* 382 392+ 477
632 634

PALLADIUM.....17.182C

119 120 203 207+ 239+ 302 332* 382 392+
477 634

OSMIUM.....17.182D

249 634 635

IRIDIUM.....17.182E

203 239+ 252* 256+ 264 332* 377 382 392+
448+ 477 632 634

PLATINUM.....17.182F

49 69 119 203 204 205 218 227+ 239+
252* 332* 381+ 391 433+ 477 534 632 634
724+

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5166

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No Space 3/4 Inch

R-1542 9-174

Blue

DN