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272769

# 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

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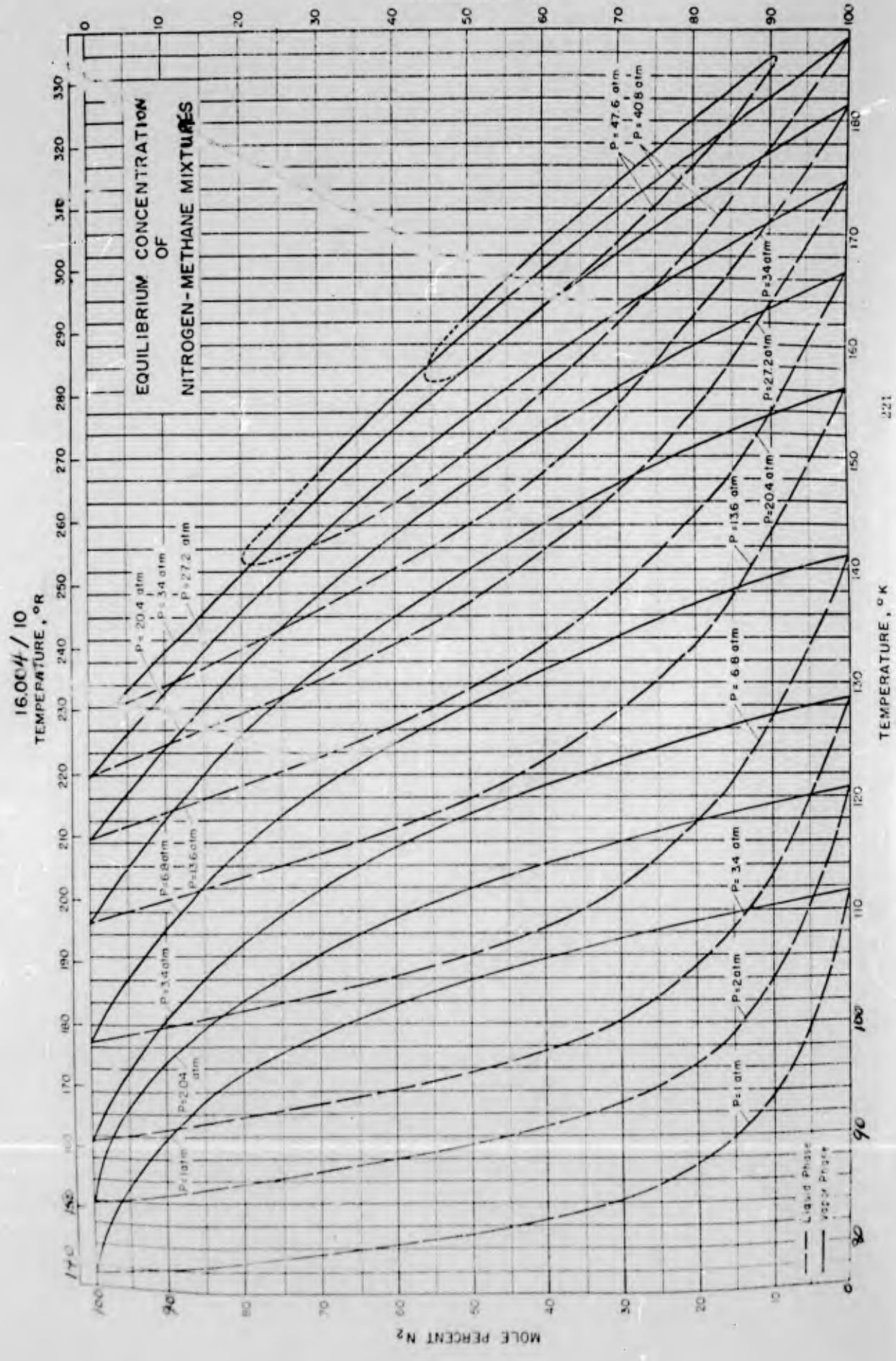
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**A COMPENDIUM OF THE PROPERTIES  
OF MATERIALS AT LOW TEMPERATURE (PHASE II)**

*RICHARD B. STEWART  
VICTOR J. JOHNSON*

*GENERAL EDITORS*

*NATIONAL BUREAU OF STANDARDS  
CRYOGENIC ENGINEERING LABORATORY  
BOULDER, COLORADO*

*DECEMBER 1961*

*DIRECTORATE OF MATERIALS AND PROCESSES  
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*AERONAUTICAL SYSTEMS DIVISION  
AIR FORCE SYSTEMS COMMAND  
UNITED STATES AIR FORCE  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO*

## 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. Fowell.

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 C. 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 (14 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:



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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\*\* 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 References, 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 Expansivity (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.

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\*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 abbreviations 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. This 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 Physikalischemische 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 (1954)

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.

## 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
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## 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:

$$\text{Amagat "density"} \quad -- \quad \text{Amagat} = \frac{\text{density}}{\text{standard density}}$$

$$\text{Amagat "volume"} \quad -- \quad \text{Amagat} = \frac{\text{volume}}{\text{standard volume}}$$

$$\text{Amagat "PV"} \quad -- \quad \text{Amagat} = \frac{PV}{\text{standard PV}}$$

(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)

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

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

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

## COMPRESSIBILITY FACTOR OF CRYOGENIC FLUIDS

likewise,  $Amagat_{pv} = Amagat_v \times p$ , (p in atm.)

or,  $Amagat_{pv} = p/Amagat_{\rho}$

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

by definition  $Amagat_{\rho} = 1$

$Amagat_v = 1$

$Amagat_{pv} = 1$

thus,  $1 Amagat_v = 1/1 Amagat_{\rho} = 1 Amagat_{pv}/1 atm. = 1$

A further example, consider helium at 80°K,  $\rho = 0.0060$  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, ( $\rho_{std} = 0.0001785$ )]

The Amagat values are as follows:

$$Amagat_v = v/v_{std} = 166.7/5601.9 = 0.02975$$

$$Amagat_{\rho} = \rho/\rho_{std} = 0.0060/0.0001785 = 33.61$$

$$Amagat_v = 1/Amagat_{\rho} = 1/33.61 = 0.02975$$

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

$$Amagat_v = Amagat_{pv}/p = 0.2975/10 atm. = 0.02975$$

Thus,  $Amagat_v = 1/Amagat_{\rho} = Amagat_{pv}/p = 0.02975$

## 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 ( $0^{\circ}\text{C} = 273.15^{\circ}\text{K}$ ) 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)

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

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

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 x 10 <sup>-3</sup>	1.02 x 10 <sup>-6</sup>	60	0.395 x 10 <sup>-3</sup>	0.65 x 10 <sup>-6</sup>
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.	B	C
18	-0.276	0.95	°C	Amagats	Amagats
20	-0.180	0.93	-150	0.509 x 10 <sup>-3</sup>	0.48 x 10 <sup>-6</sup>
22	-0.101	0.90	-100	0.521	0.40
30	0.108	0.83	- 50	0.517	0.35
40	0.251	0.76	0	0.512	0.31
50	0.338	0.70			

(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 Zeimanov

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

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	Pressure atm.	Percent Difference
18°K		53.45	1.38
5	0.932	98.8	6.18
9.930	-0.41	20°K	
14.95	-1.69	5.6	0.92
20.26	-2.39	11.21	-0.16
26.20	-1.99	16.950	-1.46
32.85	-1.25	23.1	-1.03
49.7	1.53	29.95	-1.78
60.85	3.35	37.65	-1.18
74.8	5.29	46.6	-1.18
92.65	7.13	57.20	1.12
103.05	7.67	69.75	2.512
19°K		85.25	3.91
5.3	0.93		
13.55	-0.10		

11.001

COMPRESSIBILITY FACTOR for HELIUM  
 [P = Pressure, (atm); Z = Compressibility Factor]

Density g/cc	Temperature, °K																	Density g/cc			
	20	25	30	40	50	60	70	80	90	100	120	140	150	180	220	260	300				
.0002	P																	1.007	P	.0002	
	Z																	1.001	Z		
.0004	P												1.149	1.314	1.478	1.806			1.007	P	.0004
	Z											1.001	1.001	1.001	1.001	1.001			1.001	Z	
.0010	P					1.026	1.232	1.438	1.644	1.850	2.056	2.467	2.878	3.290	3.701	4.523	5.346	6.168	1.003	P	.0010
	Z					1.002	1.002	1.002	1.002	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	Z	
.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	1.003	P	.0012
	Z					1.002	1.003	1.003	1.003	1.003	1.002	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	Z	
.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	1.004	P	.0014
	Z				1.000	1.003	1.003	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	Z	
.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	1.005	P	.0016
	Z				1.002	1.003	1.004	1.004	1.004	1.004	1.004	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	Z	
.0018	P			1.104	1.477	1.850	2.222	2.594	2.966	3.337	3.707	4.451	5.193	5.935	6.677	8.161	9.644	11.13	1.005	P	.0018
	Z			1.001	1.003	1.004	1.004	1.004	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	Z	
.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	14.02	1.005	P	.0020
	Z	.9948	.9975	1.001	1.003	1.004	1.005	1.005	1.005	1.005	1.006	1.005	1.005	1.006	1.006	1.006	1.006	1.006	1.006	Z	
.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	18.05	21.57	24.99	1.011	P	.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	1.012	1.012	1.012	1.012	1.012	Z	
.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	1.011	P	.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	1.017	1.017	Z	
.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	1.017	P	.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	1.024	Z	
.0100	P	4.031	5.101	6.175	8.326	10.44	12.61	14.74	16.86	18.98	21.09	25.32	29.55	33.77	37.99	46.44	54.89	63.34	1.023	P	.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	1.030	Z	
.0120	P	4.837	6.132	7.432	10.04	12.63	15.21	17.79	20.35	22.91	25.46	30.57	35.67	40.77	45.87	56.07	66.27	76.48	1.029	P	.0120
	Z	.9829	.9969	1.007	1.020	1.027	1.031	1.033	1.034	1.035	1.035	1.035	1.035	1.036	1.036	1.036	1.036	1.036	1.036	Z	
.0140	P	5.645	7.169	8.700	11.76	14.81	17.85	20.87	23.88	26.89	29.89	35.89	41.86	47.85	53.84	65.82	77.80	89.79	1.035	P	.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	1.043	1.043	1.043	1.043	Z	
.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		1.041	P	.0160
	Z	.9843	1.002	1.014	1.030	1.038	1.042	1.045	1.046	1.047	1.048	1.048	1.048	1.048	1.048	1.049	1.049		1.048	Z	
.0180	P	7.274	9.266	11.27	15.27	19.26	23.22	27.15	31.08	34.99	38.89	46.70	54.59	62.45	70.29	85.70			1.048	P	.0180
	Z	.9855	1.004	1.015	1.035	1.044	1.049	1.051	1.053	1.053	1.054	1.054	1.055	1.055	1.055	1.056			1.056	Z	
.0200	P	8.095	10.33	12.57	17.06	21.52	25.95	30.36	34.74	39.12	43.48	52.21	60.95	69.66	78.36	95.84			1.054	P	.0200
	Z	.9870	1.007	1.022	1.040	1.050	1.053	1.054	1.055	1.055	1.056	1.056	1.056	1.056	1.056	1.056			1.056	Z	
.0240	P	9.751	12.48	15.22	20.69	26.13	31.58	36.80	42.01	47.23	52.45	63.15	73.86	84.57	95.29				1.056	P	.0240
	Z	.9903	1.014	1.031	1.051	1.062	1.068	1.072	1.078	1.078	1.078	1.078	1.078	1.078	1.078				1.078	Z	
.0280	P	11.43	14.67	17.92	24.41	30.85	37.24	43.57	49.88	56.17	62.45	75.54							1.078	P	.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	Z	
.0320	P	13.14	16.90	20.68	28.23	35.70	43.10	50.45	57.75	65.04	72.31	86.85							1.089	P	.0320
	Z	1.001	1.030	1.051	1.076	1.088	1.095	1.099	1.100	1.102	1.102	1.103							1.103	Z	
.0360	P	14.88	19.18	23.51	32.14	40.68	49.13	57.51	65.84	74.15	82.45	99.05							1.103	P	.0360
	Z	1.000	1.039	1.062	1.089	1.102	1.109	1.113	1.115	1.116	1.117	1.118							1.118	Z	
.0400	P	16.64	21.51	26.41	36.16	45.00	53.72	62.46	71.15	79.85	88.52	98.88							1.118	P	.0400
	Z	1.015	1.049	1.073	1.102	1.117	1.124	1.128	1.128	1.130	1.132	1.133							1.133	Z	
.0440	P	18.45	23.90	29.38	40.29	51.06	61.69	72.22	82.70	93.16									1.133	P	.0440
	Z	1.023	1.060	1.086	1.117	1.132	1.140	1.144	1.146	1.148									1.148	Z	
.0480	P	20.29	26.34	32.43	44.54	56.47	68.26	79.93	91.54										1.148	P	.0480
	Z	1.031	1.071	1.099	1.132	1.148	1.156	1.160	1.163										1.163	Z	
.0520	P	22.17	28.85	35.57	48.91	62.06	75.02	87.85											1.163	P	.0520
	Z	1.040	1.082	1.112	1.147	1.164	1.173	1.177											1.177	Z	
.0600	P	25.77	34.07	42.10	58.07	73.73	89.16												1.177	P	.0600
	Z	1.060	1.108	1.141	1.180	1.199	1.203												1.203	Z	
.0700	P	31.22	41.01	50.86	70.34	89.40													1.203	P	.0700
	Z	1.088	1.143	1.181	1.225	1.246													1.246	Z	
.0800	P	36.73	48.51	60.34	83.66														1.246	P	.0800
	Z	1.120	1.183	1.226	1.275														1.275	Z	
.0900	P	42.66	56.65	70.66	98.21														1.275	P	.0900
	Z	1.156	1.225	1.275	1.333														1.333	Z	
.1000	P	49.10	65.82	81.96															1.333	P	.1000
	Z	1.198	1.278	1.333															1.333	Z	
.1100	P	56.12	75.28	94.42															1.333	P	.1100
	Z	1.244	1.335	1.396															1.396	Z	
.1200	P	63.84	86.08																1.396	P	.1200
	Z	1.297	1.400																1.400	Z	
.1300	P	72.38	98.13																1.400	P	.1300
	Z	1.358	1.473																1.473	Z	
.1400	P	81.93																	1.473	P	.1400
	Z	1.427																	1.473	Z	
.1500	P	92.72																	1.473	P	.1500

11.001

PRESSURE, psia

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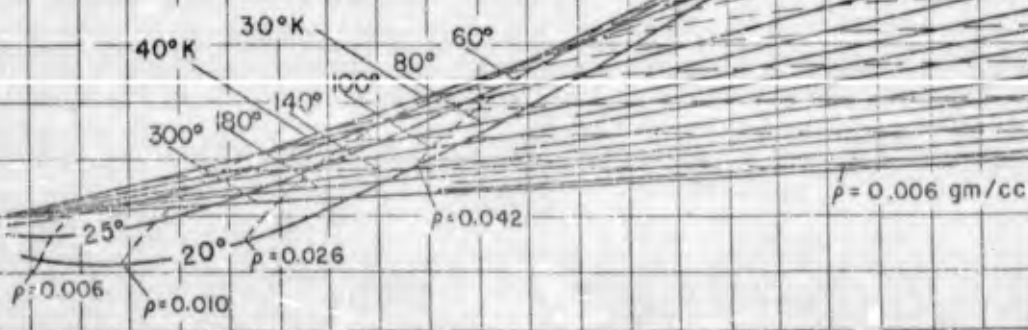
1.60  
1.56  
1.52  
1.48  
1.44  
1.40  
1.36  
1.32  
1.28  
1.24  
1.20  
1.16  
1.12  
1.08  
1.04  
1.00  
0.96

COMPRESSION FACTOR, Z

COMPRESSION FACTOR  
FOR HELIUM  
 $Z = PV / RT$

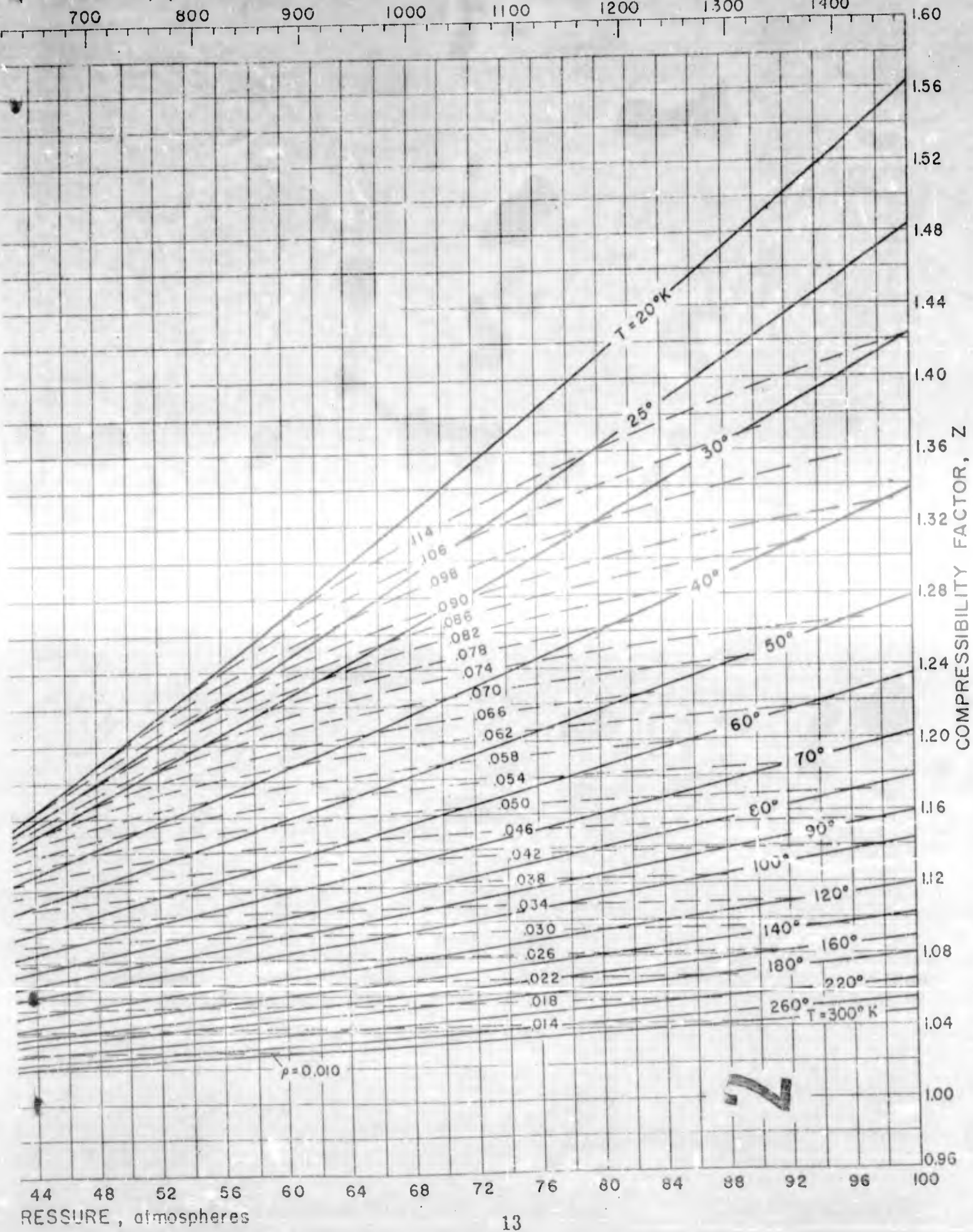
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PRESSURE, atmospheres



11.001

PRESSURE, psia  
700 800 900 1000 1100 1200 1300 1400



## COMPRESSIBILITY FACTOR FOR NORMAL HYDROGEN

$$Z = PV/RT$$

Sources of Data:

Woolley, H. W., Scott, R. E., 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,  $T = 18^\circ$  to  $70^\circ$  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  $33^\circ\text{K}$ . 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  $33^\circ\text{K}$ . 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.

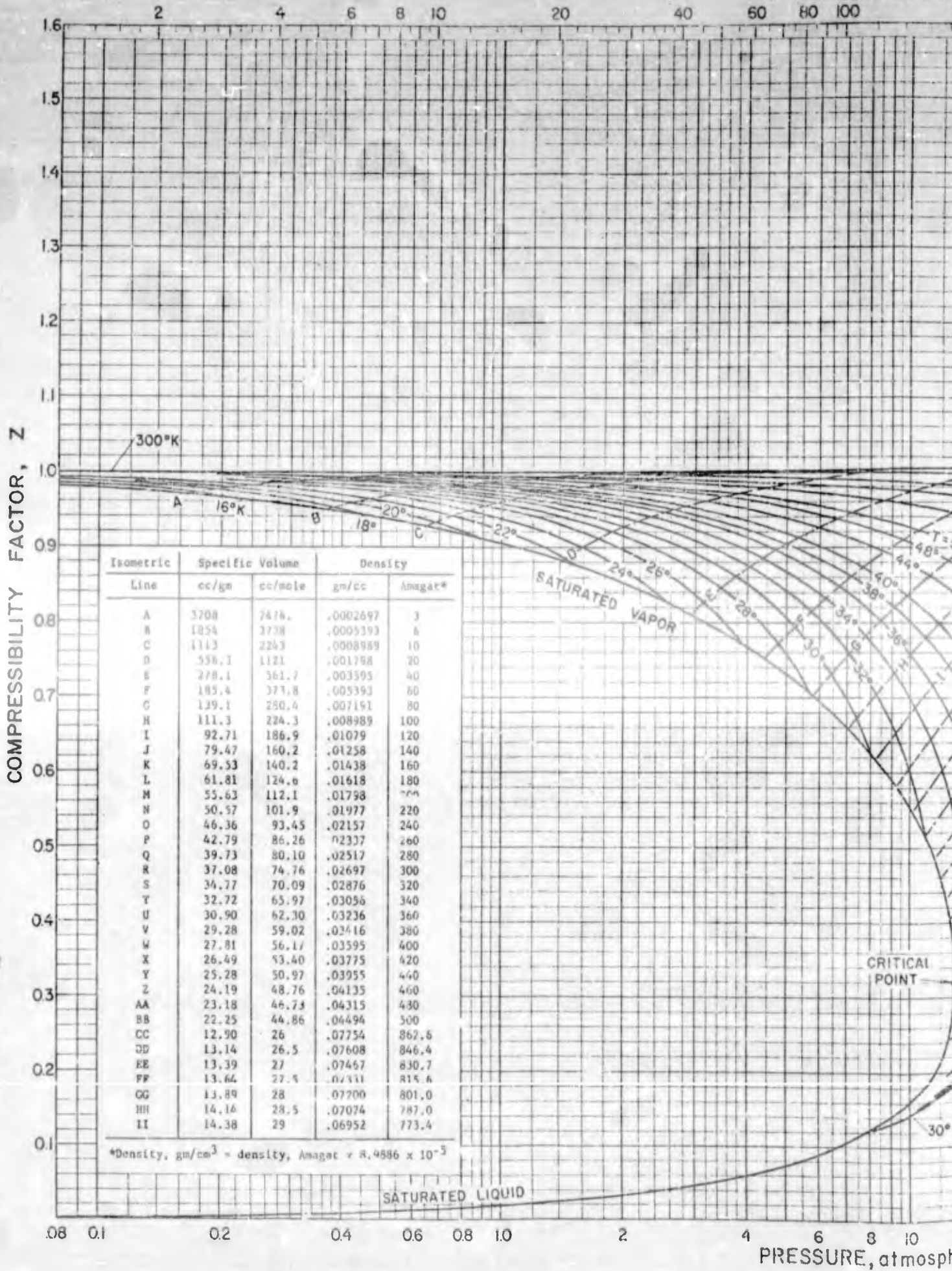
The correlation by Stewart and Johnson includes values from the two publications listed above by Johnston, et al. as well as those from the N.B.S. report. Stewart and Johnson indicated the variation between the data of Johnston et al. from  $33^\circ$  to  $80^\circ$  and that of Woolley, Scott and Brickwedde 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  $33^\circ\text{K}$ ) 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  $33^\circ\text{K}$ ) 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.



Line	Specific Volume		Density	
	cc/gm	cc/mole	gm/cc	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	373.8	.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	815.4
GG	13.89	28	.07200	801.0
HH	14.14	28.5	.07074	787.0
II	14.38	29	.06952	773.4

\*Density, gm/cm<sup>3</sup> = density, Amagat x 8.4886 x 10<sup>-5</sup>

SATURATED LIQUID

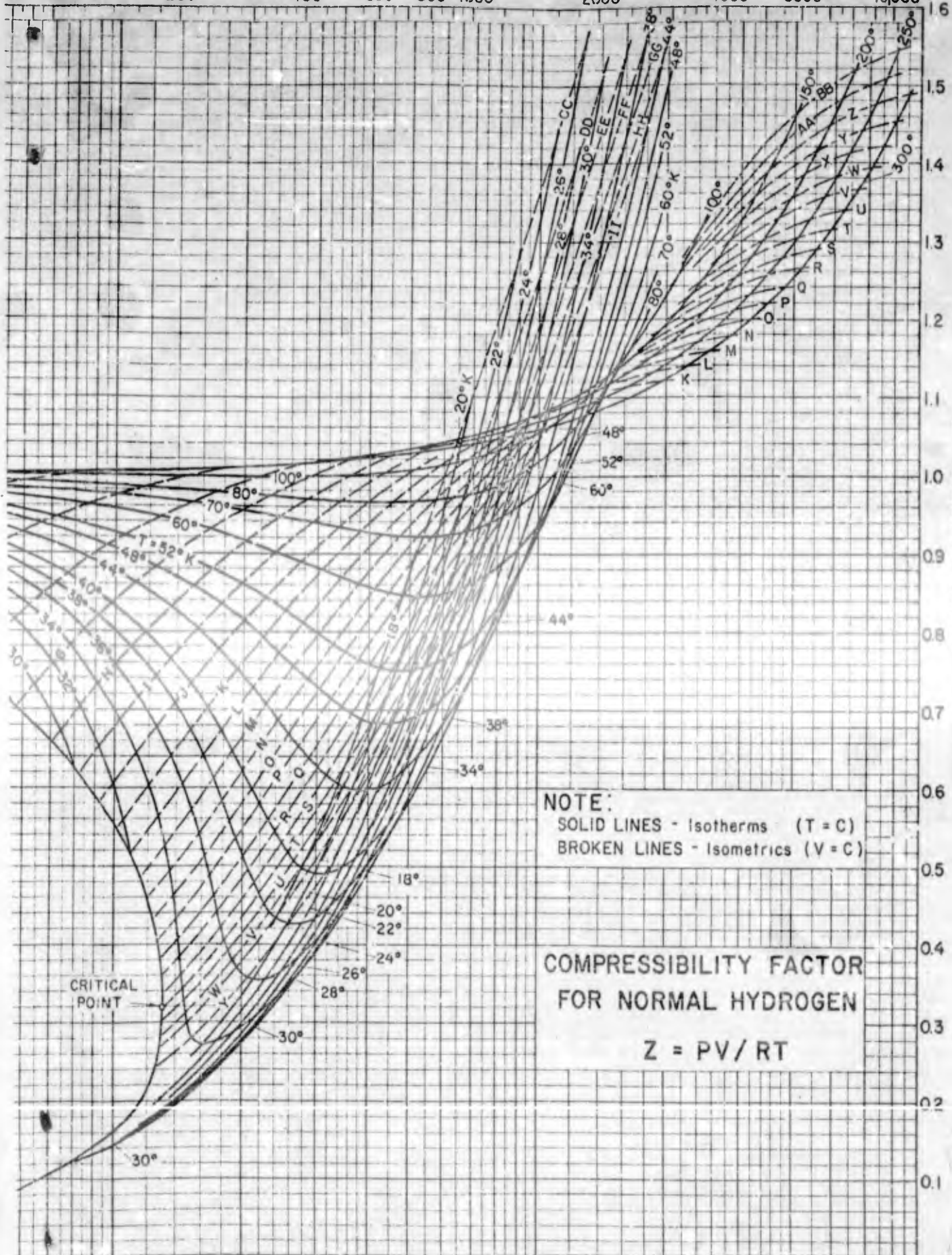
CRITICAL POINT

SATURATED VAPOR

11.002

PRESSURE, psia

80 100 200 400 600 800 1000 2000 4000 6000 10,000



NOTE:  
SOLID LINES - Isotherms (T = C)  
BROKEN LINES - Isometrics (V = C)

COMPRESSIBILITY FACTOR  
FOR NORMAL HYDROGEN  
 $Z = PV/RT$

COMPRESSION FACTOR, Z

2

6 8 10 20 40 60 80 100 200 400 600 800

PRESSURE, atmospheres



Depth (m)	Temp (°C)	Salinity	Stress (kg/cm²)	Strain (%)	Modulus (kg/cm²)	Compressibility (1/MPa)	Volume (cm³)	Area (cm²)	Length (m)	Weight (kg)
10	12.5	35.2	100	0.01	10000	1.0	1000	100	10	1000
20	13.0	35.3	200	0.02	10000	1.0	1000	100	10	1000
30	13.5	35.4	300	0.03	10000	1.0	1000	100	10	1000
40	14.0	35.5	400	0.04	10000	1.0	1000	100	10	1000
50	14.5	35.6	500	0.05	10000	1.0	1000	100	10	1000
60	15.0	35.7	600	0.06	10000	1.0	1000	100	10	1000
70	15.5	35.8	700	0.07	10000	1.0	1000	100	10	1000
80	16.0	35.9	800	0.08	10000	1.0	1000	100	10	1000
90	16.5	36.0	900	0.09	10000	1.0	1000	100	10	1000
100	17.0	36.1	1000	0.10	10000	1.0	1000	100	10	1000

Values and Compressibility coefficients for various depths, diameters, and areas

Pressure (Atm)	Coeff. %	Strain (1/100)		Volume (cm³)
		1	2	
1000	16	13.05	20.127	1000
2000	18	13.85	22.051	1000
3000	20	14.65	23.975	1000
4000	22	15.45	25.900	1000
5000	24	16.25	27.825	1000
6000	26	17.05	29.750	1000
7000	28	17.85	31.675	1000
8000	30	18.65	33.600	1000
9000	32	19.45	35.525	1000
10000	34	20.25	37.450	1000

The following table shows the values for the paper by pressure and diameter

Depth (m)	Temp (°C)	Salinity	Stress (kg/cm²)	Strain (%)	Modulus (kg/cm²)	Compressibility (1/MPa)	Volume (cm³)	Area (cm²)	Length (m)	Weight (kg)
20	13.0	35.3	200	0.02	10000	1.0	1000	100	10	1000
30	13.5	35.4	300	0.03	10000	1.0	1000	100	10	1000
40	14.0	35.5	400	0.04	10000	1.0	1000	100	10	1000
50	14.5	35.6	500	0.05	10000	1.0	1000	100	10	1000
60	15.0	35.7	600	0.06	10000	1.0	1000	100	10	1000
70	15.5	35.8	700	0.07	10000	1.0	1000	100	10	1000
80	16.0	35.9	800	0.08	10000	1.0	1000	100	10	1000
90	16.5	36.0	900	0.09	10000	1.0	1000	100	10	1000
100	17.0	36.1	1000	0.10	10000	1.0	1000	100	10	1000

## 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 ( $0^\circ\text{C} = 273.16^\circ\text{K}$ ), 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:

$$P/\rho RT - 1 = \sum (a_{pq} \rho^q / T^p) \quad \text{Note: The 12 terms of this summation have coefficients } a_{pq} \text{ listed below. In each term the subscripts of } a_{pq} \text{ are the exponents of } T \text{ and } \rho \text{ respectively.}$$

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

$\rho$  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:

$$a_{01} = 0.014208884$$

$$a_{12} = -0.050955574$$

$$a_{52} = 120477.74$$

$$a_{11} = -1.7734560$$

$$a_{32} = 103.28801$$

$$a_{53} = -7305.4880$$

$$a_{31} = -2773.7632$$

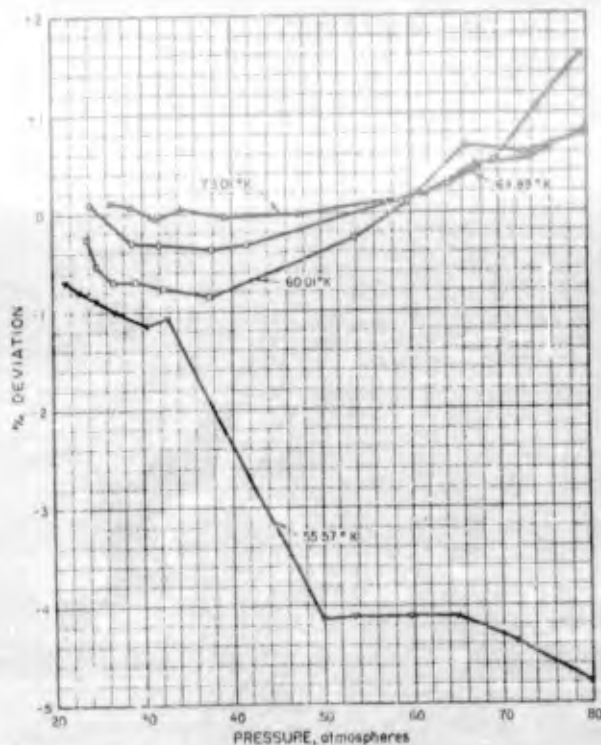
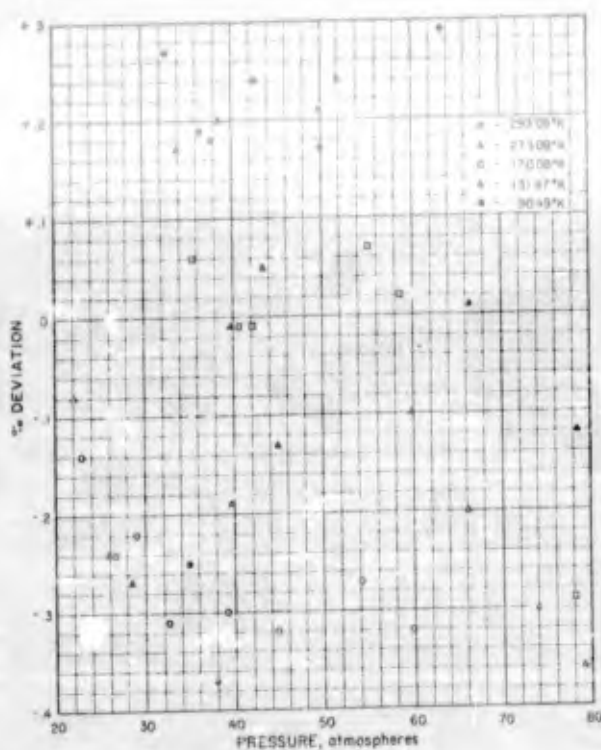
$$a_{33} = 0.66305973$$

$$a_{73} = 204222.81$$

$$a_{02} = 0.00088955035$$

$$a_{51} = 499549.48$$

$$a_{54} = 68.509204$$



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

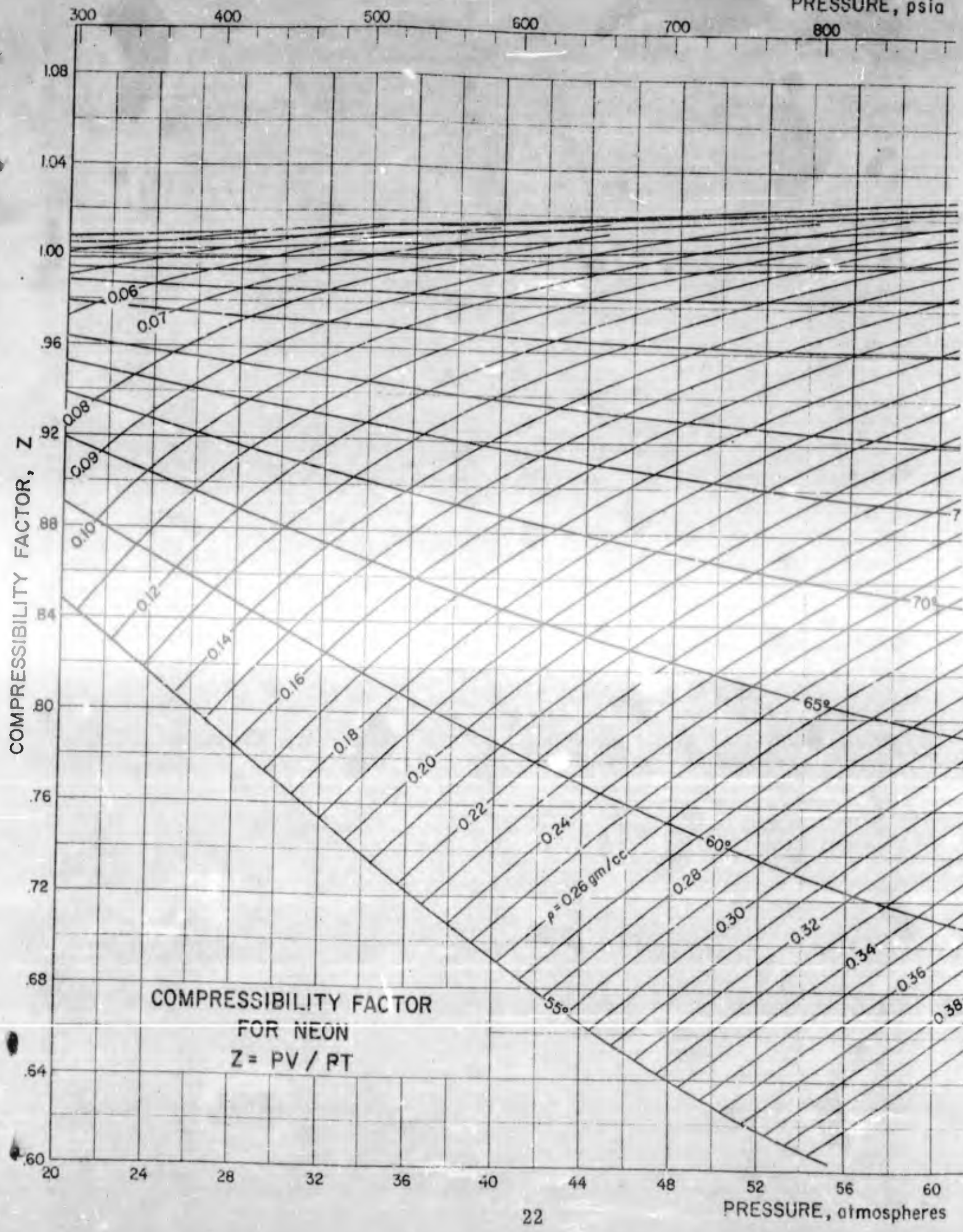
$$\% \text{ Deviation} = \frac{P_{\text{Yend.}} - P_{\text{Crom.}}}{P_{\text{Crom.}}}$$

COMPRESSIBILITY FACTOR for NEON

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

Density gm/cc	Temperature, °K																Density gm/cc
	55	60	65	70	75	80	90	100	110	120	130	150	200	300			
.01	P	2.200	2.014	2.821	3.027	3.233	3.584	4.055	4.465	4.876	5.286	6.106	6.155	12.25	P		
	Z	.983A	.9892	.9911	.9926	.9939	.9959	.9973	.9985	.9994	1.000	1.001	1.003	1.005	Z		
.02	P	4.359	5.172	5.592	5.924	6.427	7.299	8.090	8.919	9.748	10.59	12.23	16.36	24.52	P		
	Z	.9680	.9740	.9766	.9784	.9800	.9819	.9849	.9872	.9890	1.001	1.003	1.006	1.009	Z		
.03	P	6.350	7.056	7.677	8.315	9.585	10.36	12.11	13.37	14.62	15.87	18.38	24.63	37.13	P		
	Z	.9536	.9614	.9684	.9740	.9823	.9883	.9927	.9961	.9989	1.001	1.005	1.010	1.015	Z		
.04	P	8.336	9.262	10.13	10.99	12.71	14.41	16.11	17.81	19.50	21.18	24.56	32.97	49.70	P		
	Z	.9375	.9492	.9581	.9658	.9769	.9842	.9908	.9953	.9990	1.002	1.007	1.014	1.020	Z		
.05	P	10.32	11.43	12.54	13.63	15.60	17.96	20.11	22.25	24.38	26.51	30.77	41.36	62.58	P		
	Z	.9229	.9373	.9487	.9570	.9717	.9816	.9890	.9948	.9994	1.003	1.009	1.018	1.026	Z		
.06	P	12.17	13.55	14.89	16.23	18.27	21.17	24.09	26.69	29.67	31.86	37.02	49.89	75.56	P		
	Z	.9086	.9257	.9393	.9502	.9608	.9707	.9876	.9945	1.000	1.005	1.012	1.022	1.033	Z		
.07	P	14.00	15.61	17.21	18.78	21.00	25.00	28.37	31.13	34.19	37.23	43.31	58.47	88.73	P		
	Z	.8946	.9144	.9301	.9428	.9533	.9739	.9864	.9945	1.001	1.006	1.015	1.027	1.039	Z		
.08	P	15.76	17.63	19.48	21.30	24.32	28.49	32.05	35.59	39.12	42.63	49.65	67.16	103.2	P		
	Z	.8811	.9034	.9212	.9357	.9576	.9755	.9854	.9947	1.002	1.008	1.018	1.032	1.048	Z		
.09	P	17.47	19.60	21.71	23.79	27.21	31.88	36.03	40.08	44.07	48.07	56.05	75.95	115.2	P		
	Z	.8678	.8927	.9126	.9286	.9534	.9712	.9847	.9952	1.004	1.011	1.021	1.038	1.056	Z		
.10	P	19.12	21.52	23.90	26.24	30.88	35.96	40.01	44.54	49.05	53.54	62.91	84.86	128.2	P		
	Z	.8550	.8823	.9042	.9221	.9434	.9682	.9842	.9959	1.005	1.013	1.025	1.044	1.064	Z		
.11	P	20.72	23.40	26.05	28.67	33.53	38.94	44.00	49.04	54.06	59.06	69.04	93.90	142.2	P		
	Z	.8424	.8722	.8967	.9157	.9437	.9674	.9839	.9969	1.007	1.016	1.029	1.050	1.070	Z		
.12	P	22.28	25.24	28.17	31.06	36.77	42.11	47.00	52.56	58.10	64.52	75.63	102.3	155.2	P		
	Z	.8302	.8624	.8883	.9095	.9421	.9689	.9839	.9981	1.010	1.019	1.034	1.057	1.077	Z		
.13	P	23.79	27.05	30.26	33.43	39.70	45.88	52.02	58.11	64.18	70.24	82.31	111.2	168.2	P		
	Z	.8183	.8528	.8807	.9036	.9389	.9682	.9842	.9996	1.012	1.022	1.038	1.062	1.082	Z		
.14	P	25.26	28.81	32.31	35.78	42.61	49.36	56.05	62.59	69.31	75.91	89.05	120.3	178.2	P		
	Z	.8068	.8436	.8734	.8980	.9358	.9682	.9846	1.001	1.015	1.025	1.043	1.068	1.088	Z		
.15	P	26.68	30.54	34.34	38.10	45.51	52.84	60.09	67.30	74.18	81.64	95.90	128.8	190.2	P		
	Z	.7955	.8346	.8664	.8925	.9330	.9687	.9894	1.003	1.018	1.030	1.048	1.074	1.094	Z		
.16	P	28.07	32.24	36.35	40.41	48.42	56.53	64.16	71.95	79.70	87.43	103.3	138.2	200.2	P		
	Z	.7846	.8253	.8596	.8874	.9304	.9682	.9863	1.006	1.021	1.034	1.052	1.078	1.098	Z		
.17	P	29.42	33.90	38.32	42.69	51.39	59.88	68.26	76.63	84.97	93.29	111.3	148.2	215.2	P		
	Z	.7740	.8175	.8530	.8824	.9251	.9627	.9876	1.008	1.025	1.038	1.056	1.082	1.102	Z		
.18	P	30.74	35.54	40.26	44.96	54.21	63.34	72.38	81.36	90.31	99.22	118.2	158.2	225.2	P		
	Z	.7636	.8094	.8467	.8777	.9266	.9665	.9890	1.011	1.028	1.042	1.060	1.086	1.106	Z		
.19	P	32.02	37.15	42.21	47.22	57.12	66.86	76.53	86.14	95.70	105.2	125.2	165.2	235.2	P		
	Z	.7536	.8015	.8407	.8733	.9281	.9681	.9907	1.014	1.032	1.046	1.064	1.090	1.110	Z		
.20	P	33.27	38.73	44.13	49.47	60.00	70.41	80.72	90.96	101.1	111.2	131.2	171.2	241.2	P		
	Z	.7439	.7935	.8349	.8691	.9324	.9681	.9927	1.017	1.036	1.050	1.068	1.094	1.114	Z		
.21	P	34.49	40.29	46.03	51.71	62.91	73.97	84.94	95.84	106.6	117.3	137.2	177.2	247.2	P		
	Z	.7345	.7865	.8293	.8650	.9323	.9687	.9942	1.020	1.039	1.054	1.072	1.100	1.120	Z		
.22	P	35.68	41.83	47.91	53.93	65.68	76.58	87.48	98.34	109.1	120.0	140.0	180.0	250.0	P		
	Z	.7253	.7790	.8233	.8613	.9336	.9707	.9972	1.024	1.044	1.059	1.078	1.106	1.126	Z		
.23	P	36.85	43.35	49.58	55.15	67.51	78.34	89.24	100.1	111.0	122.0	142.0	182.0	252.0	P		
	Z	.7165	.7715	.8168	.8578	.9349	.9727	.9992	1.027	1.047	1.062	1.082	1.110	1.130	Z		

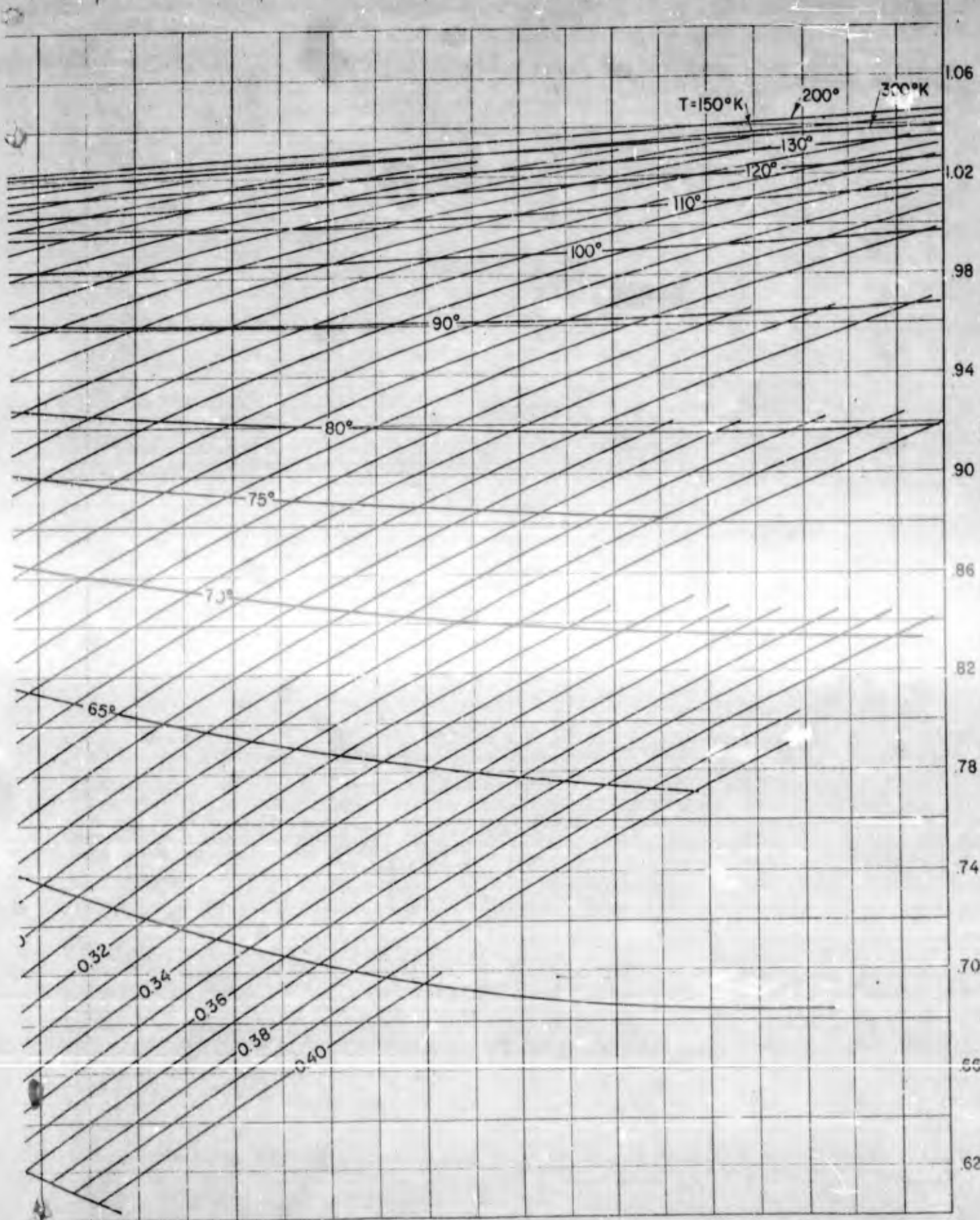
.17	P Z	.8204	.5011	.9204	.9076	1.008	1.025	1.038	P Z	.17
.18	P Z	63.34	63.34	63.34	72.36	81.36	90.31	99.22	P Z	.18
.19	P Z	.9816	.9007	.9241	.9617	1.014	1.028	1.043	P Z	.19
.20	P Z	57.11	57.11	57.11	76.53	86.14	95.70		P Z	.20
.21	P Z	60.00	60.00	60.00	80.72	90.96			P Z	.21
.22	P Z	.9224	.8979	.9224	.927	1.017			P Z	.22
.23	P Z	62.91	62.91	62.91	84.94	95.84			P Z	.23
.24	P Z	.9627	.952	.9627	.9949	1.030			P Z	.24
.25	P Z	77.58	77.58	77.58	89.20				P Z	.25
.26	P Z	.9935	.9929	.9935	.9973				P Z	.26
.27	P Z	81.13	81.13	81.13	93.51				P Z	.27
.28	P Z	.9646	.9607	.9646	1.000				P Z	.28
.29	P Z	71.87	71.87	71.87	97.86				P Z	.29
.30	P Z	.9559	.9588	.9559	.988				P Z	.30
.31	P Z	88.50	88.50	88.50	97.35				P Z	.31
.32	P Z	.9074	.9177	.9074					P Z	.32
.33	P Z	92.21	92.21	92.21					P Z	.33
.34	P Z	.921	.9175	.921					P Z	.34
.35	P Z	80.57	80.57	80.57					P Z	.35
.36	P Z	.9742	.9742	.9742					P Z	.36
.37	P Z	95.75	95.75	95.75					P Z	.37
.38	P Z	.9742	.9742	.9742					P Z	.38
.39	P Z	99.74	99.74	99.74					P Z	.39
.40	P Z	.9735	.9735	.9735					P Z	.40
.41	P Z	52.74	52.74	52.74					P Z	.41
.42	P Z	.9158	.9158	.9158					P Z	.42
.43	P Z	95.55	95.55	95.55					P Z	.43
.44	P Z	.9209	.9209	.9209					P Z	.44
.45	P Z	99.00	99.00	99.00					P Z	.45
.46	P Z	.9223	.9223	.9223					P Z	.46
.47	P Z	91.51	91.51	91.51					P Z	.47
.48	P Z	.8826	.8826	.8826					P Z	.48
.49	P Z	94.27	94.27	94.27					P Z	.49
.50	P Z	.8833	.8833	.8833					P Z	.50
.51	P Z	97.06	97.06	97.06					P Z	.51
.52	P Z	.8342	.8342	.8342					P Z	.52
.53	P Z	99.89	99.89	99.89					P Z	.53
.54	P Z	.8854	.8854	.8854					P Z	.54
.55	P Z	90.17	90.17	90.17					P Z	.55
.56	P Z	.8338	.8338	.8338					P Z	.56
.57	P Z	92.58	92.58	92.58					P Z	.57
.58	P Z	.8341	.8341	.8341					P Z	.58
.59	P Z	95.01	95.01	95.01					P Z	.59
.60	P Z	.8346	.8346	.8346					P Z	.60



11.003

PRESSURE, psia

800 900 1000 1100 1200 1300 1.10



PRESSURE, atmospheres

2

## 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.

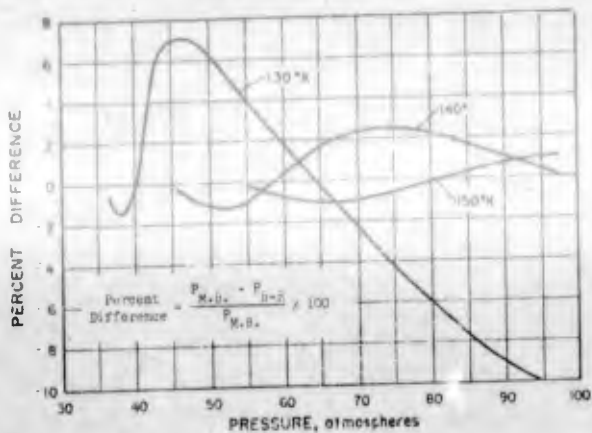


FIGURE 1a. COMPARISON OF COMPRESSIBILITY FACTOR FROM BLOOMER AND RAO, AND M. BENEDECT

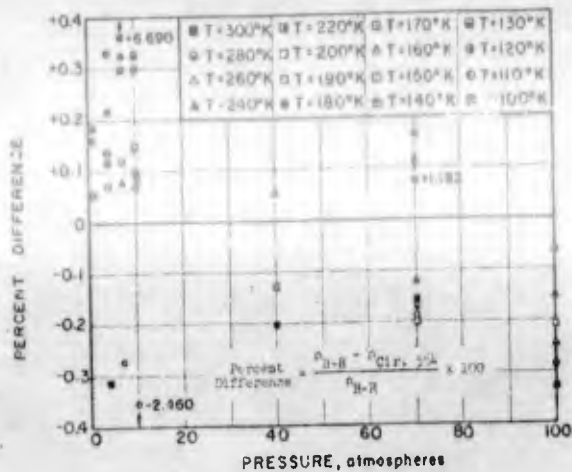


FIGURE 2. COMPARISON OF DENSITY FROM BLOOMER-RAO EQUATION AND NEW CIRCULAR 564 (Variations of less than ± 0.05% are not illustrated.)

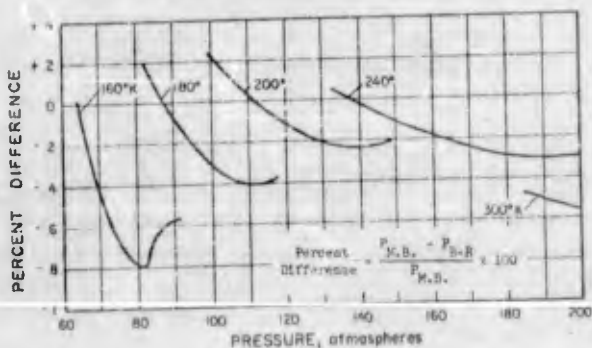
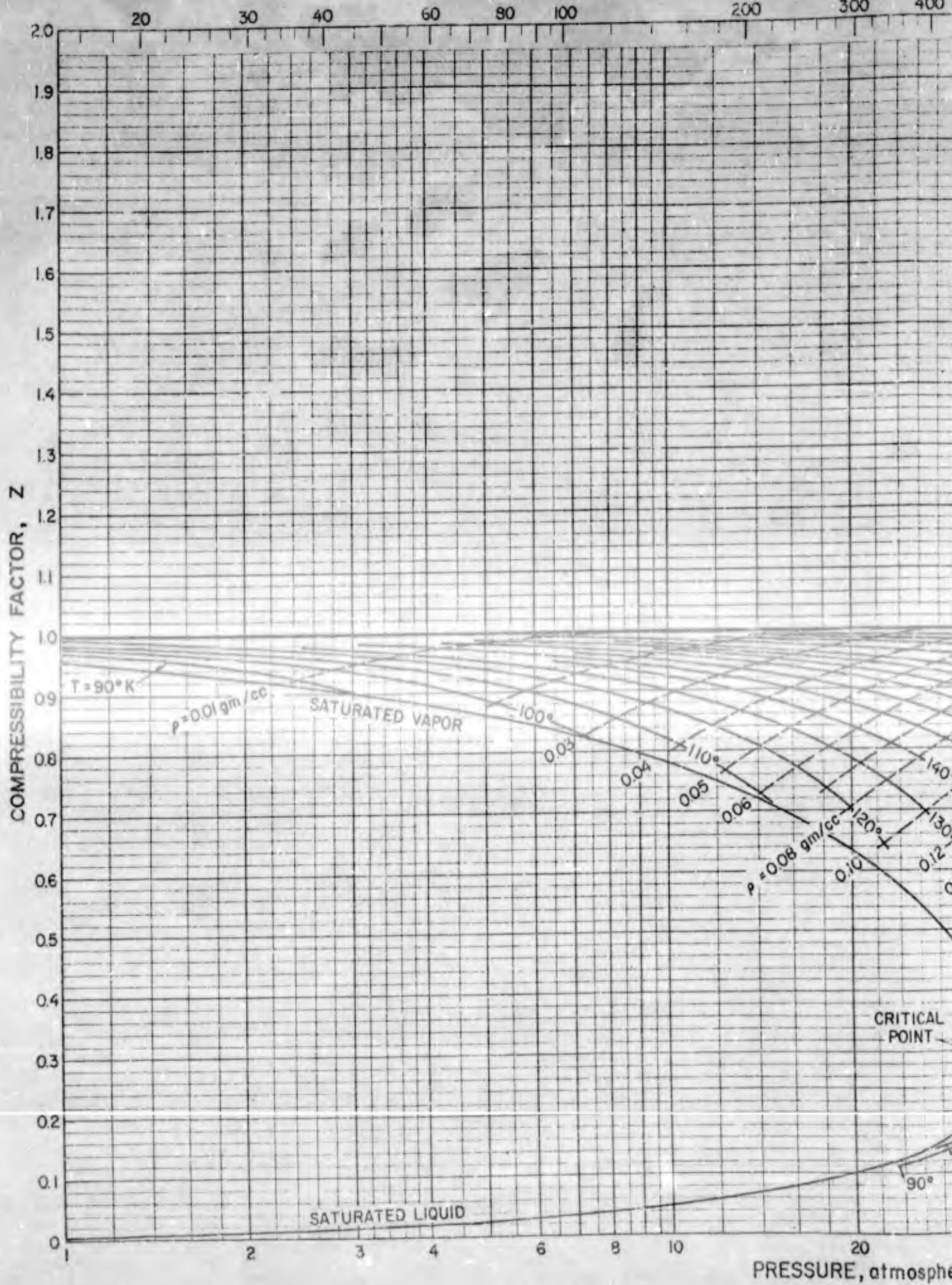


FIGURE 1b. COMPARISON OF COMPRESSIBILITY FACTOR FROM BLOOMER AND RAO, AND M. BENEDECT

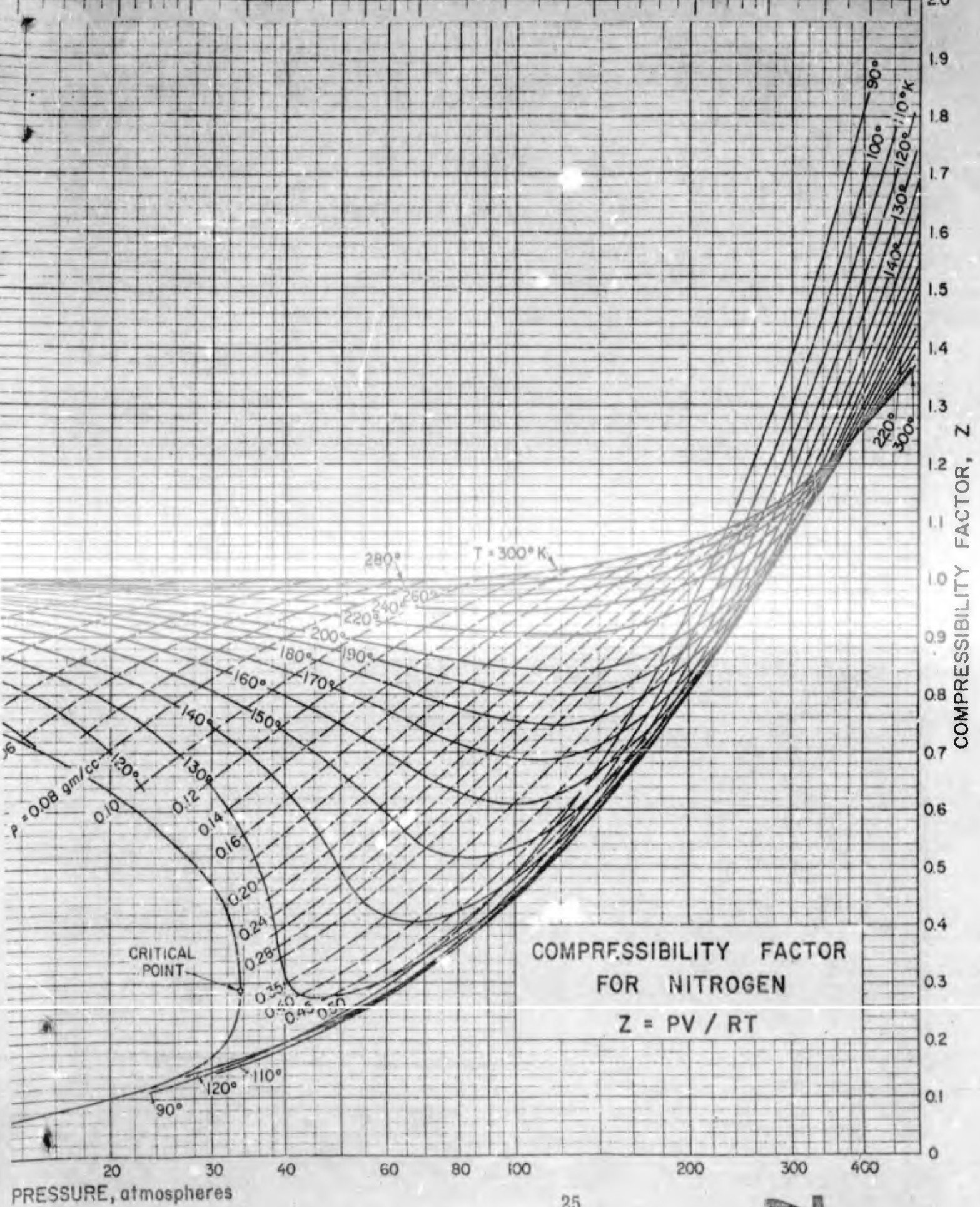


1

11.004

PRESSURE, psia

200 300 400 600 800 1000 2000 3000 4000 6000



COMPRESSIBILITY FACTOR  
FOR NITROGEN  
 $Z = PV / RT$



## COMPRESSIBILITY FACTOR for NITROGEN (Cont.)

$$Z = PV/RT$$

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

$$P = RTP + \left[ B_0 RT - A_0 - \frac{C_0}{T^2} - \frac{D_0}{T^4} \right] \rho^2 + \rho^3 \left[ bRT - a + \left( \frac{c}{T^2} + \frac{\delta}{T^4} \right) (1 + \gamma \rho^2) e^{-\gamma \rho^2} \right] + \alpha \rho^6$$

where T is in °K (0°C = 273.16°K)  
mole wt. N<sub>2</sub> = 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:

$$B_0 = 0.0484324$$

$$b = 0.00232373$$

$$A_0 = 1.27389$$

$$a = 0.0178444$$

$$C_0 = 4273.00$$

$$c = 475.000$$

$$D_0 = 7.61781 \times 10^6$$

$$\delta = 0.832 \times 10^6$$

$$\gamma = 0.0065$$

$$\alpha = 0.00015300$$

The equation of state determined by Benedict is:

$$PV = A + \beta p$$

$$A = 1.00046 T/T_0$$

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

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:

$$T_0 = 273.20^\circ K$$

$$t = 0.91512$$

$$p = -1.66453$$

$$\mu = 2.06932$$

$$q = -1.35938$$

$$v = -1.21342$$

$$\gamma = 11.3200$$

$$W = 107.03$$

$$s = 0.67617$$

$$x = 6.975$$

Rao

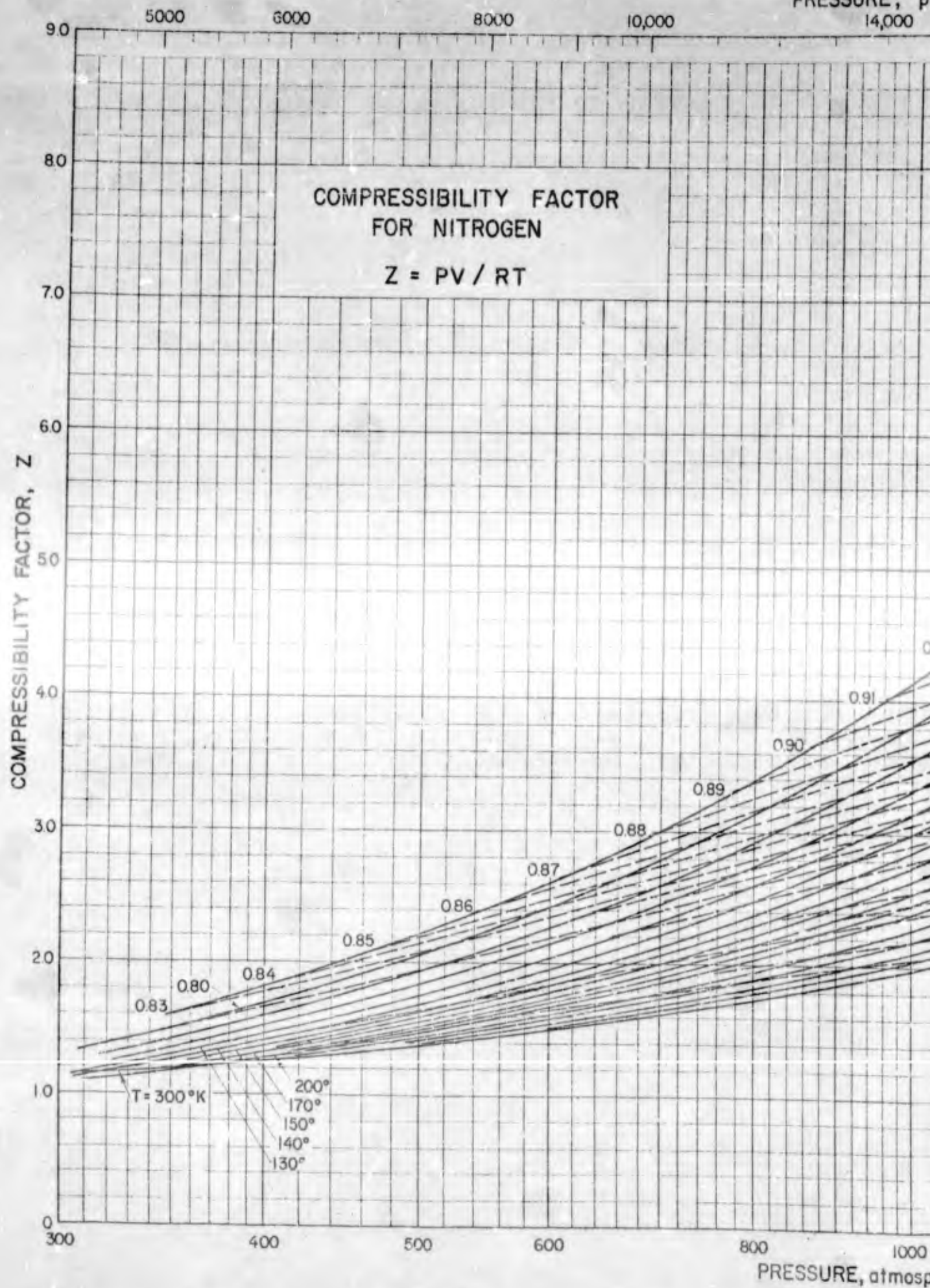
$$\gamma p^2 + a \alpha p^6$$

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

$$10^{-x p^2}$$

, 0°C)



COMPRESSIBILITY FACTOR  
FOR NITROGEN  
 $Z = PV / RT$

COMPRESSIBILITY FACTOR, Z

PRESSURE, atmospheres

11.004

PRESSURE, psia  
14,000

20,000

30,000

40,000

90

$\rho = 0.99 \text{ gm/cc}$

90°K

0.98

100°

0.97

110°

0.96

120°

0.95

130°

0.94

140°

0.93

150°

0.92

160°

0.91

170°

0.90

180°

T = 190°K

200°

0.92

220°

0.91

240°

0.90

250°

0.78

0.82

0.76

0.81

0.74

$\rho = 0.72 \text{ gm/cc}$

0.70

280°K

300°

0.65

0.60

COMPRESSIBILITY FACTOR, Z

30

20

10

0

100

1000

1400

2000

3000

PRESSURE, atmospheres

27

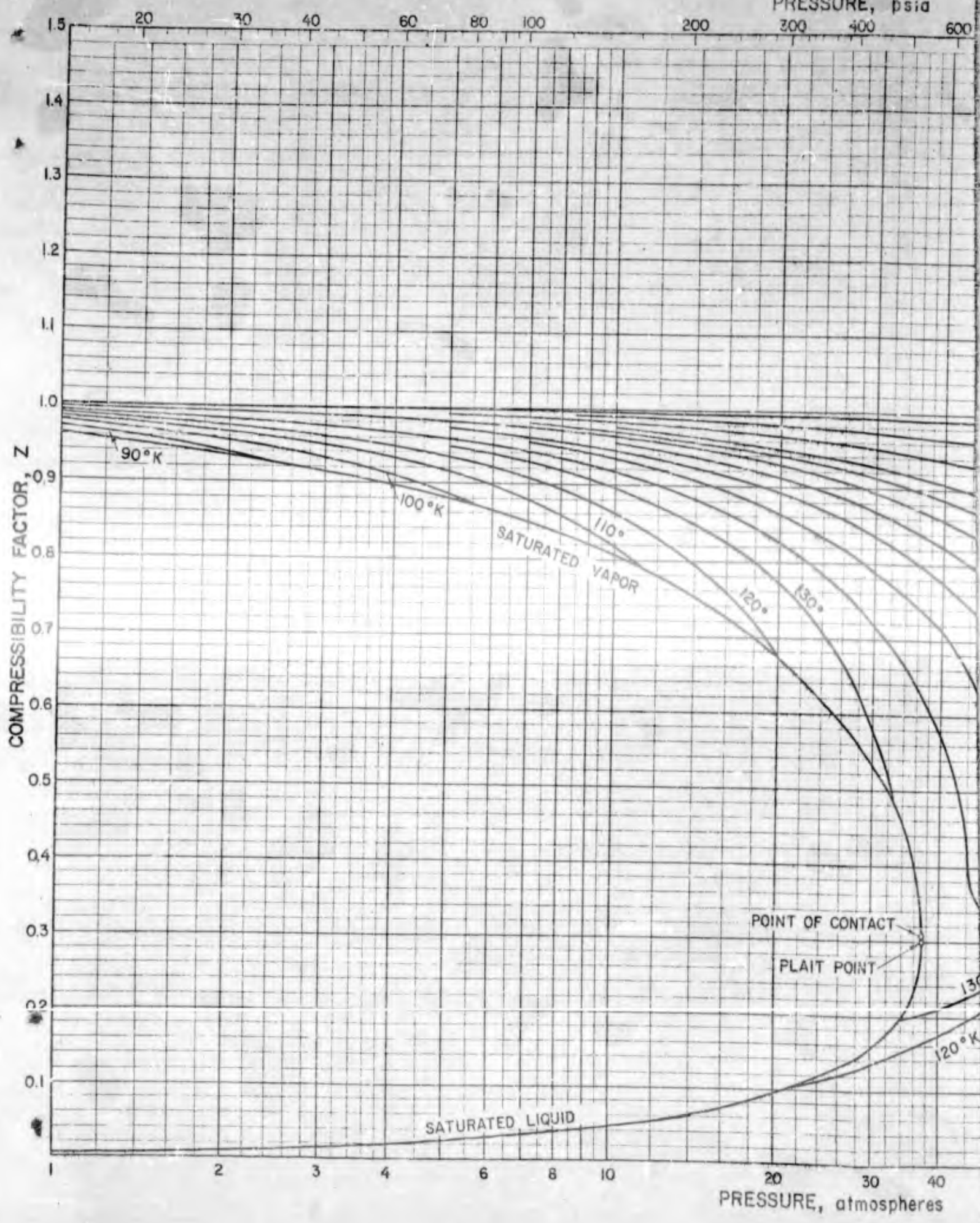
2

11.004  
 COMPRESSIBILITY FACTOR for NITROGEN\*  
 [P=Pressure, (atm); Z = Compressibility 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	2.141	2.756	3.066	3.373	3.681	4.088	4.594	5.100	5.605	6.110	6.615	7.120	7.625	8.130	8.635	9.140	9.645		
	Z	.9558	.9409	.9216	.9036	.8861	.8691	.8526	.8365	.8208	.8055	.7906	.7760	.7617	.7477	.7339	.7204	.7071	.6940	
.02	P	5.176	5.869	6.302	6.603	6.878	7.128	7.354	7.556	7.734	7.889	8.023	8.137	8.231	8.306	8.363	8.403	8.437	8.465	
	Z	.8835	.8635	.8435	.8283	.8141	.8008	.7884	.7768	.7659	.7556	.7458	.7365	.7277	.7193	.7114	.7040	.6971	.6907	
.03	P	7.276	8.302	9.301	10.28	11.25	12.21	13.15	14.06	14.94	15.79	16.61	17.40	18.16	18.90	19.61	20.29	20.94	21.57	22.18
	Z	.8275	.8085	.7901	.7743	.7591	.7445	.7305	.7171	.7043	.6920	.6802	.6689	.6581	.6478	.6380	.6287	.6199	.6116	.6038
.04	P	10.30	11.88	13.23	14.36	15.28	16.09	16.80	17.41	17.93	18.45	18.97	19.49	20.01	20.53	21.05	21.57	22.09	22.61	23.13
	Z	.8145	.7975	.7811	.7663	.7521	.7385	.7254	.7128	.7007	.6891	.6780	.6674	.6572	.6475	.6382	.6294	.6210	.6130	.6054
.06	P	14.11	16.36	18.17	20.57	23.47	26.87	30.77	35.17	39.97	45.17	50.77	56.77	63.17	69.97	77.17	84.77	92.77	101.17	109.97
	Z	.7899	.7736	.7581	.7433	.7291	.7155	.7024	.6898	.6777	.6660	.6548	.6441	.6339	.6241	.6147	.6057	.5970	.5887	.5808
.08	P	19.89	22.50	25.54	29.04	33.09	37.69	42.84	48.54	54.79	61.54	68.89	76.84	85.39	94.54	104.29	114.64	125.59	137.14	149.29
	Z	.7071	.6936	.6806	.6681	.6561	.6446	.6335	.6229	.6127	.6029	.5935	.5845	.5759	.5677	.5598	.5522	.5449	.5379	.5312
.10	P	22.07	25.60	29.45	33.73	38.45	43.61	49.21	55.35	62.03	69.25	77.01	85.31	94.15	103.53	113.45	123.91	134.91	146.45	158.53
	Z	.6446	.6323	.6205	.6091	.5981	.5875	.5773	.5675	.5581	.5491	.5404	.5320	.5239	.5161	.5086	.5014	.4945	.4879	.4815
.12	P	29.67	34.47	39.65	45.31	51.45	58.07	65.17	72.75	80.81	89.35	98.37	107.87	117.85	128.31	139.25	150.67	162.57	174.95	187.81
	Z	.6492	.6377	.6266	.6159	.6056	.5956	.5859	.5765	.5674	.5586	.5501	.5418	.5337	.5258	.5182	.5108	.5036	.4966	.4898
.14	P	32.97	38.14	43.79	49.94	56.59	63.74	71.39	79.54	88.19	97.34	106.99	117.14	127.79	138.94	150.59	162.74	175.39	188.54	202.19
	Z	.6034	.5931	.5831	.5734	.5640	.5549	.5461	.5375	.5291	.5209	.5129	.5051	.4975	.4901	.4829	.4759	.4691	.4624	.4559
.16	P	34.18	40.04	46.39	53.24	60.59	68.44	76.79	85.64	94.99	104.84	115.19	126.04	137.39	149.24	161.59	174.44	187.79	201.64	215.99
	Z	.5610	.5517	.5427	.5340	.5256	.5174	.5094	.5016	.4940	.4866	.4793	.4722	.4652	.4584	.4517	.4452	.4388	.4325	.4264
.18	P	35.75	42.13	48.97	56.26	64.01	72.22	80.89	89.94	99.37	109.19	119.41	130.03	141.05	152.47	164.29	176.51	189.13	202.15	215.57
	Z	.5223	.5139	.5058	.4979	.4902	.4827	.4754	.4682	.4611	.4541	.4472	.4404	.4337	.4271	.4206	.4142	.4079	.4017	.3956
.20	P	36.83	43.86	51.39	59.42	67.95	76.98	86.51	96.44	106.77	117.50	128.62	140.04	151.75	163.76	176.07	188.68	201.59	214.81	228.33
	Z	.4837	.4765	.4695	.4627	.4561	.4496	.4433	.4371	.4310	.4250	.4191	.4133	.4076	.4020	.3965	.3911	.3858	.3805	.3753
.22	P	37.56	45.16	53.29	61.94	71.11	80.79	90.98	101.58	112.59	124.01	135.83	148.05	160.57	173.39	186.51	199.93	213.65	227.67	241.99
	Z	.4485	.4423	.4363	.4304	.4246	.4189	.4133	.4078	.4024	.3971	.3919	.3867	.3816	.3765	.3715	.3665	.3615	.3566	.3517
.24	P	38.12	46.39	55.14	64.47	74.27	84.54	95.27	106.45	118.08	130.16	142.69	155.67	169.01	182.70	196.74	211.13	225.87	240.96	256.40
	Z	.4172	.4121	.4071	.4022	.3974	.3926	.3879	.3832	.3786	.3741	.3696	.3652	.3608	.3565	.3522	.3480	.3438	.3396	.3355
.26	P	38.57	47.49	56.84	66.72	77.05	87.83	99.06	110.74	122.87	135.45	148.48	161.96	175.89	190.27	205.10	220.28	235.81	251.69	267.93
	Z	.3897	.3856	.3815	.3775	.3735	.3695	.3656	.3617	.3578	.3540	.3502	.3464	.3426	.3388	.3351	.3314	.3277	.3240	.3204
.28	P	38.99	48.56	58.54	69.02	79.90	91.18	102.86	114.94	127.42	140.30	153.58	167.26	181.34	195.82	210.70	225.88	241.36	257.14	273.22
	Z	.3658	.3627	.3596	.3565	.3534	.3503	.3473	.3443	.3413	.3383	.3353	.3323	.3293	.3263	.3233	.3203	.3173	.3143	.3113
.30	P	39.40	49.64	60.24	71.31	82.74	94.52	106.65	119.13	131.96	145.14	158.67	172.55	186.78	201.36	216.29	231.57	247.20	263.18	279.42
	Z	.3450	.3428	.3406	.3384	.3362	.3340	.3318	.3296	.3274	.3252	.3230	.3208	.3186	.3164	.3142	.3120	.3098	.3076	.3054
.35	P	40.64	51.56	62.84	74.57	86.65	99.08	111.86	124.99	138.47	152.30	166.48	180.91	195.59	210.52	225.70	241.13	256.81	272.74	288.92
	Z	.3090	.3077	.3064	.3051	.3038	.3025	.3012	.2999	.2986	.2973	.2960	.2947	.2934	.2921	.2908	.2895	.2882	.2869	.2856
.40	P	42.73	54.39	66.44	78.98	91.91	105.24	118.96	133.07	147.57	162.46	177.74	193.41	209.37	225.62	242.16	258.99	276.12	293.55	311.28
	Z	.2806	.2803	.2800	.2797	.2794	.2791	.2788	.2785	.2782	.2779	.2776	.2773	.2770	.2767	.2764	.2761	.2758	.2755	.2752
.45	P	47.31	59.74	72.54	85.81	99.54	113.73	128.28	143.19	158.46	174.09	190.07	206.40	223.08	240.11	257.49	275.22	293.30	311.73	330.51
	Z	.2768	.2765	.2762	.2759	.2756	.2753	.2750	.2747	.2744	.2741	.2738	.2735	.2732	.2729	.2726	.2723	.2720	.2717	.2714

11.006

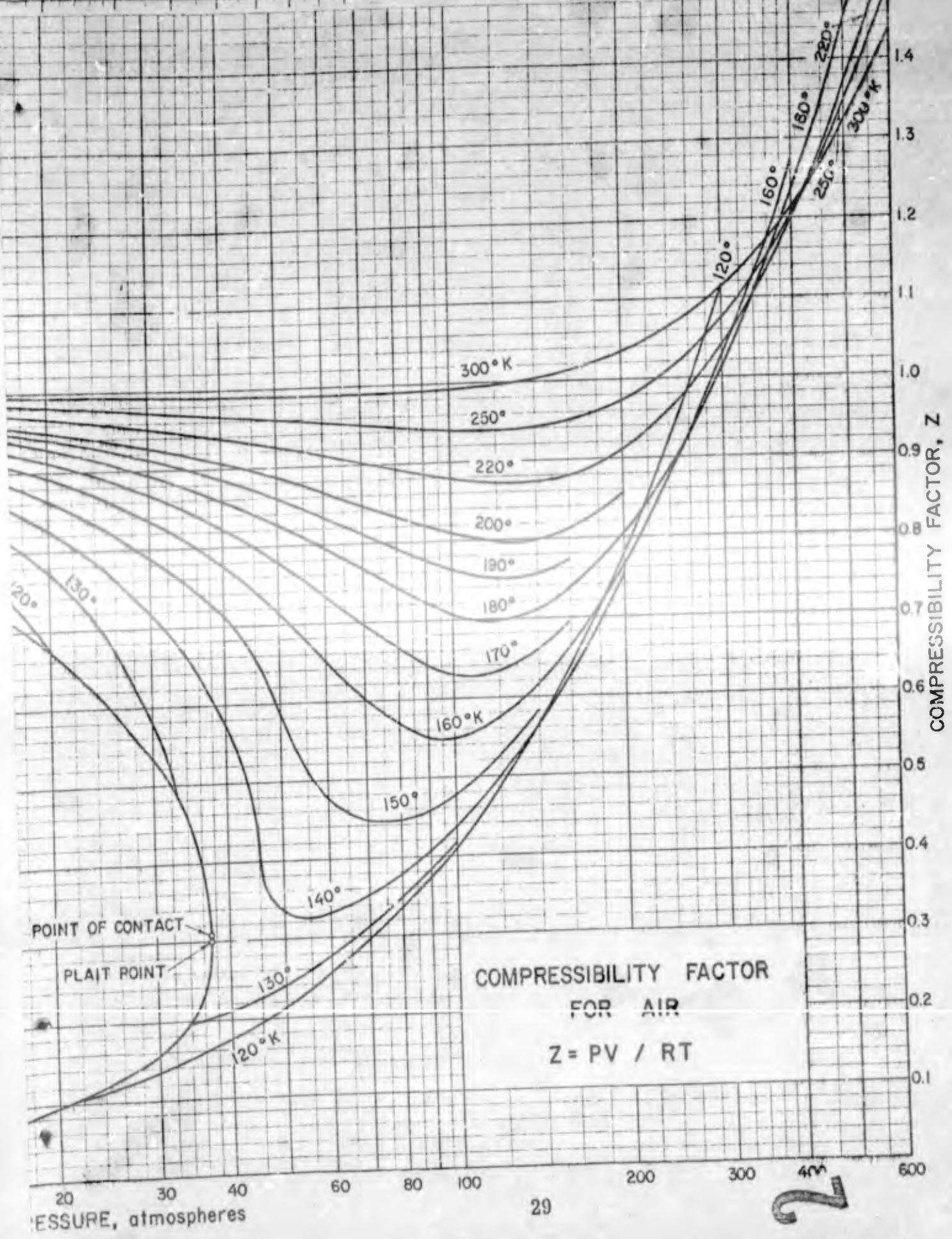
PRESSURE, psia



11.006

PRESSURE, psia

300 400 600 800 1000 2000 3000 4000 6000 8000



11.006

COMPRESSIBILITY FACTOR for AIR

Z = PV/RT

PERCENT DIFFERENCE  
+1  
0  
-1

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.

Comments

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.-lbf/lbm°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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1

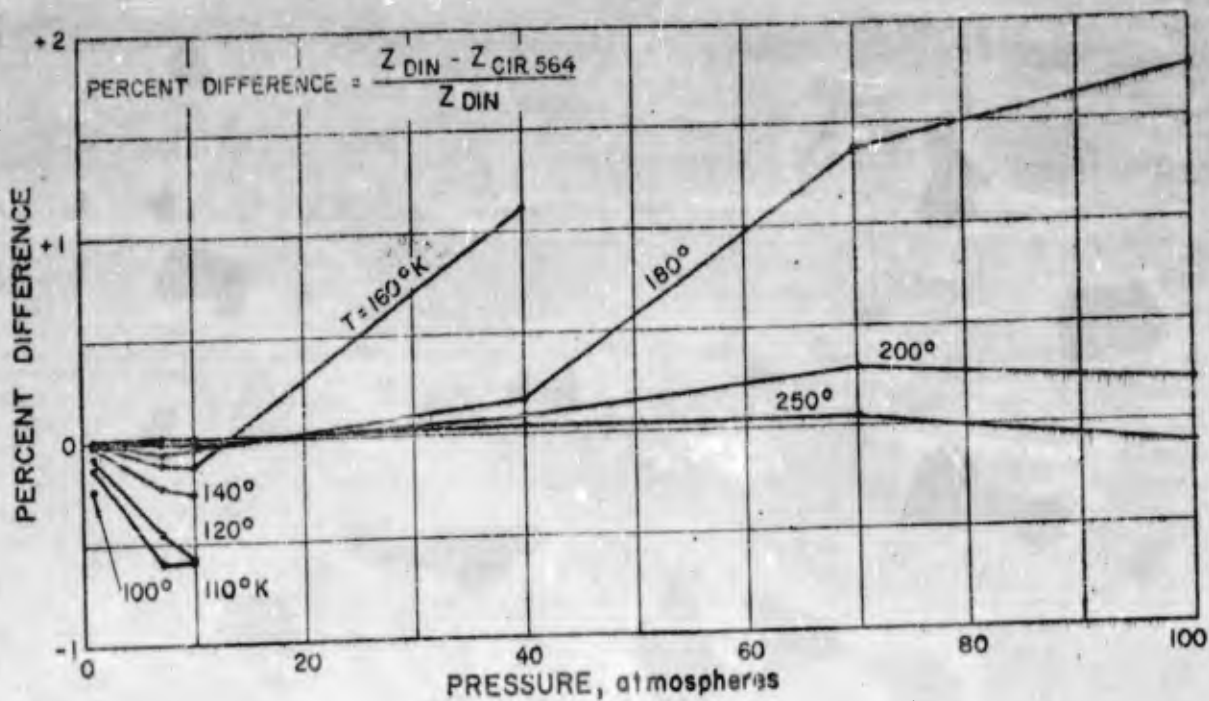


FIGURE 1  
DIFFERENCE BETWEEN VALUES OF COMPRESSIBILITY FACTOR, Z  
FROM F. DIN AND NBS CIR 564.

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

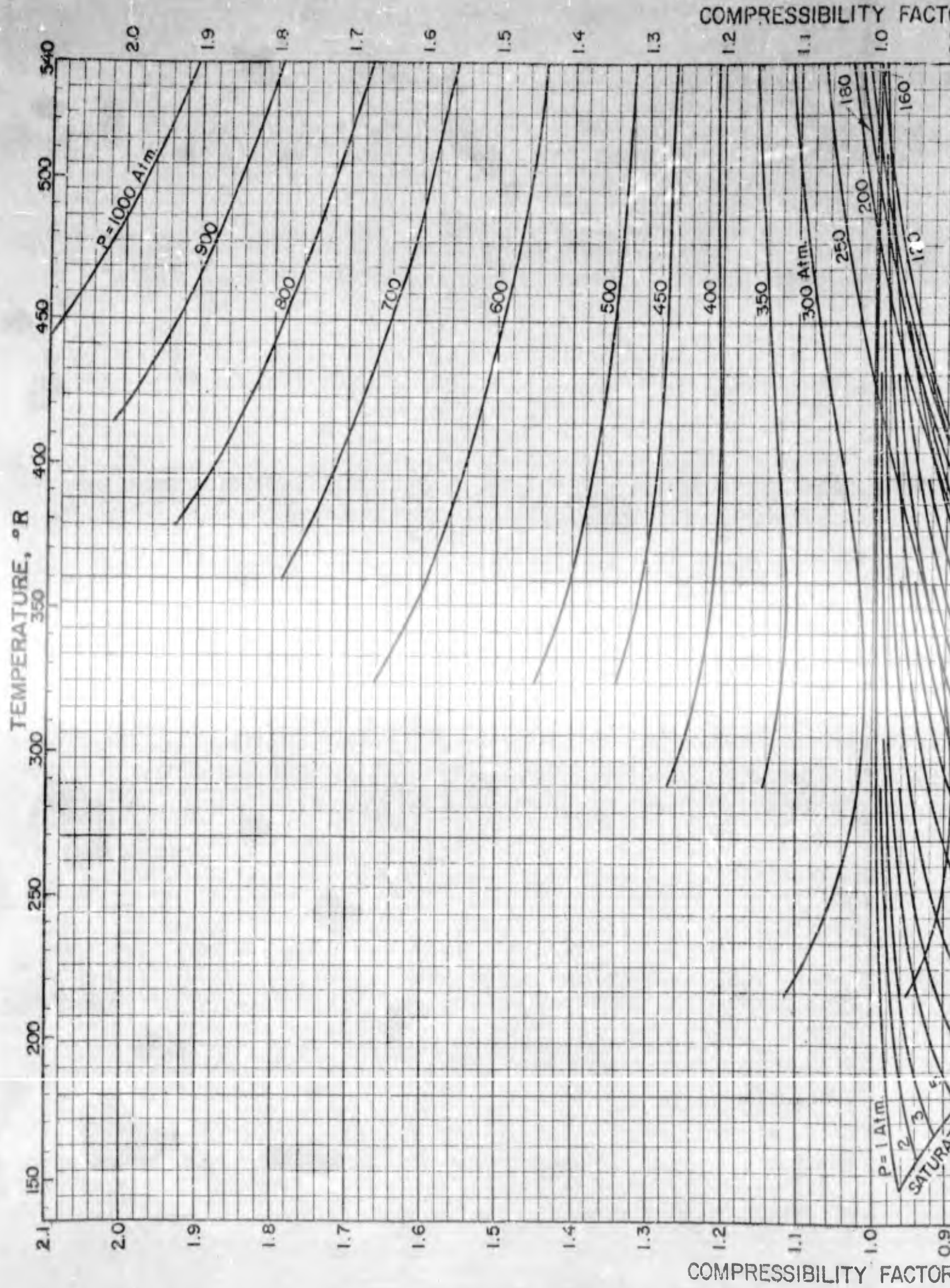
Point of Contact:

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.

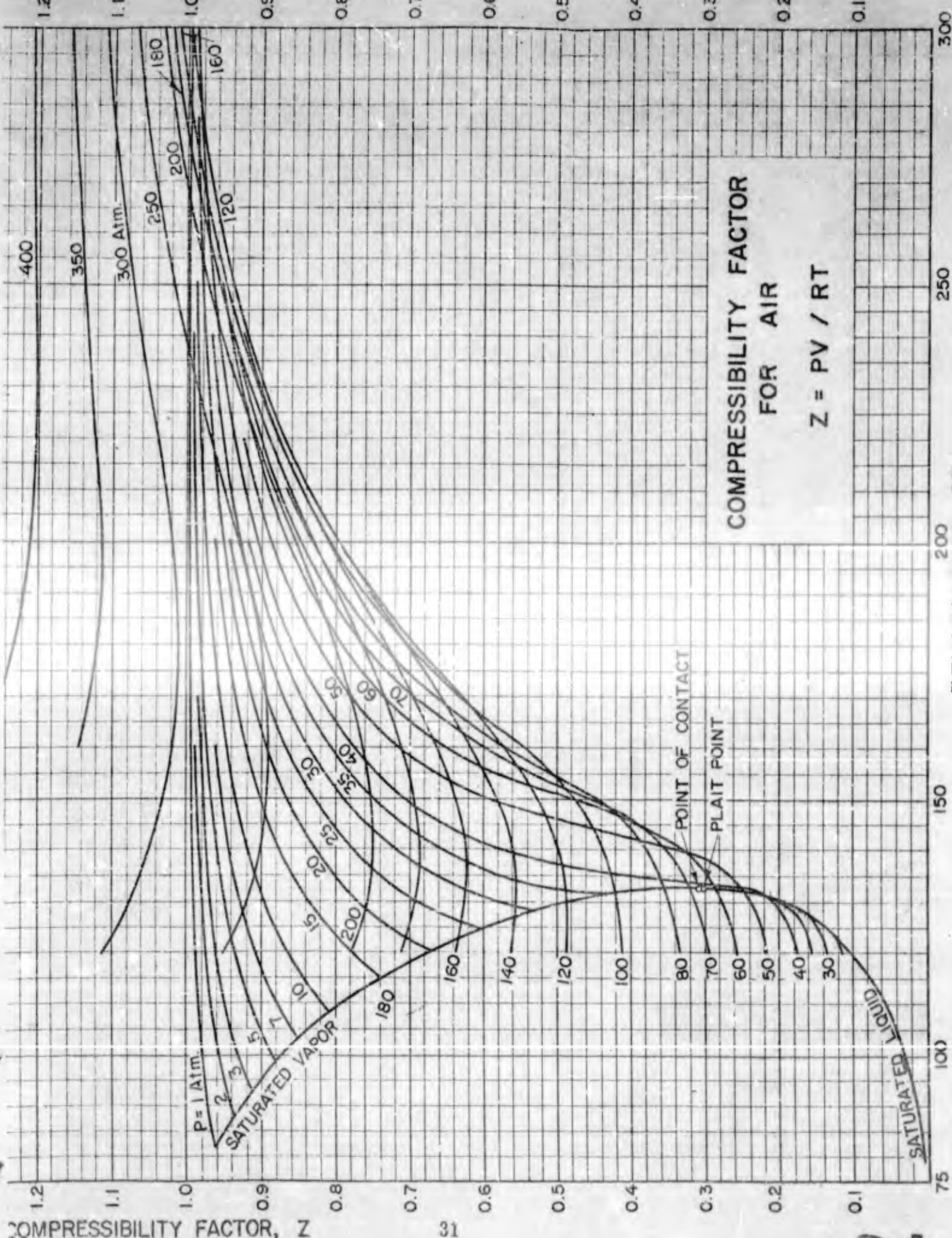
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11.006



COMPRESSIBILITY FACTOR

COMPRESSIBILITY FACTOR, Z



COMPRESSIBILITY FACTOR, Z

TEMPERATURE, °K

Z

## COMPRESSIBILITY FACTOR FOR AIR

$$Z = PV/RT \text{ (Cont.)}$$

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 atm.	Temperature °K				
	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 atm.	Saturated Liquid			Saturated Vapor		
	Temp.	V	Z	Temp.	V	Z
	°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

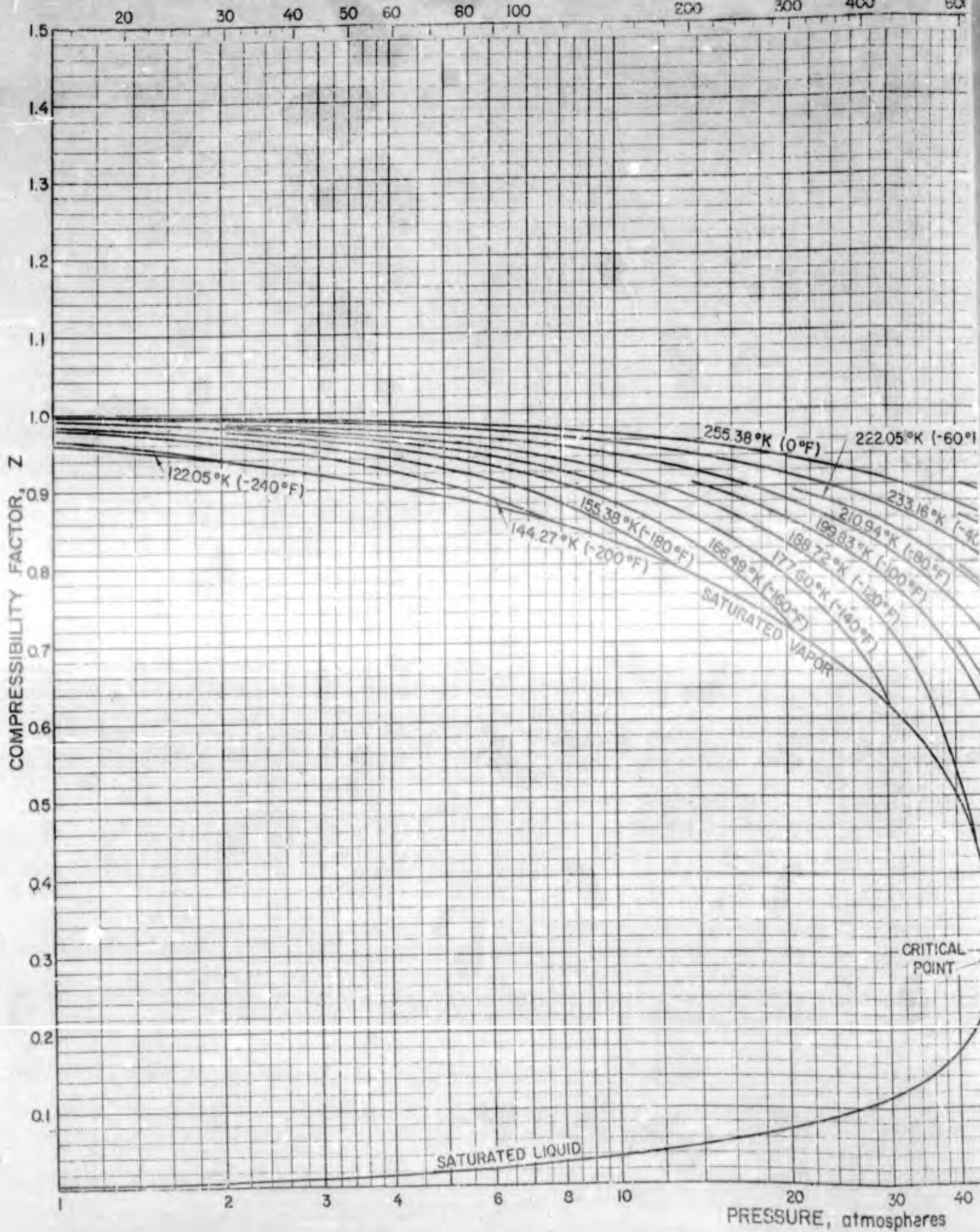
# COMPRESSIBILITY FACTOR for GASEOUS AIR

[ 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	77.34	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	.9888	.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	9.511	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	.9439	.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	.9383	.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	.9730	.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	.9582	.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	4.407
	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	.996	.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	1.22	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	1.56	1.62
	Z									2.13	2.04	1.97
1200	V										1.42	1.47
	Z										2.31	2.22

11.010

PRESSURE, psia  
300 400 600



1

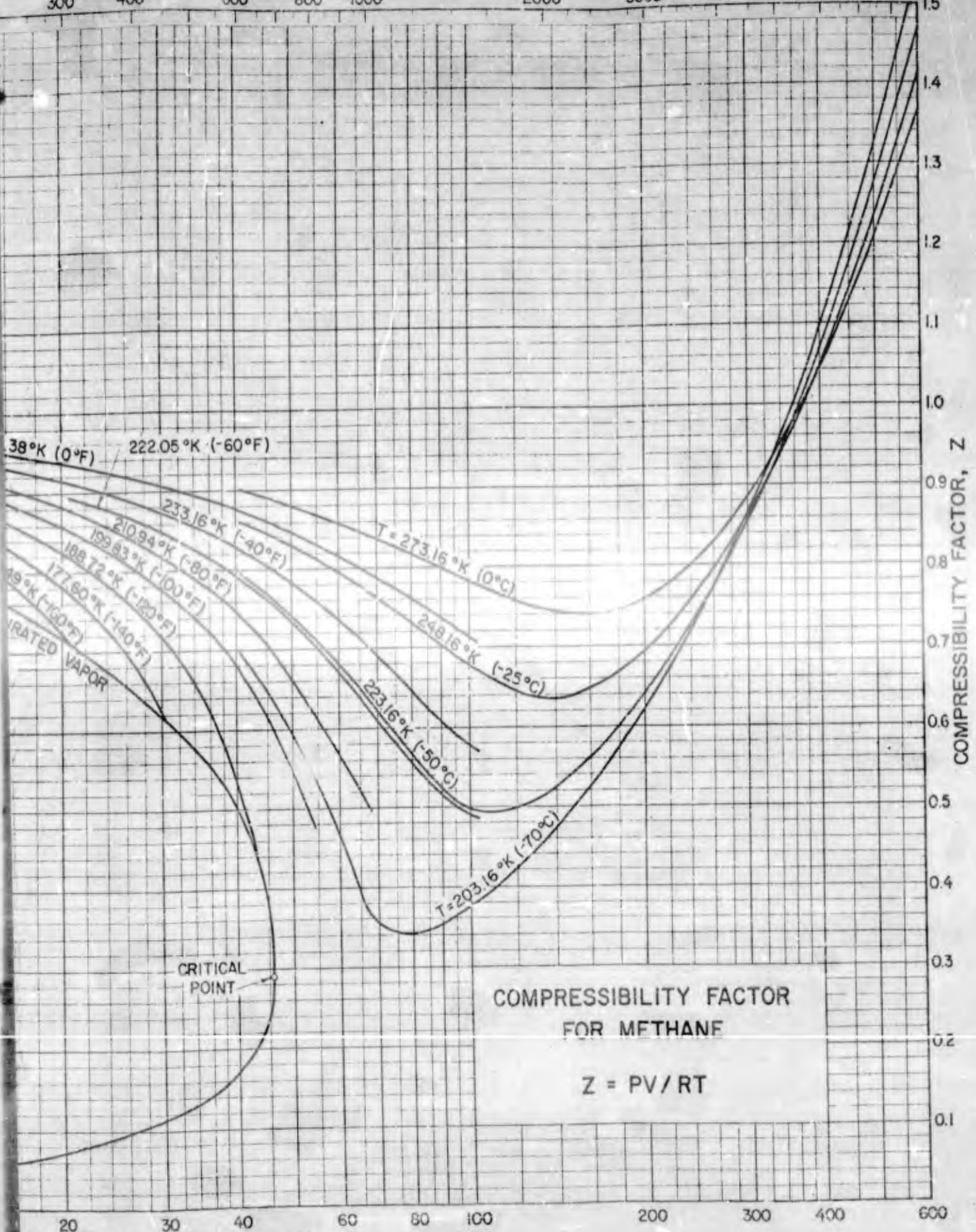
SATURATED LIQUID

PRESSURE, atmospheres

11.010

PRESSURE, psia

300 400 600 800 1000 2000 3000 4000 6000 8000



PRESSURE, atmospheres

35

2

## 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:

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

$$R = 0.0036695 \text{ (Amagat)(}^\circ\text{K)}^{-1} \quad \text{Kvalnes and Gaddy values}$$

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. psia	Temperature (°F)										
	-240°F	-200°F	-160°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	.697	.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	.7243	.8833
60	.3366	.5551	.6651	.8611
70	.2633	.5059	.6051	.8199
80	.2556	.4604	.5651	.8199
90		.4266		
100	.2808	.4088	.6167	.7853
140	.3543	.4304	.5801	.7457
160	.3915	.4601	.5891	.7425
200	.4556	.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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(Continued)

PREFACE to the THERMAL CONDUCTIVITY INTEGRALS of SOLIDS at LOW TEMPERATURES

The thermal conductivity 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

$\lambda$  = 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:

$$\int_{T_0}^{T_L} \lambda dT$$

where  $T_0$  and  $T_L$  are temperatures along a heat flow path communicating between heat reservoirs at  $T_0 = 4^\circ\text{K}$  and  $T_L$  at length  $L$  from  $T_0$ . 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.,

$$Q \frac{L}{A} = \int_{T_1}^{T_2} \lambda dT = \int_{T_0}^{T_2} \lambda dT - \int_{T_0}^{T_1} \lambda dT$$

(Continued on following page)

## THERMAL CONDUCTIVITY INTEGRALS

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## PREFACE TO THE THERMAL CONDUCTIVITY INTEGRALS OF SOLIDS AT LOW TEMPERATURES

(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:

<u>Metals</u>	<u>Index</u>	<u>Transition Temperature *</u>
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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

Q = heat flow in watts

A = cross sectional area in cm<sup>2</sup>

L = length in cm

$\lambda$  = thermal conductivity in watts/cm-°K

T = temperature in °K

T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K					$\int_{T_0}^{T_L} \lambda \, dT$ 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

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = 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
70	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

13.112-1

## THERMAL CONDUCTIVITY INTEGRALS

for COPPERS (cont.)

Temp. °K	$\int_{T_0}^{T_L} \lambda \, dT$ 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	30.2	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

RLP/EGP/JRK/ALB Issued: 1-12-60

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_0}^{T_L} \lambda \, dT$ 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

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

Q = heat flow in watts

A = cross sectional area in cm<sup>2</sup>

L = length in cm

$\lambda$  = thermal conductivity in watts/cm-°K

T = temperature in °K

T<sub>0</sub> = initial temperature (4°K for Beryllium 1, Magnesium 1 and Magnesium 2; 20°K for Beryllium 2)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_0}^{T_L} \lambda dT$ 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					
20	30 *	14	10	.59	388	189	119	
25	28	12	9.3	.72	534	254	167	3.28
30	27	9.5 *	7.8	.85	671	308	210	7.2
35	26	7.5 *	6.4	.98	804	350	246	11.8
40	25	6.3 *	5.3	1.1	931	385	275	17.0
50	23	4.5 *	3.8	1.35	1170	439	320	29.2
60	20	3.5 *	2.8	1.6	1390	479	353	44.0
70	18.4	2.8 *	2.3	1.8	1580	510	379	61.0
76	17.5	2.6 *	2.1	1.9	1680	527	392	72.1
80	16.5	2.5 *	1.9	2.0	1750	538	400	79.9
90	15.0	2.2 *	1.78	2.3	1910	560	418	101
100	13.5	1.9 *	1.70	2.5	2050	581	436	125
120	11.5*	1.7 *	1.63	2.6	2300	617	469	176
140	10.0*	1.63*	1.61	2.4 *	2520	650	501	226
160	8.5*	1.61*	1.61*	2.2 *	2700	682	534	272
180	7.5*	1.61*	1.61*	1.9 *	2860	715	566	313
200	6.5*	1.61*	1.61*	1.75*	3000	747	590	350
250	5.0*	1.61*	1.61*	1.4 *	3290	827	678	429
300	4.0*	1.61*	1.61*	1.15*	3520	908	759	492

\* Extrapolated Values

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_0}^{T_L} \lambda \, dT$ 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity			$\int_{T_0}^{T_L} \lambda \, dT$		
	watts/cm-°K			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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (°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	28.0	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	$\int_{T_0}^{T_L} \lambda dT$ 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	230	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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_0}^{T_L} \lambda \, dT$ 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

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = 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	.050	.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

13.142-1

THEMAL CONDUCTIVITY INTEGRALS  
for CARBONS (cont.)

Temp. °K	$\int_{T_0}^{T_L} \lambda dT$ 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_0}^{T_L} \lambda \, dT$ 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

13.142-3

THEMAL 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_0}^{T_L} \lambda dT$ watts/cm	
	Tin	Lead	Tin	Lead
4	25	20*	48.0	27.0
6	24	7.0	86.0	37.3
8	14.9	3.3	110	42.4
10	9.1	1.8	143	49.0
15	4.0	.82	159	52.5
20	2.5	.59	171	55.2
25	2.2	.5	181	57.6
30	2.0	.47	191	59.9
35	1.9	.44	201	63.3
40	1.9*	.42	220	69.9
50	1.9*	.40	239	73.8
60	1.9*	.38	258	77.6
70	1.9*	.38	269	79.9
76	1.9*	.37	277	81.3
80	1.9*	.37	295	85.0
90	1.8*	.37	313	88.7
100	1.8*	.36	349	95.9
120	1.8*	.36	385	103
140	1.8*	.36	421	110
160	1.8*	.36	457	117
180	1.8*	.36	493	125
200	1.8*	.35	583	142
250	1.8*	.35	673	160
300	1.8*	.35		

\* Extrapolated Values † See second page of the preface.

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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
A = cross sectional area in cm<sup>2</sup>  
L = length in cm  
λ = thermal conductivity in watts/cm-°K  
T = temperature in °K  
T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_0}^{T_L} \lambda \, dT$ 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_0}^{T_L} \lambda \, dT$ 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K			$\int_{T_0}^{T_L} \lambda \, dT$ 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

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K		$\int_{T_0}^{T_L} \lambda dT$ watts/cm	
	Manganese	Rhenium	Manganese	Rhenium
4	.0094	7.0		
6	.0125	10.0		
8	.0150	12.5	.0219	17.0
10	.0170	14.0	.0494	39.5
15	.021	13.0	.0814	66.0
20	.025	8.5	.176	134
25	.028	5.0	.291	187
30	.030	3.0	.424	221
35	.033	2.0	.569	241
40	.036	1.4	.726	254
50	.040	.90	.899	262
60	.044	.75	1.28	274
70	.049	.68	1.70	282
76	.051	.67	2.16	289
80	.052	.66	2.46	293
90	.056	.63	2.67	296
100	.059	.62*	3.21	302
120	.067*	.62*	3.78	308
140	.073*	.61*	5.04	321
160	.080*	.61*	6.44	333
180	.085*	.61*	7.97	345
200	.090*	.61*	9.62	357
250	.095*	.61*	11.4	370
300	.100*	.61*	16.0	400
			20.9	430

\* Extrapolated Values

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

Q = heat flow in watts

A = cross sectional area in cm<sup>2</sup>

L = length in cm

$\lambda$  = thermal conductivity in watts/cm-°K

T = temperature in °K

T<sub>0</sub> = initial temperature (6°K for Nickel 2; 4°K for all others)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_0}^{T_L} \lambda dT$ 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

RLP/EGP/JRK/ALB Issued: 1-12-60

## THERMAL CONDUCTIVITY INTEGRALS

for RHODIUM, PALLADIUM, IRIIDIUM 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

Q = heat flow in watts

A = cross sectional area in cm<sup>2</sup>

L = length in cm

$\lambda$  = thermal conductivity in watts/cm-°K

T = temperature in °K

T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_0}^{T_L} \lambda \, dT$ 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

Q = heat flow in watts

A = cross sectional area in cm<sup>2</sup>

L = length in cm

$\lambda$  = thermal conductivity in watts/cm-°K

T = temperature in °K

T<sub>0</sub> = 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*	.59*	.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

13.212-1

THERMAL CONDUCTIVITY INTEGRALS  
for COPPER ALLOYS (cont.)

Temp. °K	$\int_{T_0}^{T_L} \lambda \, dT$ watts/cm					
	Phos. Deox. Copper	Silicon Bronze	Manganin	(Po) 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	.713	.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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross-sectional area in cm<sup>2</sup>
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity watts/cm-°K				$\int_{T_0}^{T_L} \lambda \, dT$ 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				
8	.052*	.038	.027	.026	.059	.034	.024	.024
10	.068*	.057	.037	.036	.148	.095	.067	.066
15	.10 *	.106	.07	.063	.268	.190	.131	.128
20	.124	.16	.103	.088	.688	.353	.399	.375
25	.142	.21	.137	.108	1.25	1.02	.831	.753
30	.16	.25	.17	.12	1.92	1.94	1.43	1.24
35	.18	.28	.20	.132	2.67	3.09	2.20	1.81
40	.20	.32	.23	.14	3.52	4.42	3.12	2.44
50	.23	.35	.28	.15	4.47	1.92	4.20	3.12
60	.27	.37	.32	.16	6.62	9.27	6.75	4.57
70	.30	.38	.34	.165	9.12	12.9	9.75	6.12
76	.33	.38	.36	.169	12.0	16.6	13.0	7.75
80	.34	.38	.37	.170	13.9	18.9	15.1	8.75
90	.37	.38*	.38*	.170	15.2	20.4	16.6	9.43
100	.40	.38*	.40*	.170	18.7	24.2	20.4	11.1
120	.45	.39*	.42*	.171	22.6	28.0	24.3	12.8
140	.50	.39*	.42*	.174	31.1	35.7	32.5	16.2
160	.54	.39*	.42*	.180	40.6	43.5	40.9	19.7
180	.58	.39*	.42*	.183	51.0	51.3	49.3	23.2
200	.60	.40*	.42*	.19	62.2	59.1	57.7	26.9
250	.65*	.40*	.42*	.21	74.0	67.0	66.1	30.6
300	.68*	.40*	.42*	.23	105	87.0	87.1	40.6
					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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = 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	$\int_{T_0}^{T_1} \lambda \, dT$ watts/cm									
	1100-F	6063-T5	3003-F	4 S	5052-0	5154-0	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		

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = 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	$\int_{T_0}^{T_L} \lambda \, dT$ 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

RLP/EGP/JRK/ALB Issued: 1-12-60

## 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 Rose'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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

Q = heat flow in watts

A = cross sectional area in cm<sup>2</sup>

L = length in cm

$\lambda$  = thermal conductivity in watts/cm-°K

T = temperature in °K

T<sub>0</sub> = 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	$\int_{T_0}^{T_L} \lambda dT$ 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda \, dT$$

Where:

- Q = heat of flow in watts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in watts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = 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	$\int_{T_0}^{T_L} \lambda \, dT$ , 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	3.23	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	

## 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.

$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda dT; \quad Q \frac{L}{A} = \int_{T_0}^{T_L} \lambda dT$$

Where:

- Q = heat flow in milliwatts  
 A = cross sectional area in cm<sup>2</sup>  
 L = length in cm  
 λ = thermal conductivity in milliwatts/cm-°K  
 T = temperature in °K  
 T<sub>0</sub> = initial temperature (4°K)

Temp. °K	Thermal Conductivity milliwatts/cm-°K				$\int_{T_0}^{T_L} \lambda dT$ milliwatts/cm			
	glass	teflon	perspex	nylon	glass	teflon	perspex	nylon
4	.97	.46	.58	.125				
6	1.14	.67	.60	.196				
8	1.19	.82	.60	.29	2.11	1.13	1.18	.321
10	1.20	.96	.61	.38	4.43	2.62	2.38	.807
15	1.3	1.22	.63	.67	6.81	4.4	3.59	1.48
20	1.46	1.41	.75	.98	13.1	9.85	6.69	4.10
25	1.68	1.60	.97	1.28*	20.0	16.4	10.1	8.23
30	1.9	1.74	1.18*	1.5 *	27.9	23.9	14.4	13.9
35	2.2	1.86	1.35*	1.78*	36.8	32.3	19.6	20.8
40	2.4	1.95	1.50*	1.99*	47.1	41.3	25.9	29.0
50	2.9	2.1	1.80*	2.4 *	58.6	50.8	33.0	38.5
60	3.4	2.2	1.95*	2.7 *	84.6	71.6	49.5	60.4
70	3.9	2.3	2.10*	2.8 *	115	93.6	68.3	85.9
76	4.2	2.3	2.15*	2.9 *	151	116	88.5	113
80	4.4	2.35	2.20*	2.9 *	175	130	101.	131
90	5.0	2.4 *	2.25*	3.0 *	194	139	110.	142
100	5.5	2.45*	2.25*	3.1 *	240	163	132.	173
120	6.4	2.45*	2.30*	3.2 *	292	187	155.	204
140	7.3	2.5 *	2.35*	3.3 *	408	237	200.	269
160	7.9	2.55*	2.40*	3.4 *	542	287	247.	336
180	8.5	2.60*	2.40*	3.5 *	694	338	294.	405
200	9.0	2.60*	2.40*	3.5 *	858	390	342.	475
250	9.8	2.60*	2.40*	3.5 *	1030	442	390.	545
300	10.2	2.60*	2.40*	3.5 *	1500	572	510.	720
					1990	702	630.	895

\* Extrapolated Values

## 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., Commun. 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 original data is limited to three significant figures.

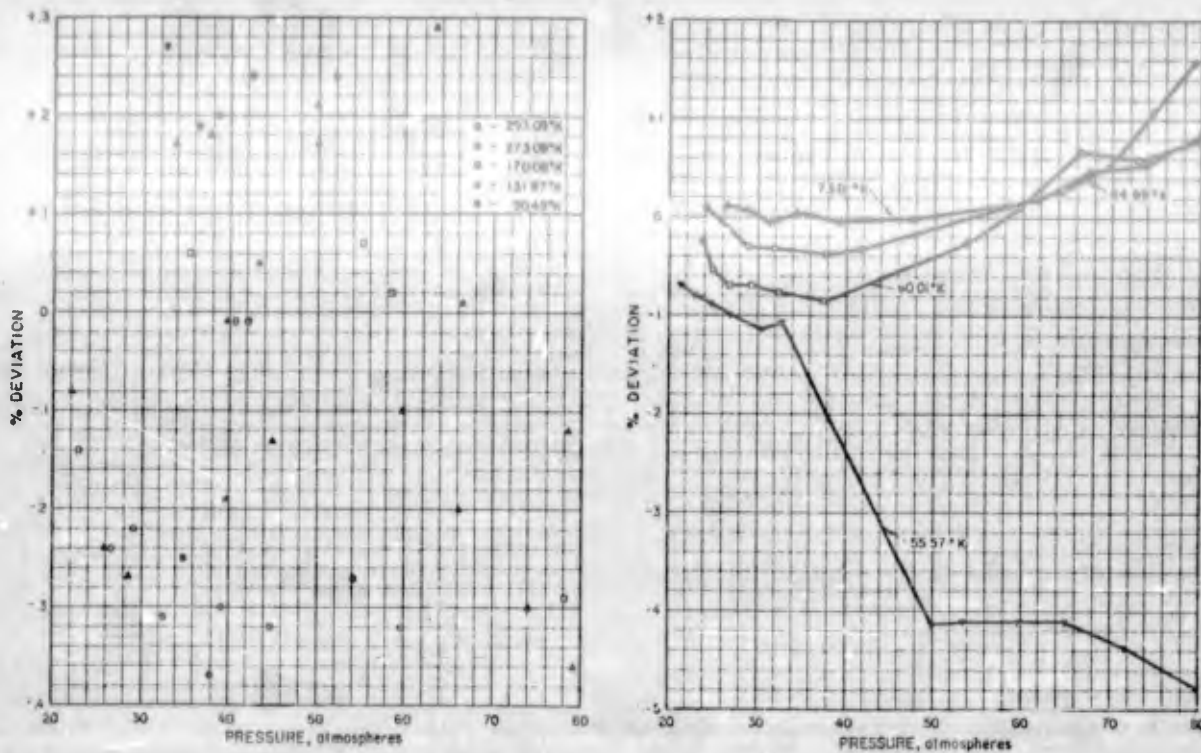
A comparison was made between the experimental pressures reported by Crommelin, et al., and the pressures calculated from Yendall's equation of state. The results of this study (see graph below) indicate good agreement between the experimental data and the calculated values, except at 55.57°K. A comparison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

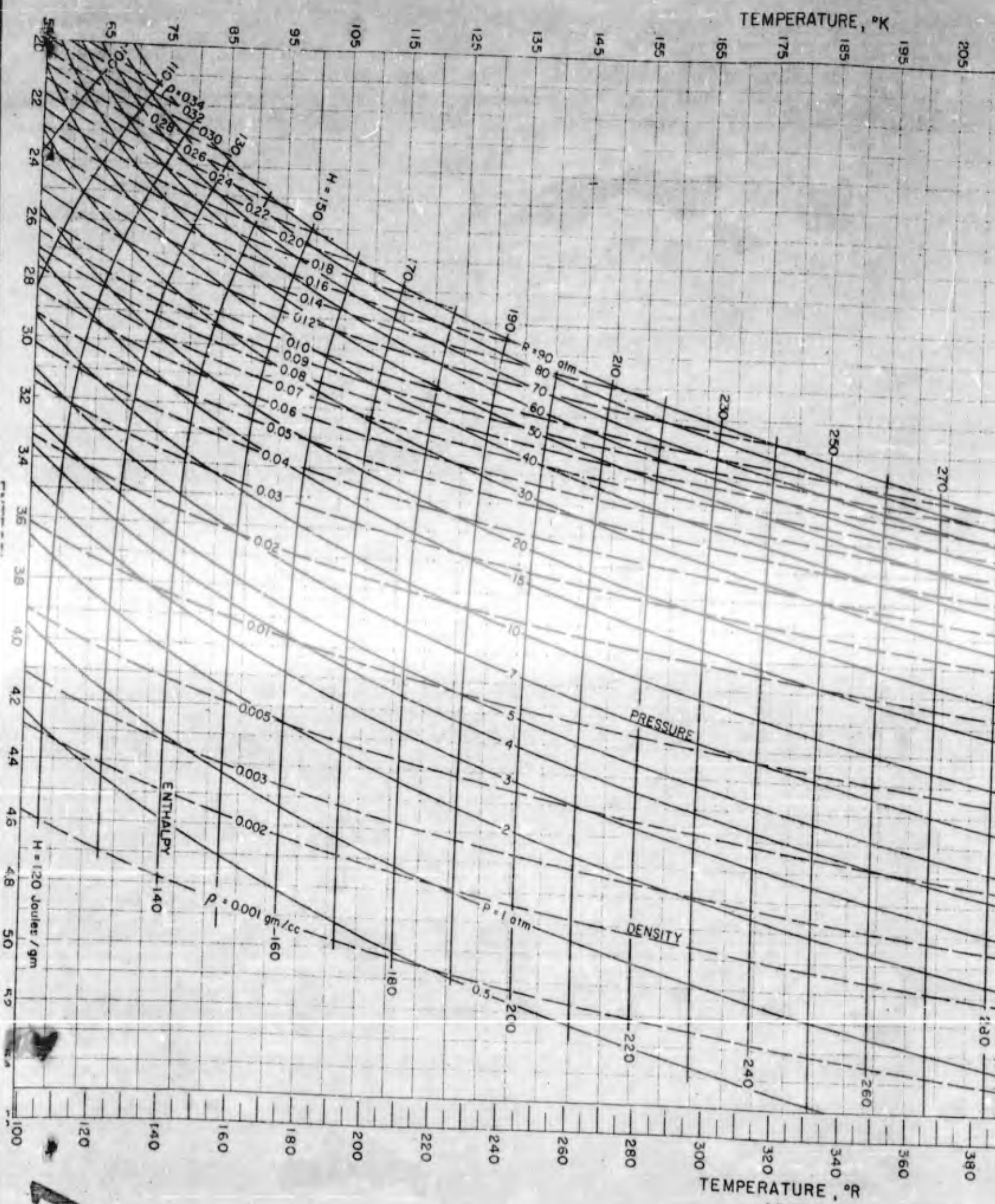
percentage deviation of 0.57%. These comparisons and the study of the data as discussed above, both indicated a departure in the original data at 55°K from the general pattern as compared to values of 60°K and higher. It therefore, seems valid to assume that there is basis for doubt in the relative accuracy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

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



TEMPERATURE, °K

TEMPERATURE, °R

55  
50  
45  
40  
38  
36  
34  
32  
30  
28  
26  
24  
22  
20

205  
195  
185  
175  
165  
155  
145  
135  
125  
115  
105  
95  
85  
75  
65  
50

100  
120  
140  
160  
180  
200  
220  
240  
260  
280  
300  
320  
340  
360  
380

ENTHALPY

PRESSURE

DENSITY

$H = 120 \text{ Joules / gm}$

$\rho = 0.001 \text{ gm/cc}$

$P = 1 \text{ atm}$

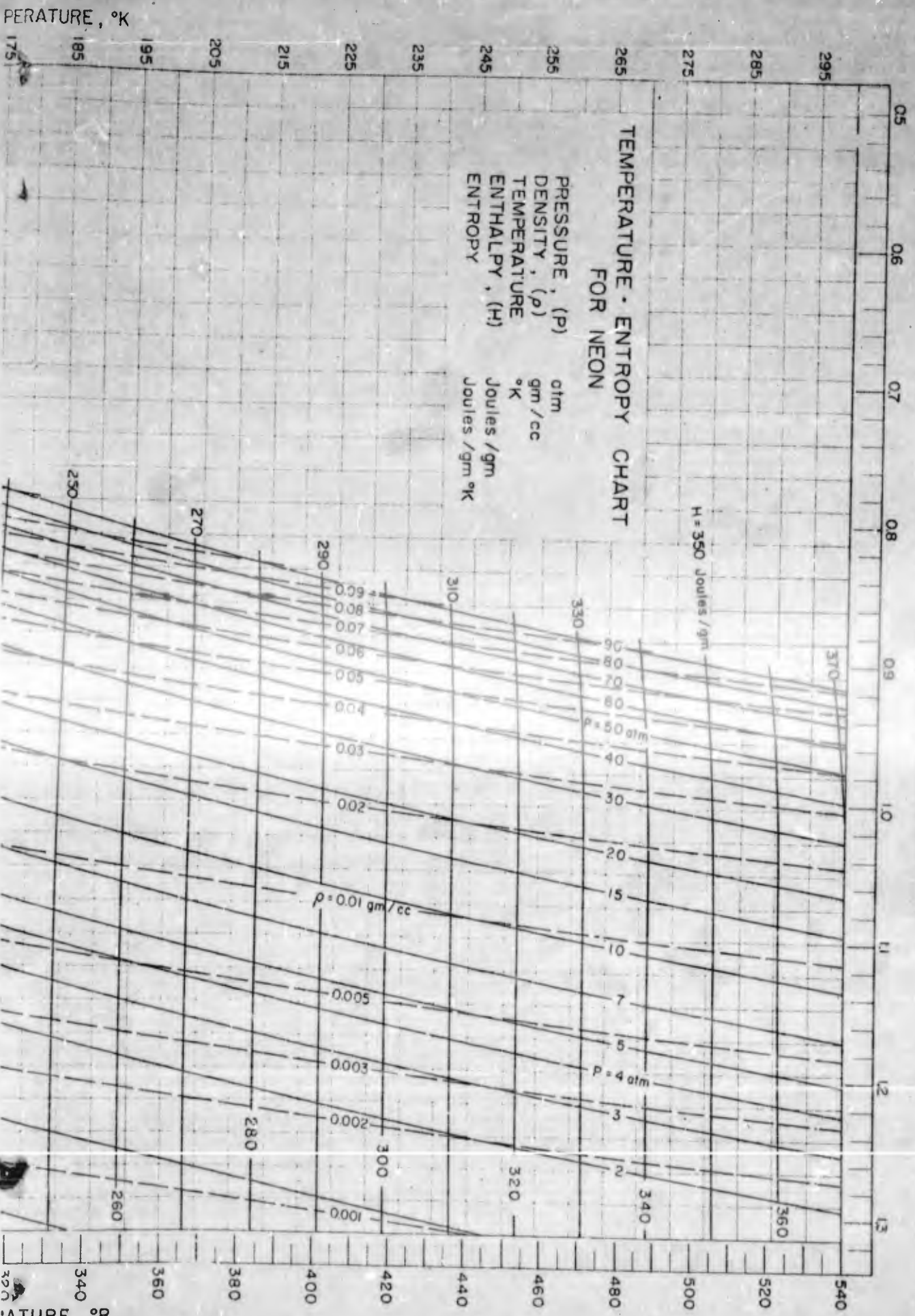
$P = 90 \text{ atm}$

$H = 150$

$P = 0.34$

14.003

ENTROPY, Cal/gm °K or BTU/lb °R



TEMPERATURE - ENTROPY CHART  
FOR NEON

PRESSURE, (P) atm  
DENSITY, ( $\rho$ ) gm/cc  
TEMPERATURE °K  
ENTHALPY, (H) Joules/gm  
ENTROPY Joules/gm °K

TEMPERATURE, °K

TEMPERATURE, °R





100	h	4.802	100.1	157.7	157.6	157.4	157.0	156.5	155.7	154.8	153.1	151.5	150.1	1328	1597	1558	2114	2355
100	p	0.01250	0.01461	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	1.091	1.328	1.597	2.114	2.355
100	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
110	h	4.853	173.5	173.5	173.5	173.5	173.5	173.5	173.5	173.5	173.5	173.5	173.5	3.071	2.938	2.632	2.593	2.535
110	p	0.01265	0.01500	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	3.071	2.938	2.632	2.593	2.535
110	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
120	h	5.043	183.2	183.2	183.2	183.2	183.2	183.2	183.2	183.2	183.2	183.2	183.2	3.232	3.107	2.824	2.785	2.730
120	p	0.01280	0.01525	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	3.232	3.107	2.824	2.785	2.730
120	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
130	h	5.128	194.2	194.2	194.2	194.2	194.2	194.2	194.2	194.2	194.2	194.2	194.2	3.394	3.274	3.005	2.966	2.911
130	p	0.01295	0.01545	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	3.394	3.274	3.005	2.966	2.911
130	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
140	h	5.202	204.2	204.2	204.2	204.2	204.2	204.2	204.2	204.2	204.2	204.2	204.2	3.556	3.441	3.185	3.146	3.091
140	p	0.01310	0.01565	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	3.556	3.441	3.185	3.146	3.091
140	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
150	h	5.273	214.2	214.2	214.2	214.2	214.2	214.2	214.2	214.2	214.2	214.2	214.2	3.718	3.607	3.365	3.326	3.271
150	p	0.01325	0.01585	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	3.718	3.607	3.365	3.326	3.271
150	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
160	h	5.340	224.2	224.2	224.2	224.2	224.2	224.2	224.2	224.2	224.2	224.2	224.2	3.892	3.785	3.545	3.506	3.451
160	p	0.01340	0.01605	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	3.892	3.785	3.545	3.506	3.451
160	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
170	h	5.402	234.2	234.2	234.2	234.2	234.2	234.2	234.2	234.2	234.2	234.2	234.2	4.070	3.967	3.728	3.689	3.634
170	p	0.01355	0.01625	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	4.070	3.967	3.728	3.689	3.634
170	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
180	h	5.458	244.2	244.2	244.2	244.2	244.2	244.2	244.2	244.2	244.2	244.2	244.2	4.254	4.153	3.915	3.876	3.821
180	p	0.01370	0.01645	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	4.254	4.153	3.915	3.876	3.821
180	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
190	h	5.517	254.2	254.2	254.2	254.2	254.2	254.2	254.2	254.2	254.2	254.2	254.2	4.444	4.345	4.107	4.068	4.013
190	p	0.01385	0.01665	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	4.444	4.345	4.107	4.068	4.013
190	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
200	h	5.570	264.2	264.2	264.2	264.2	264.2	264.2	264.2	264.2	264.2	264.2	264.2	4.640	4.543	4.305	4.266	4.211
200	p	0.01400	0.01685	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	4.640	4.543	4.305	4.266	4.211
200	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
210	h	5.615	274.2	274.2	274.2	274.2	274.2	274.2	274.2	274.2	274.2	274.2	274.2	4.842	4.747	4.509	4.470	4.415
210	p	0.01415	0.01705	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	4.842	4.747	4.509	4.470	4.415
210	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
220	h	5.660	284.2	284.2	284.2	284.2	284.2	284.2	284.2	284.2	284.2	284.2	284.2	5.050	4.957	4.719	4.680	4.625
220	p	0.01430	0.01725	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	5.050	4.957	4.719	4.680	4.625
220	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
230	h	5.700	294.2	294.2	294.2	294.2	294.2	294.2	294.2	294.2	294.2	294.2	294.2	5.264	5.171	4.933	4.894	4.839
230	p	0.01445	0.01745	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	5.264	5.171	4.933	4.894	4.839
230	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
240	h	5.735	304.2	304.2	304.2	304.2	304.2	304.2	304.2	304.2	304.2	304.2	304.2	5.484	5.391	5.153	5.114	5.059
240	p	0.01460	0.01765	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	5.484	5.391	5.153	5.114	5.059
240	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
250	h	5.765	314.2	314.2	314.2	314.2	314.2	314.2	314.2	314.2	314.2	314.2	314.2	5.714	5.621	5.383	5.344	5.289
250	p	0.01475	0.01785	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	5.714	5.621	5.383	5.344	5.289
250	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
260	h	5.800	324.2	324.2	324.2	324.2	324.2	324.2	324.2	324.2	324.2	324.2	324.2	5.950	5.857	5.619	5.580	5.525
260	p	0.01490	0.01805	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	5.950	5.857	5.619	5.580	5.525
260	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
270	h	5.830	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	6.184	6.091	5.853	5.814	5.759
270	p	0.01505	0.01825	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	6.184	6.091	5.853	5.814	5.759
270	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
280	h	5.860	344.2	344.2	344.2	344.2	344.2	344.2	344.2	344.2	344.2	344.2	344.2	6.424	6.331	6.093	6.054	6.000
280	p	0.01520	0.01845	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	6.424	6.331	6.093	6.054	6.000
280	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
290	h	5.890	354.2	354.2	354.2	354.2	354.2	354.2	354.2	354.2	354.2	354.2	354.2	6.668	6.575	6.337	6.298	6.243
290	p	0.01535	0.01865	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	6.668	6.575	6.337	6.298	6.243
290	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507
300	h	5.920	364.2	364.2	364.2	364.2	364.2	364.2	364.2	364.2	364.2	364.2	364.2	6.922	6.829	6.591	6.552	6.497
300	p	0.01550	0.01885	0.01734	0.02094	0.02545	0.03085	0.03719	0.04458	0.05305	0.06370	0.07675	0.09240	6.922	6.829	6.591	6.552	6.497
300	s	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	163.3	3.434	3.359	2.999	2.568	2.507

## VELOCITY of SOUND IN CRYOGENIC FLUIDS

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

- Atkins, K. R. and Osborne, D. V.; Phil. Mag. 41, 1078 (1950)  
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 Pellam, J. R. and Squire, C. F.; Phys. Rev. 72, 1245 (1947)  
 Fippard, A. B.; Phil. Mag. 42, 1209 (1951)  
 Van Itterbeek, A. and Forrez, G.; Physica 20, 133 (1954)  
 Van den Berg, G. J., Van Itterbeek, A., Van Aardeane, G. M. V. and Herfkens, J. H. J.; Physica 21, 860 (1955)

Comments:

The values of velocity of sound reported here are for ordinary sound in He<sup>4</sup> 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.

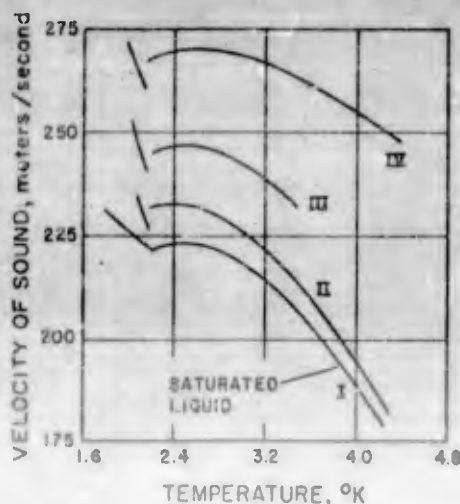
It will be noted that the graph indicates a discontinuity at the  $\lambda$  point (phase boundary between Helium I and Helium II). The work of Findlay, Pitt, Smith and Wilhelm showed a drop in the velocity of sound in liquid Helium I as the  $\lambda$  point (2.19°K) was approached, and below the  $\lambda$  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

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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  $\lambda$  point was due to inclusions of He II in He I immediately above the  $\lambda$  point, and inclusions of He I in He II immediately below the  $\lambda$  point. Pippard also stated that these inclusions should have a mean radius of  $2.1 \times 10^{-7}$  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  $\lambda$  point. Atkins and Chase determined the velocity curve both above and below the  $\lambda$  point and found no discontinuity. Their velocities were slightly lower than those of Findlay et al. near the  $\lambda$  point. Atkins and Stasiar 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	387	420			
2.50	222	244	265	298	326	348	369	390	422	451		
3.00	218	242	264	298	327	349	370	391	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 Stasiar

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				

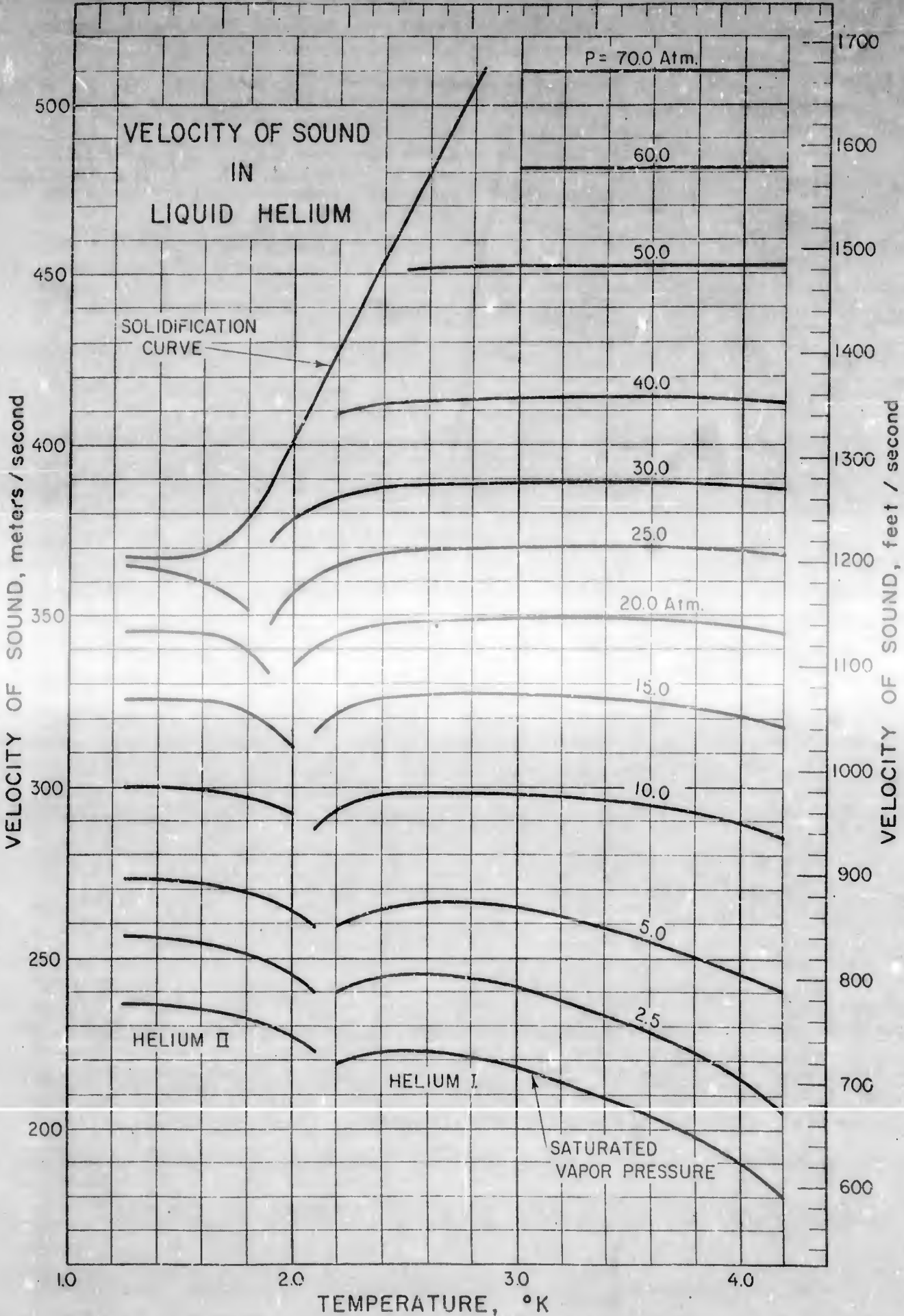
Table VII. Velocity of Sound at 4.223°K\*\*

Frequency Kc/sec	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 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)
- Van Itterbeek, A. and Thys, L., *Physica* 5, 889 (1938)
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Other References:

- Keesom, W. H. and Van Itterbeek, A., *Koninkl. Ned. Akad. Wetenschappen, 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

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## VELOCITY of SOUND in GASEOUS HELIUM (Cont.)

Comments: (cont.)

pressure. These data are tabulated 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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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	Temperature °K	Velocity m/sec
Van Itterbeek & Keesom		Van Itterbeek & Van Doninck	
15.181	229.1	20.3	265.9
17.186	244.2	75	509.9
18.424	253.1	80	526.9
20.429	266.2	85	542.9
20.519	266.2	90	559.5
Van Itterbeek & Thys		90.2	559.5
290.6	997.0	Schneider & Thiessen	
Keesom & Van Itterbeek		194.99	822.5
4.247	103.94	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	Pressure atm.	Velocity m/sec	Pressure atm.	Velocity m/sec
4.228°K		.3944	106.25	.0508	94.27
0	121.00	.4291	105.41	.0669	93.63
.0195	120.87	.5048	103.34	.0813	93.15
.0346	120.69	.5563	101.86	.0923	92.66
.0528	120.47	3.184°K		.1156	91.72
.0837	120.01	0	105.01	2.259°K	
.1285	119.34	.0350	104.28	0	88.44
.1804	118.54	.0708	103.33	.0226	87.92
.2305	117.75	.1098	102.29	.0269	87.80
.2991	116.63	.1514	101.10	.0335	87.56
.3700	115.46	.1913	99.88	.0391	87.28
.4459	113.94	.2487	98.04	.0455	87.00
.5513	112.16	2.824°K		.0506	86.76
.6330	110.55	0	98.89	2.218°K	
.7538	107.95	.0231	98.24	0	87.64
.8828	104.78	.0341	98.03	.0256	87.11
3.760°K		.0437	97.74	.0314	86.70
0	114.12	.0683	96.94	.0382	86.24
.0153	114.11	.1074	95.58	.0446	85.70
.0255	113.92	.1482	94.05	2.078°K	
.0378	113.70	2.642°K		0	84.85
.0873	112.80	0	95.65	.0182	84.25
.1227	112.10	.0169	95.55	.0245	83.93
.1724	111.12	.0207	95.46	.0298	83.59
.2923	108.63	.0285	95.19		
.3534	107.21	.0390	94.76		

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

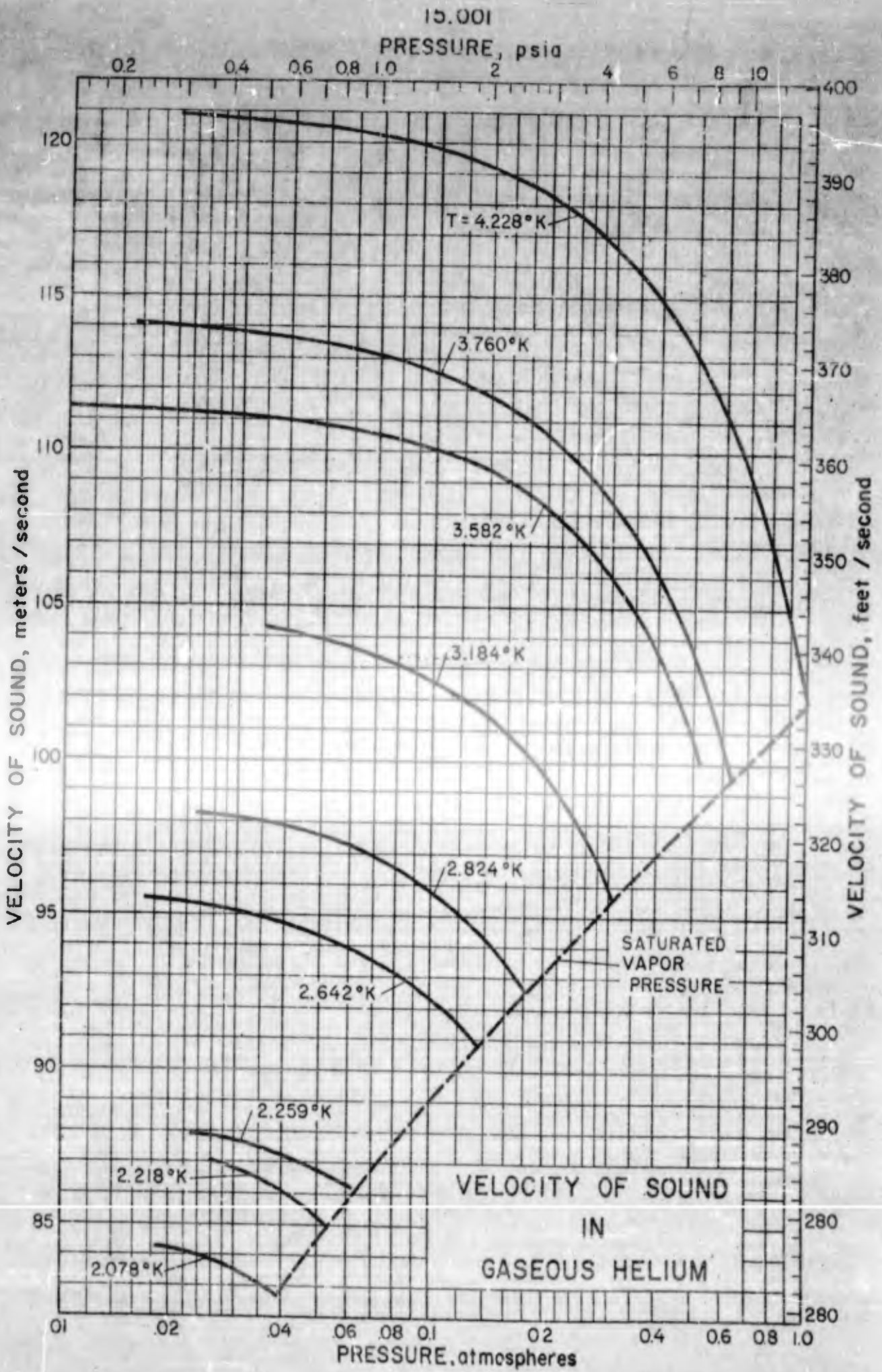
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## VELOCITY of SOUND in GASEOUS HELIUM (Cont.)

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



15.001

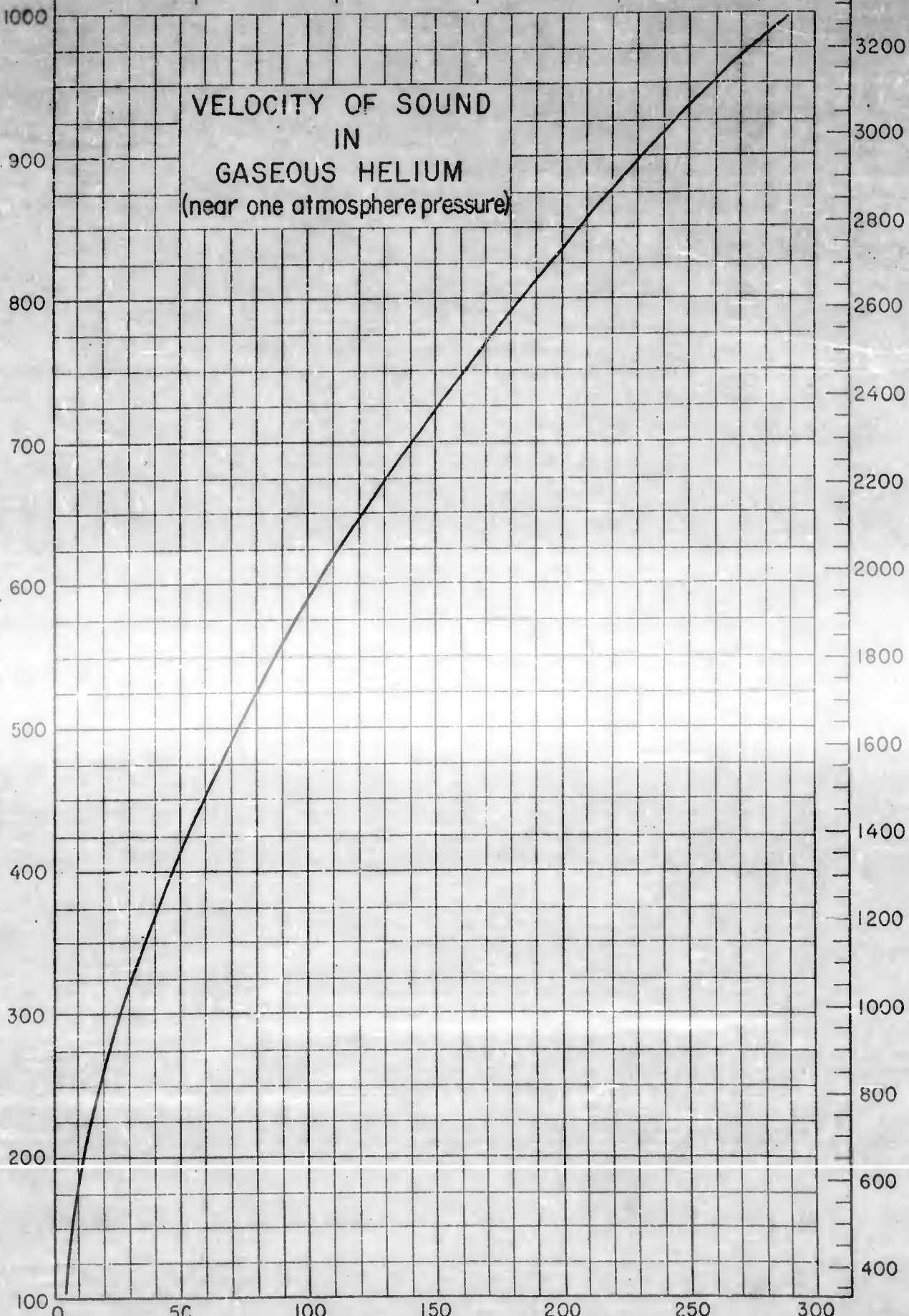
TEMPERATURE, °R

0 100 200 300 400 500

VELOCITY OF SOUND  
IN  
GASEOUS HELIUM  
(near one atmosphere pressure)

VELOCITY OF SOUND, meters / second

VELOCITY OF SOUND, feet / second



TEMPERATURE, °K

0 50 100 150 200 250 300

## 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.; Verhandl. 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  $\pm 1^\circ$  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.)

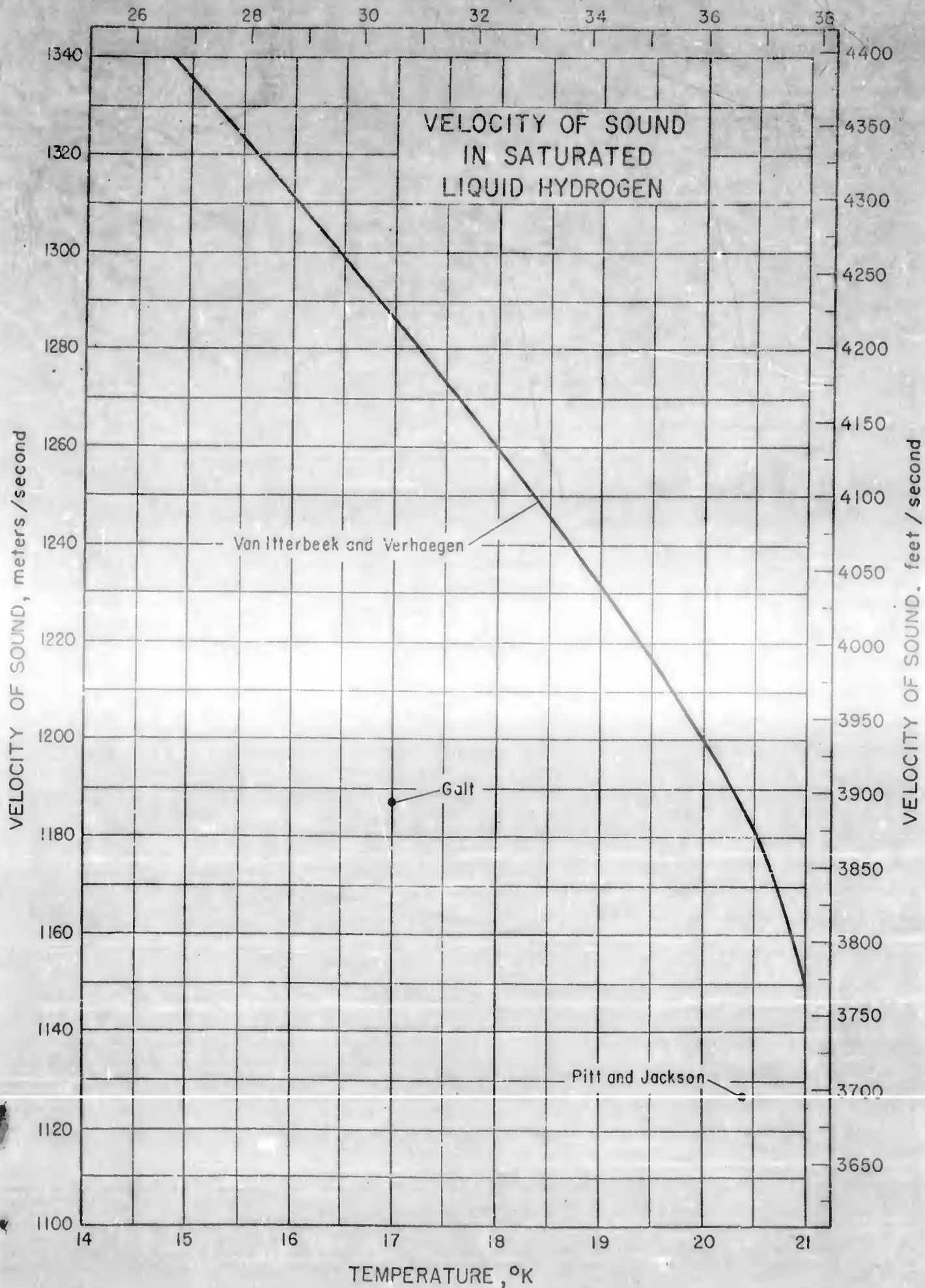
from about 1140 m/sec to 1240 m/sec. They state that this increase with time is not due to a temperature drift, but probably to a transformation of the normal to parahydrogen in the liquid phase. They also assume that a value of 1340 m/sec at 14.8°K corresponds to a more complete transformation into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

FEEG/RDM/RS Issued: 4/19/61

15.002

TEMPERATURE, °R



TEMPERATURE, °K

## VELOCITY of SOUND in GASEOUS HYDROGEN

Sources of Data:

- Brown, E. H.; J. Research Natl. Bur. Standards 54C, 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 Woikers, 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  $Mc^2/RT = (\partial \rho Z / \partial \rho)_T + 1/C_V (\partial T Z / \partial T)_\rho^2$ ; where R is the gas constant; M the molecular weight; T the temperature;  $\rho$  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  $c/c^0$ , where  $c^0$  is the velocity of sound in the ideal gas and is given by:  $c^0 = \sqrt{RT\gamma^0}$ . Selected values of  $c^0$  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 ( $T = 20.39^\circ\text{K}$ ) to  $400^\circ\text{K}$ . 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  $17^\circ$  to  $20^\circ\text{K}$ . 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  $18.60^\circ\text{K}$  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  $\gamma$  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 ( $0^\circ\text{C} = 273.16^\circ\text{K}$ ), pressure in atmospheres ( $g = 980.665$ ), density in Amagats (density,  $\text{gm}/\text{cm}^3 = \text{density, Amagat} \times 8.9885 \times 10^{-2}$ ) 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		

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## 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."

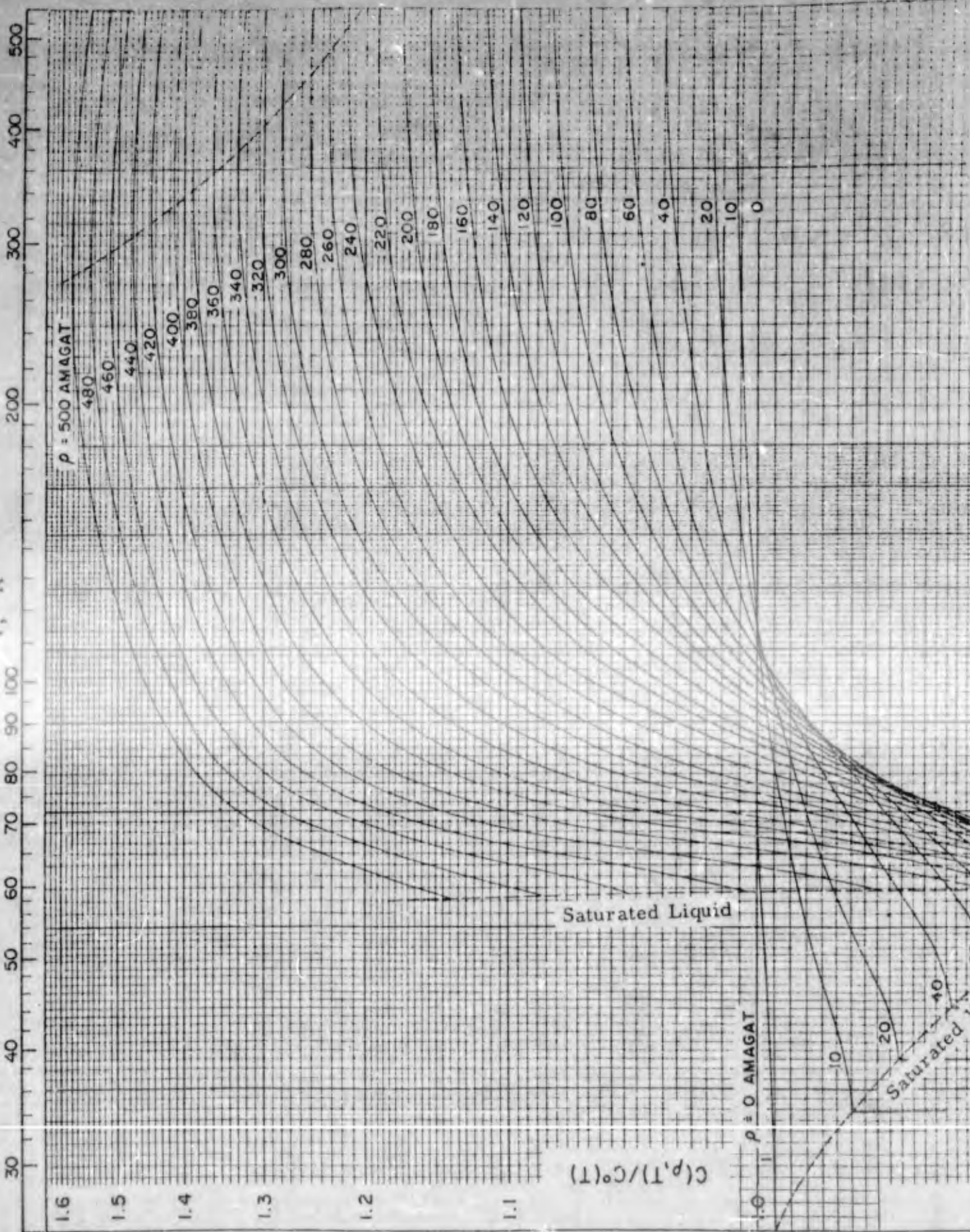
Darrow, using frequencies from 400 to 2000 cycles/sec concluded that the velocity in hydrogen was 3.792 times as great as in air. By interpolation of the data published in 1955 by Michels, Wassenaar and Wolkers, we find the velocity in air at 0°C and 1 atm. to be 331.54 m/sec. Using this value, Darrow's 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.

15.002

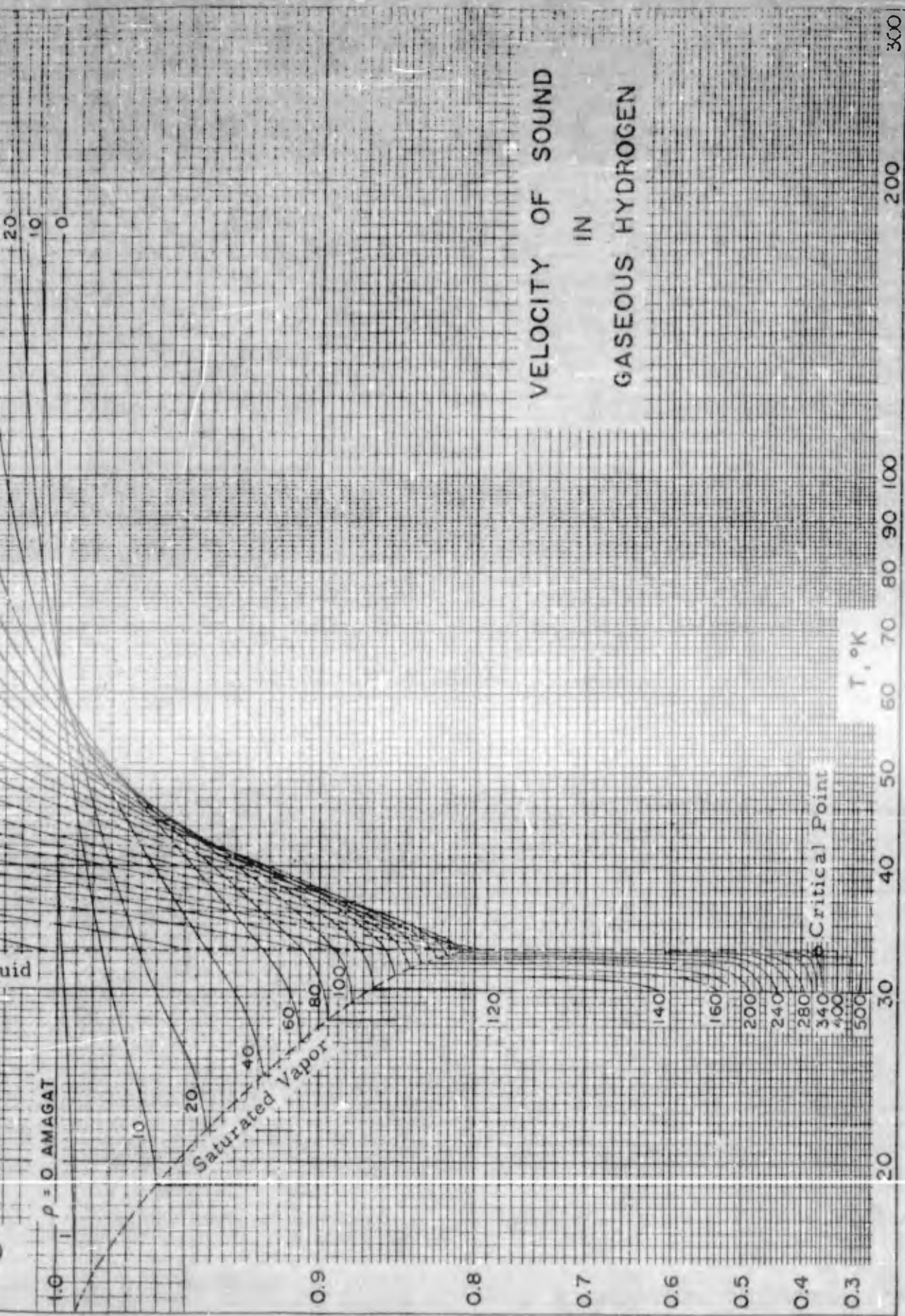
T, °R



p = 0 AMAGAT

Saturated

$C_p(T)/C_v(T)$



2

SONIC VELOCITY  $c(\rho, T)$  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

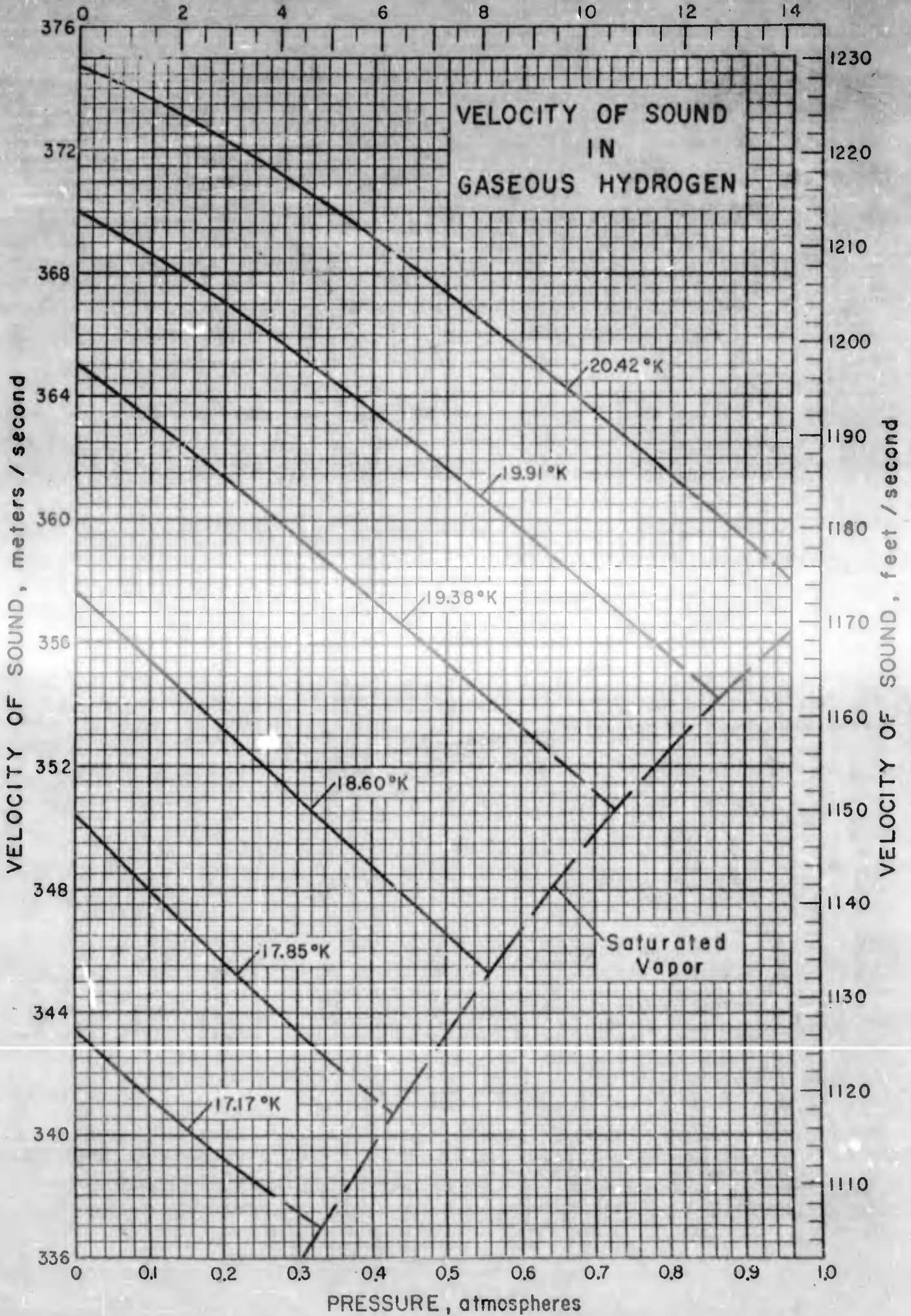
$$\frac{Mc^2}{RT} = \left(\frac{\partial pZ}{\partial p}\right)_T + \frac{R}{c_v} \left(\frac{\partial T Z}{\partial T}\right)_p$$

-----  
 Sonic Velocity  $c^0(T) = \sqrt{\frac{R}{M} T \gamma^0(T)}$  of  
Normal Hydrogen in the Perfect Gas State

T°K	$c^0$ m/sec.	T°K	$c^0$ 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

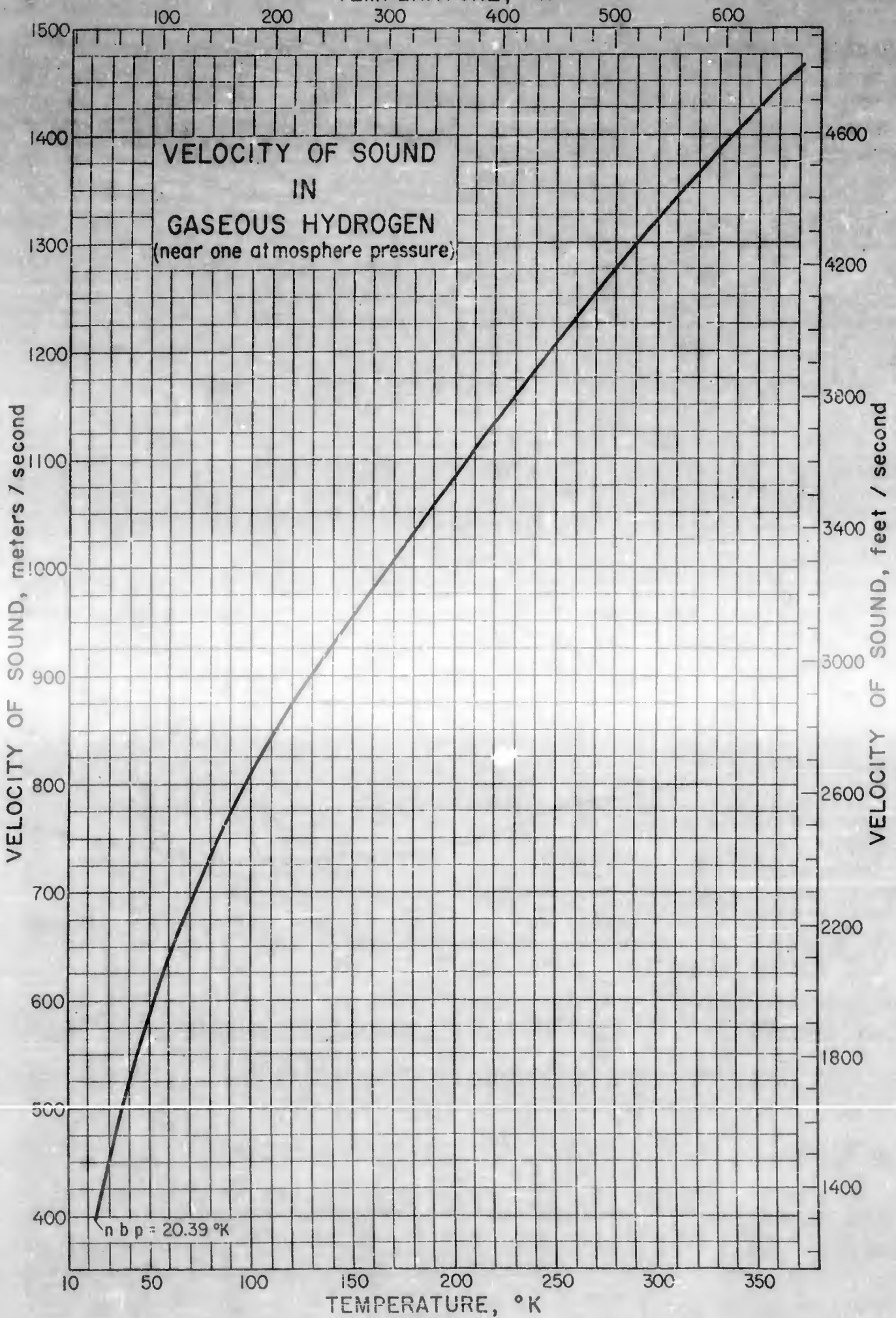
\*from Edmund H. Brown, Expansion Engines for hydrogen liquefiers, J. Research NBS 64C, 25 (January-March 1960).

15.002  
PRESSURE, psia



15.002

TEMPERATURE, °R



## VELOCITY of SOUND in GASEOUS NEON

Source of Data:

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

Other References:

Grennspon, 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  $\gamma$  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.

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## 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		

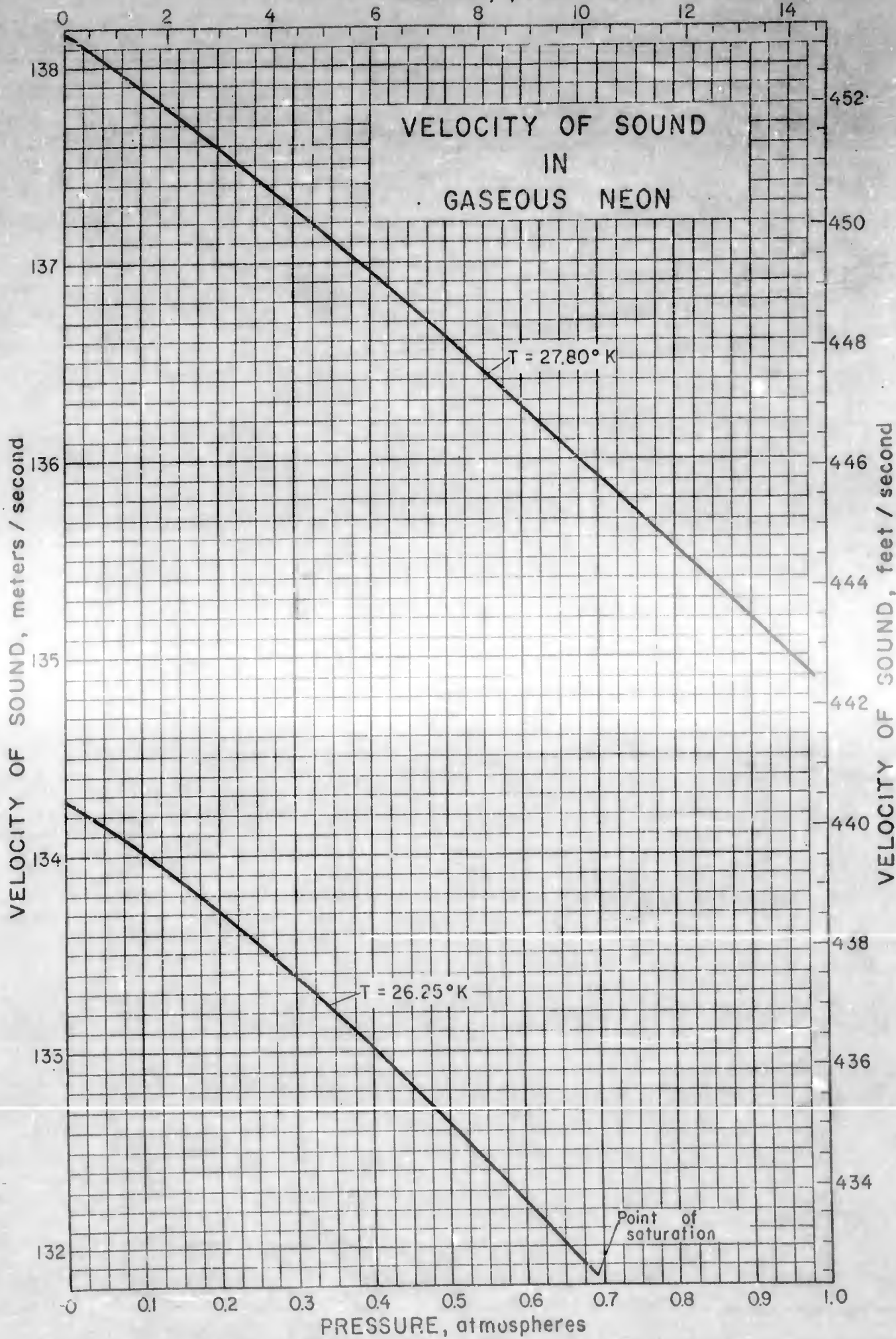
Van Itterbeek and Thys made measurements of the velocity of sound in neon gas using a sound wave with a frequency of 304.4 kilocycles per second; whereas Keesom and Van Lammeren had used audible sound. From these measurements they calculated the value of the velocity of sound at 0°C and 1 atmosphere 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.

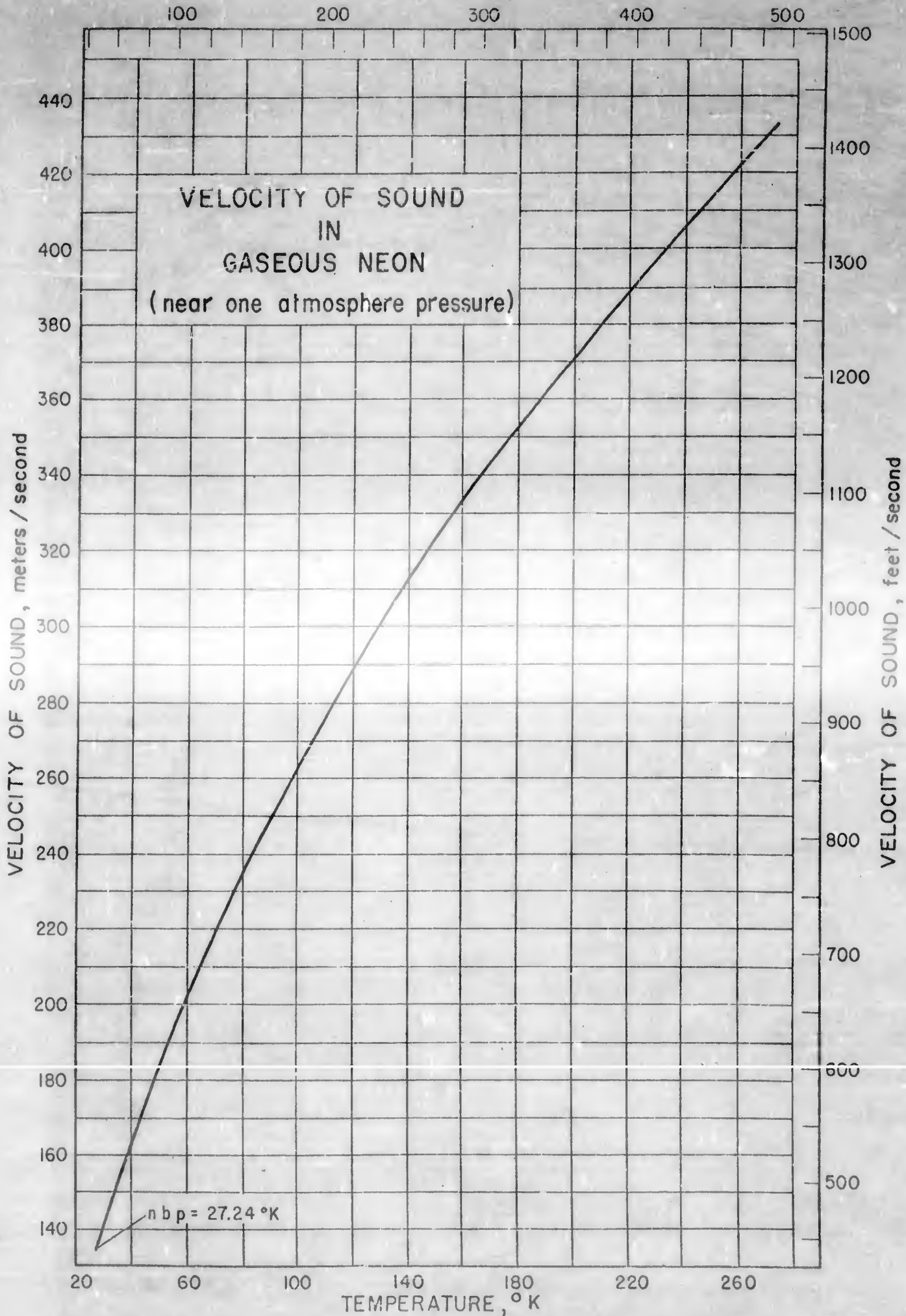
Skudrzyk derived relations of absorption and velocity of sound and compared them with the classical hypothesis of Stokes. The specific behavior of helium and neon was also explained.

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



15.003  
TEMPERATURE, °R



## 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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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

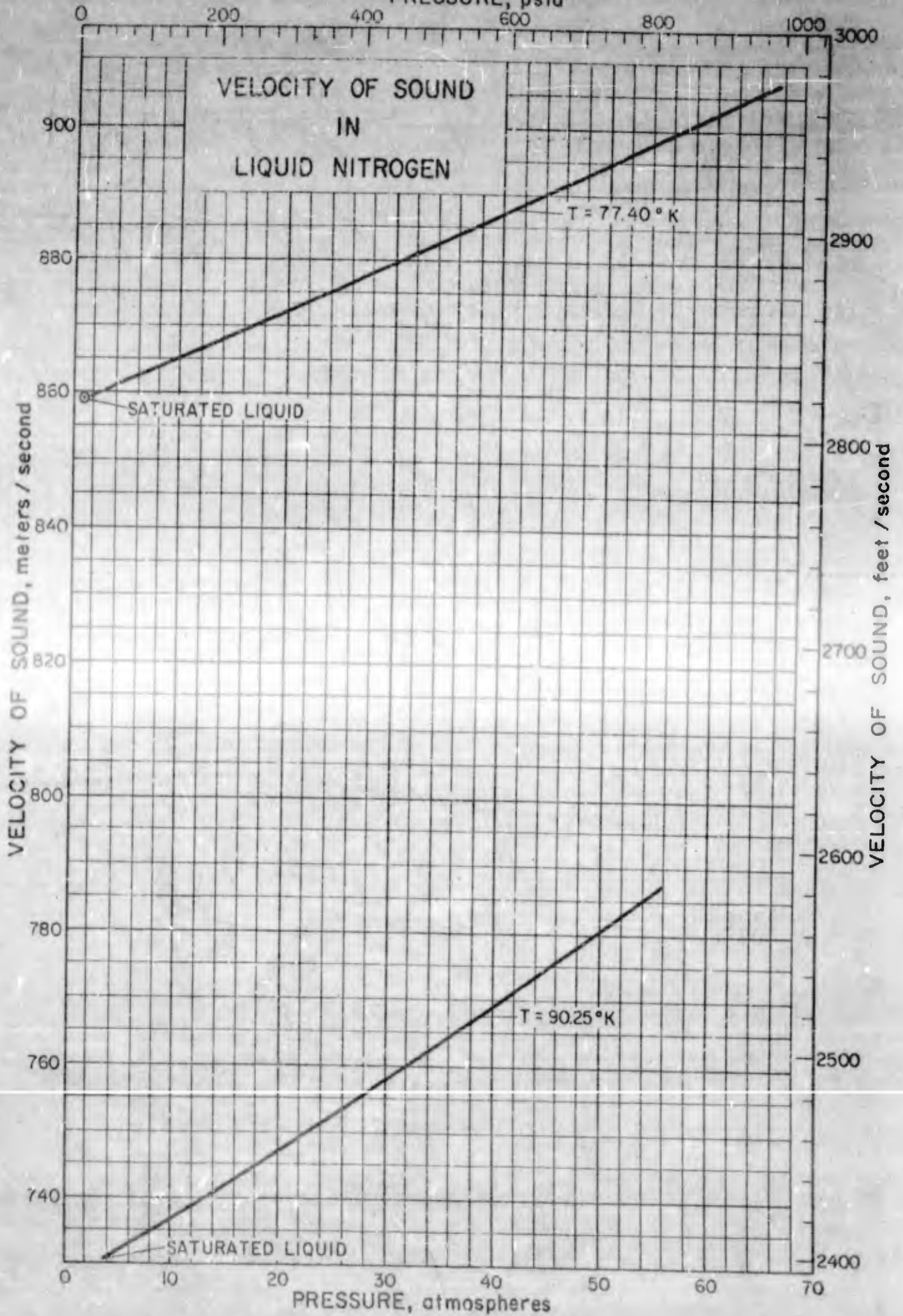
Van Itterbeek, de Bock and Verhaegan			
Temp. °K	Velocity m/sec	Temp. °K	Velocity m/sec
64.5	1009.6	70.2	945.8
65.4	1002.5	71.9	921.3
66.4	998.2	74.7	907.2
67.5	964.7	77.5	857.1

Velocity of Sound in Liquid Nitrogen  
as a Function of Pressure

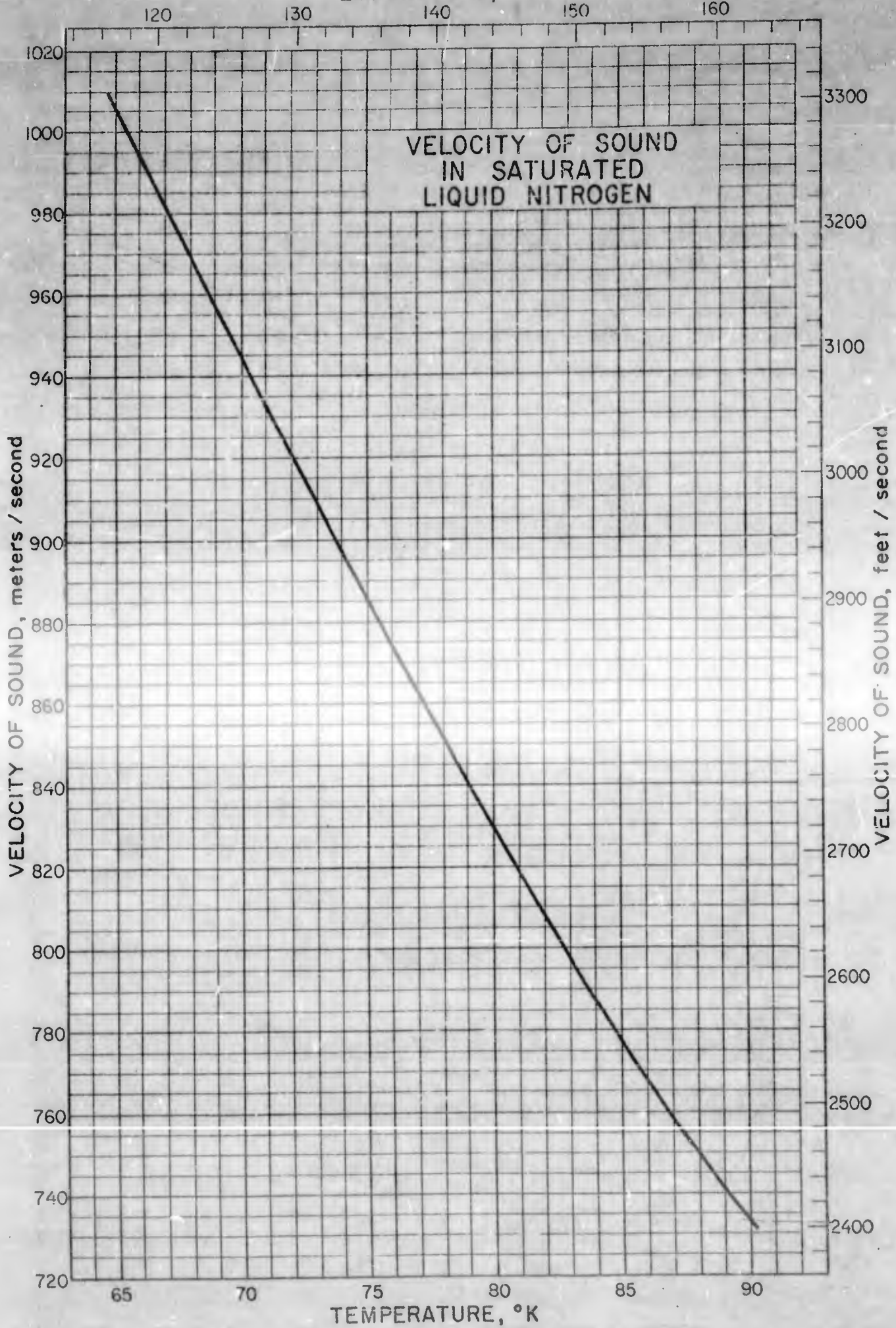
Van Itterbeek and Van Dael			
Pressure atm.	Velocity m/sec	Pressure atm.	Velocity m/sec
77.40°K		8.3	735.7
4.2	861.6	10.2	737.3
9.2	863.2	15.5	743.3
13.9	868.0	15.9	743.0
31.8	881.2	19.2	743.4
42.0	885.4	24.8	753.2
42.1	889.1	28.8	756.2
49.6	894.7	32.3	759.7
51.9	896.5	38.6	769.2
54.1	898.1	39.3	767.4
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

15.004  
PRESSURE, psia



15.004  
TEMPERATURE, °R



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  $\gamma$  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  $a/a_0$ , 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  $a_0$  ( $a_0 = 336.96$  m/sec) is the velocity of sound at  $0^\circ\text{C}$  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 ( $0^\circ\text{C} = 273.16^\circ\text{K}$ ), 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. atm.	Velocity, m/sec					
	$-125^\circ\text{C}$	$-100^\circ\text{C}$	$-75^\circ\text{C}$	$-50^\circ\text{C}$	$-25^\circ\text{C}$	$0^\circ\text{C}$
0	248.1	268.2	286.9	304.6	321.1	337.0
10	241	264	285	304	322	338
30	229	250	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
90.37	0.9299*	191.0	71.92	0.7122	176.9
	0.7293	191.7		0.5789	177.5
	0.5541	192.2		0.4380	178.0
	0.4380	192.6		0.3029	178.7
	0.3207	192.9		0.2025	179.2
	0.1973	193.3		0.1183	179.7
82.95	0.1176	193.3	0.3879	170.9	
	1.0146*	181.8	0.3382	171.1	
	0.7957	182.8	0.2627	171.6	
	0.5953	183.4	0.1931	172.0	
	0.4179	184.0	0.1188	172.6	
	0.2923	184.6	Hilsenrath, et al.		
0.1921	185.0	1.00.0	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 = 5 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.

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## VELOCITY of SOUND in GASEOUS NITROGEN (Cont.)

Comments: (cont.)

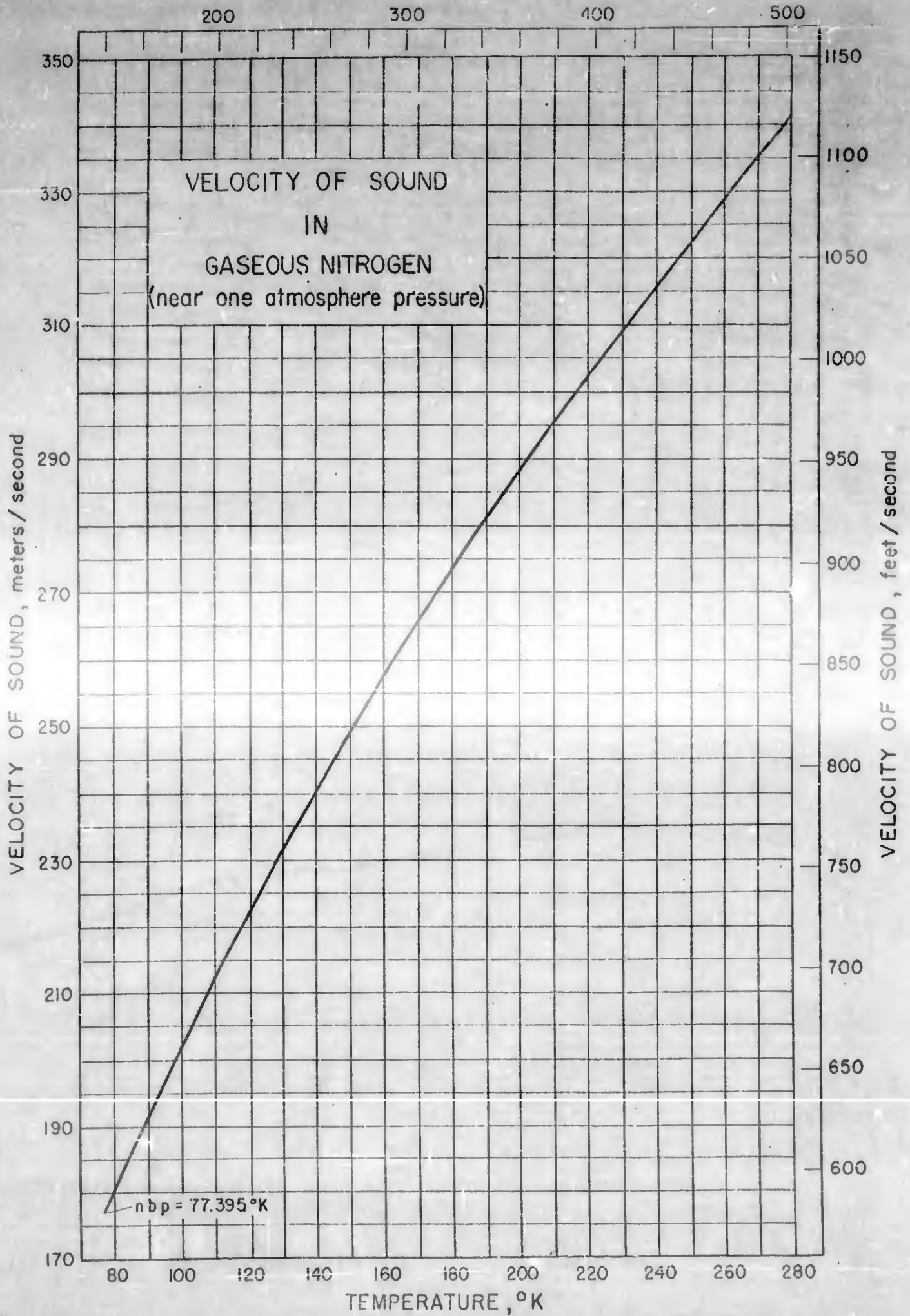
Work done by other investigators is also of interest. Foley made a critical review of all work on the velocity of sound in nitrogen prior to 1928 for inclusion in the section on sound in the International Critical Tables and reported 337.7 m/sec at 0°K and 1 atm. pressure. Dixon and co-workers gave a 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.

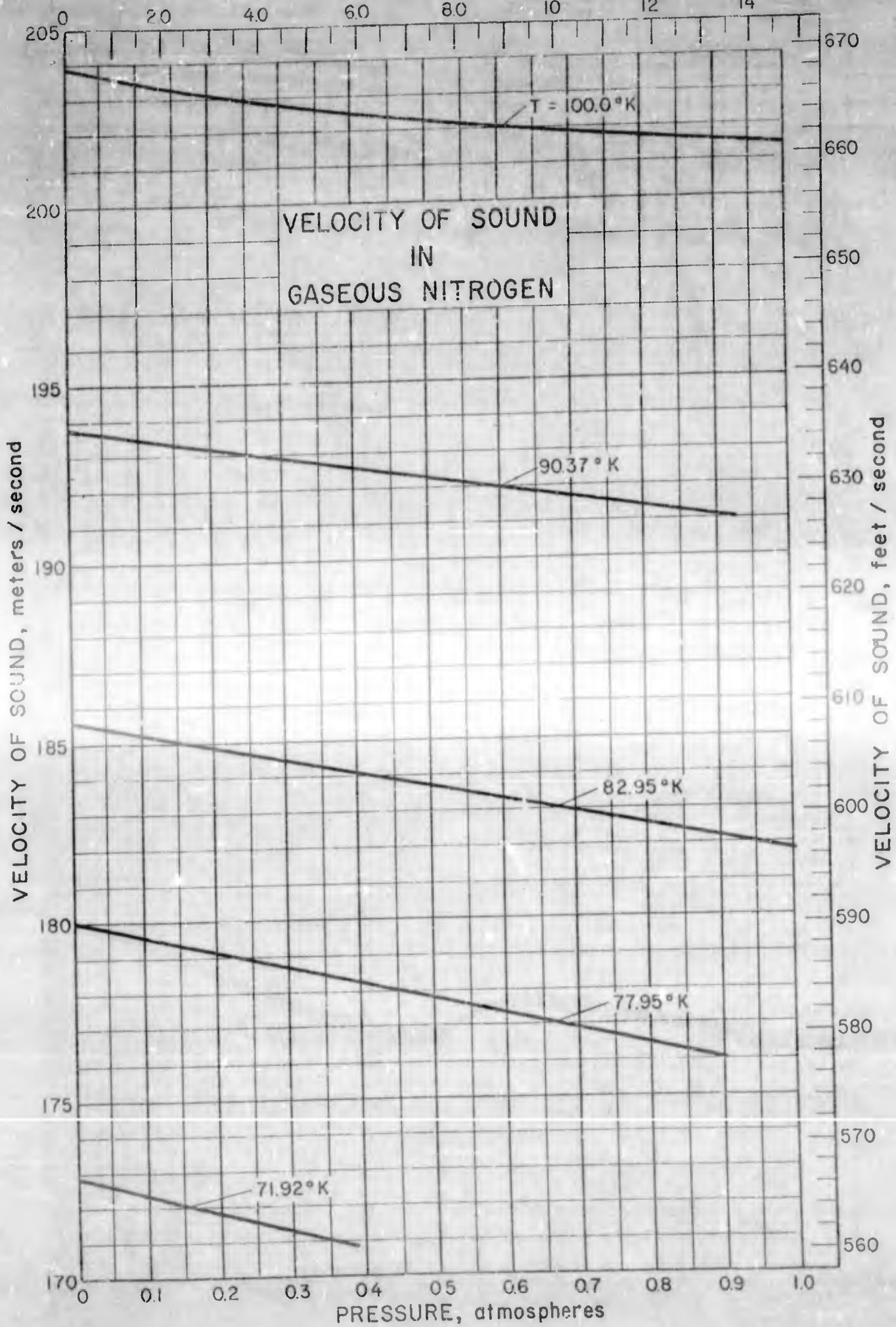
The above authors also give values for the velocity as a function of pressure ranging from 183.1 m/sec at zero pressure and 80°K to about 180 m/sec at 0.8 atmospheres.

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

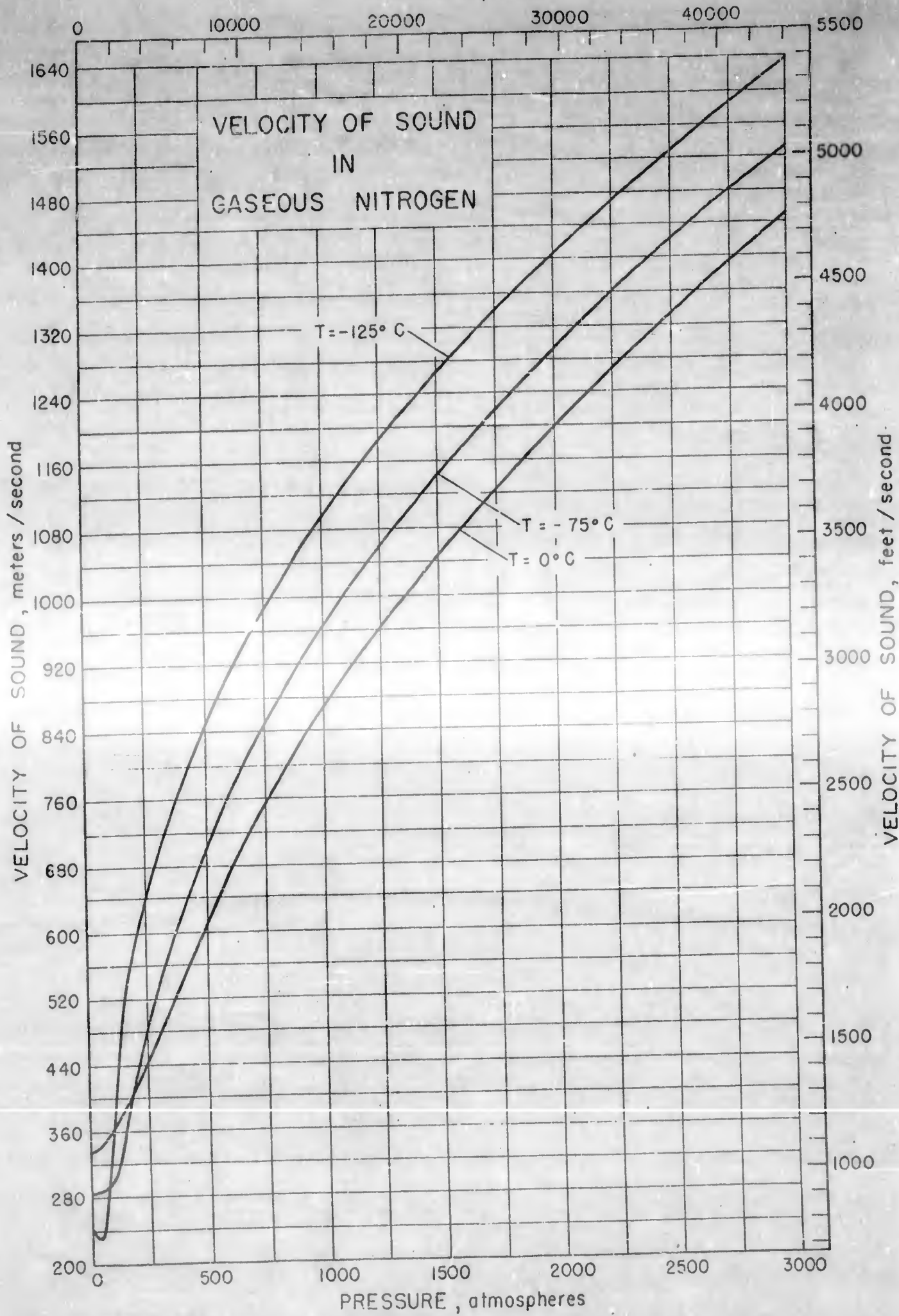
15.004  
TEMPERATURE, °R



15.004  
PRESSURE, psia



15.004  
PRESSURE, psia



## 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  $-182.9^{\circ}\text{C}$  to be 912 m/sec. By means of the scattering of light by ultrasonic waves in liquids, Bär found the velocity at  $-183.6^{\circ}\text{C}$  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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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	Temperature °K	Velocity m/sec.
Galt		Van Itterbeek & de Bock	
60 ± 5	1119	73.0	1034
70 ± 1	1094	75.0	1022
87.0 ± 0.2	952	77.5	1007
de Bock		80.0	991
73.00	1036.3	82.5	974
76.55	1014.4	85.0	956
76.75	1011.2	87.5	935
80.45	987.1	90.0	909
80.65	938.0	Van Itterbeek, de Bock & Verhaegen	
83.45	967.0	60.5	1128.9
83.45	968.6	62.0	1137.4
85.30	955.6	64.5	1111.1
85.30	955.1	67.9	1083.0
87.50	935.1	78.6	1007.3
87.50	936.2	82.5	966.8
90.30	904.9	86.1	938.5
		90.5	902.3

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## VELOCITY of SOUND in LIQUID OXYGEN (Cont.)

Comments: (cont.)

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

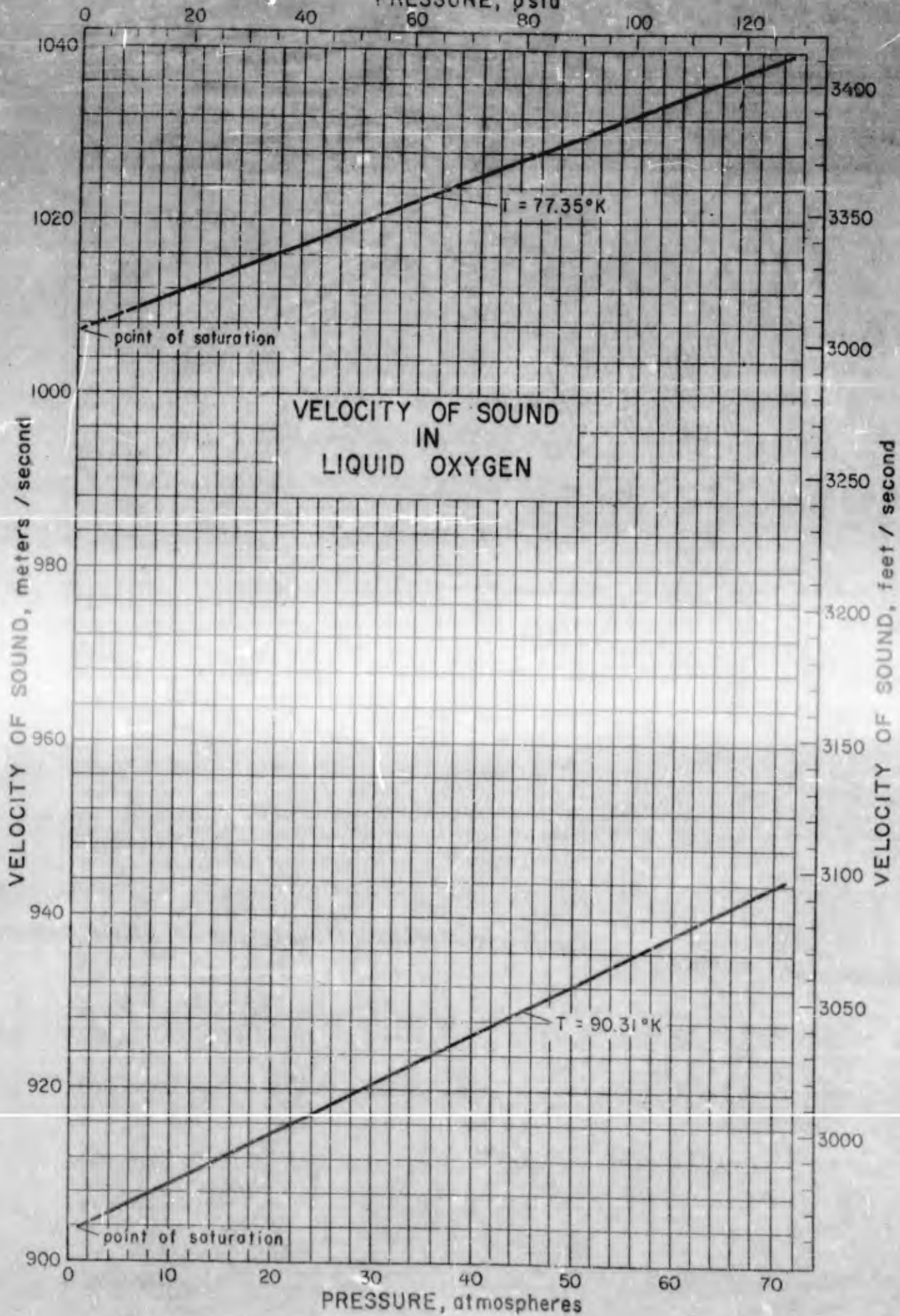
Liepmann (1938)					
Temp. °C ± 0.1	Velocity, m/sec*		Temp. °C ± 0.1	Velocity, m/sec*	
	7500 kc/sec	1537 kc/sec		7500 kc/sec	1537 kc/sec
-183.6	911	---	-197.3	1028	---
-183.7	---	915	-198.4	---	1042
-185.8	932	928	-198.5	---	1044
-187.2	945	---	-199.2	1043	---
-187.7	---	948	-200.7	---	1072
-189.2	954	---	-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%.

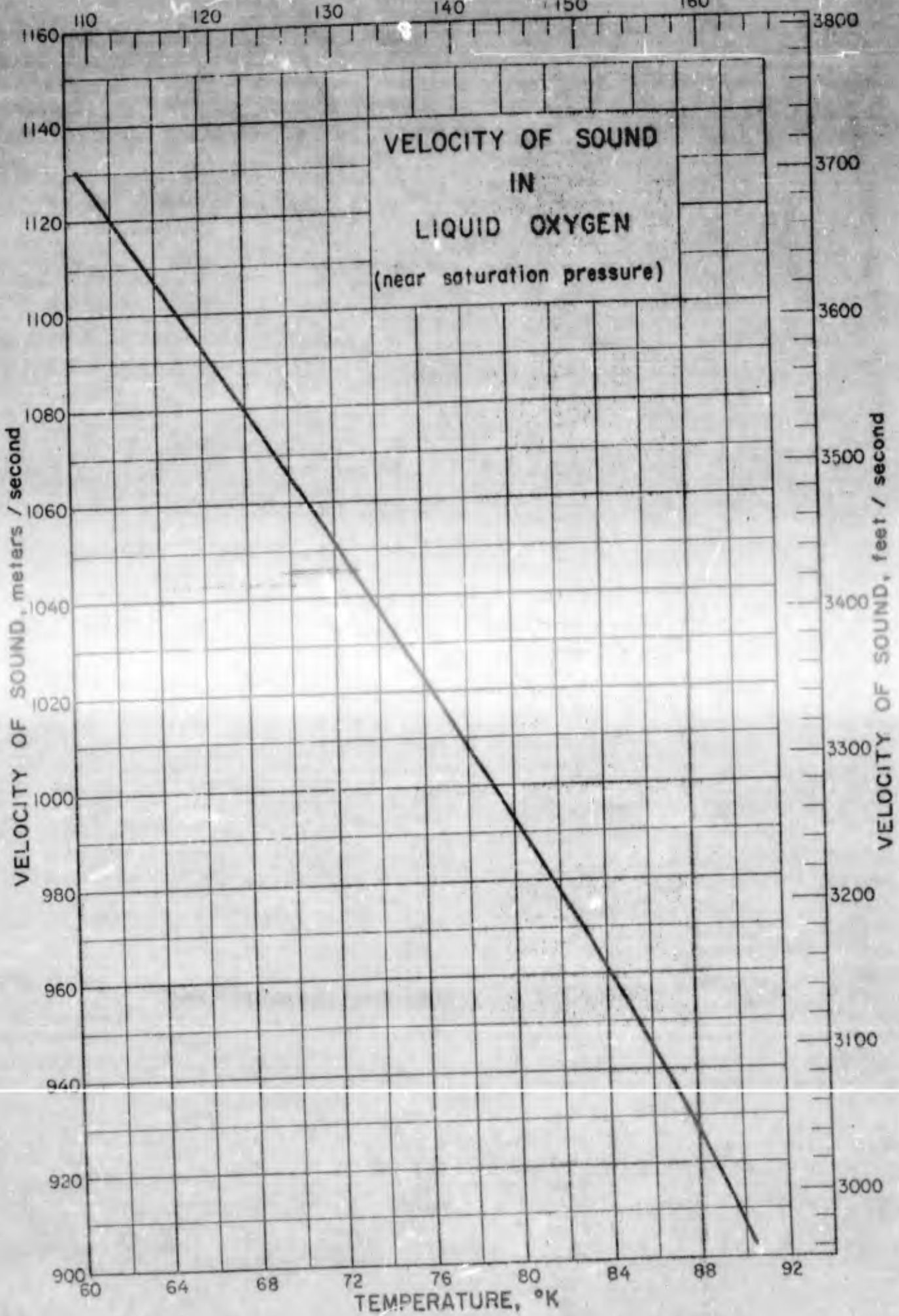
Velocity of Sound in Liquid Oxygen  
as a Function of Pressure

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



13.000  
TEMPERATURE, °R



## 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)  
 Plelemeier, 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  $\gamma$  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

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## VELOCITY of SOUND in GASEOUS OXYGEN (Cont.)

Comments: (cont.)

in the form of  $a/a_0$ , where  $a$  is the value of the velocity of sound at low frequency at a given temperature and pressure, and  $a_0$  is a datum value ( $a_0 = 314.82$  m/sec) at  $0^\circ\text{C}$  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 ( $0^\circ\text{C} = 273.16^\circ\text{K}$ ), 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	80.60°K		76.00°K	
0.2606	181.9	84.95°K		0.2624	169.5	0.1329	165.3
86.92°K		0.4776	173.5	0.2526	169.8	0.0892	165.8
0.6250	174.9	0.3454	173.9	0.1803	169.9	0.0517	166.1
0.3007	176.2	0.2276	174.5	0.1091	170.4	0.01139	165.3
0.1108	177.1	0.1203	175.1	0.0566	170.9	74.12°K	
0.5164	175.5					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.

Pielemeyer 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.

15.005

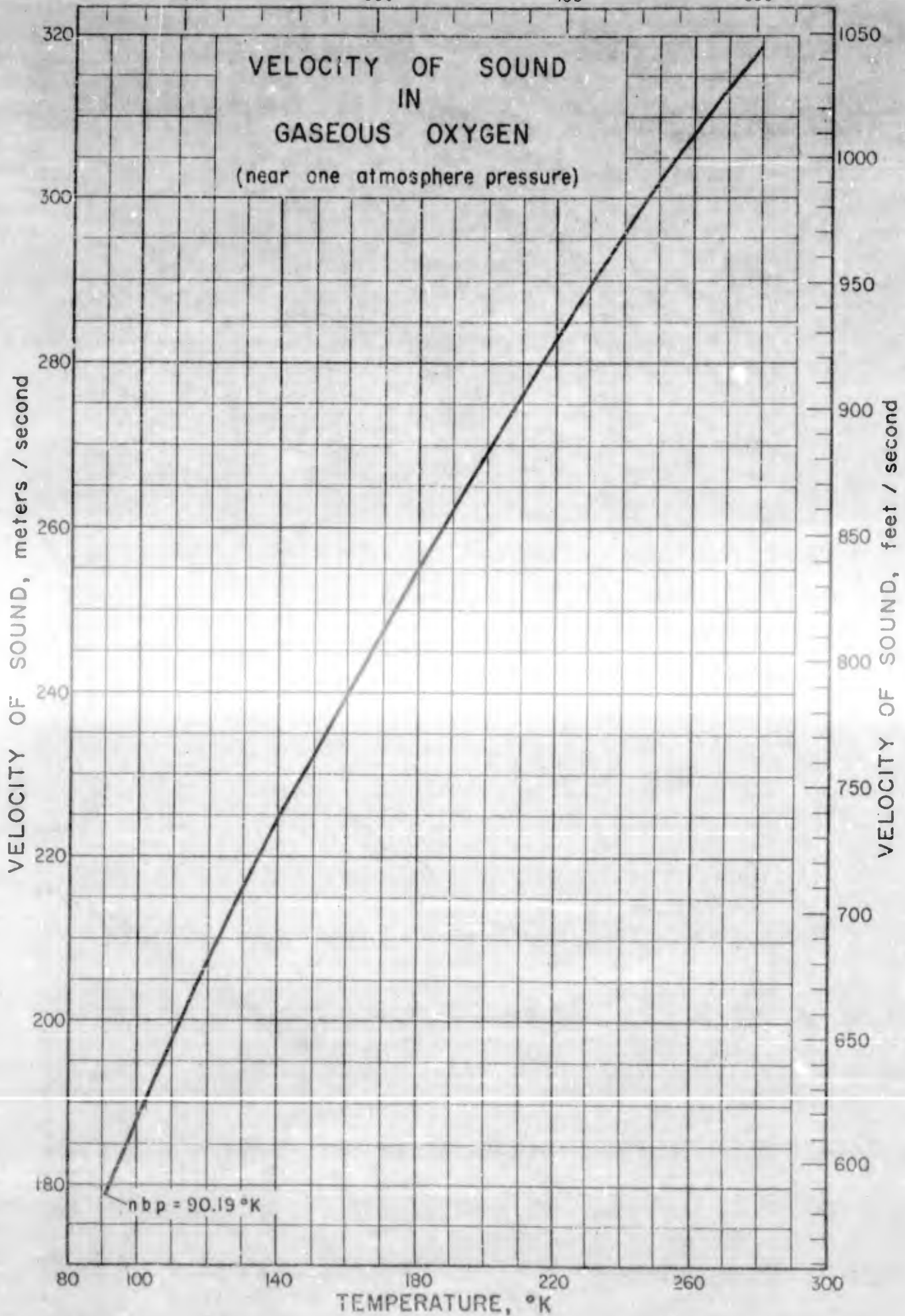
TEMPERATURE, °R

200

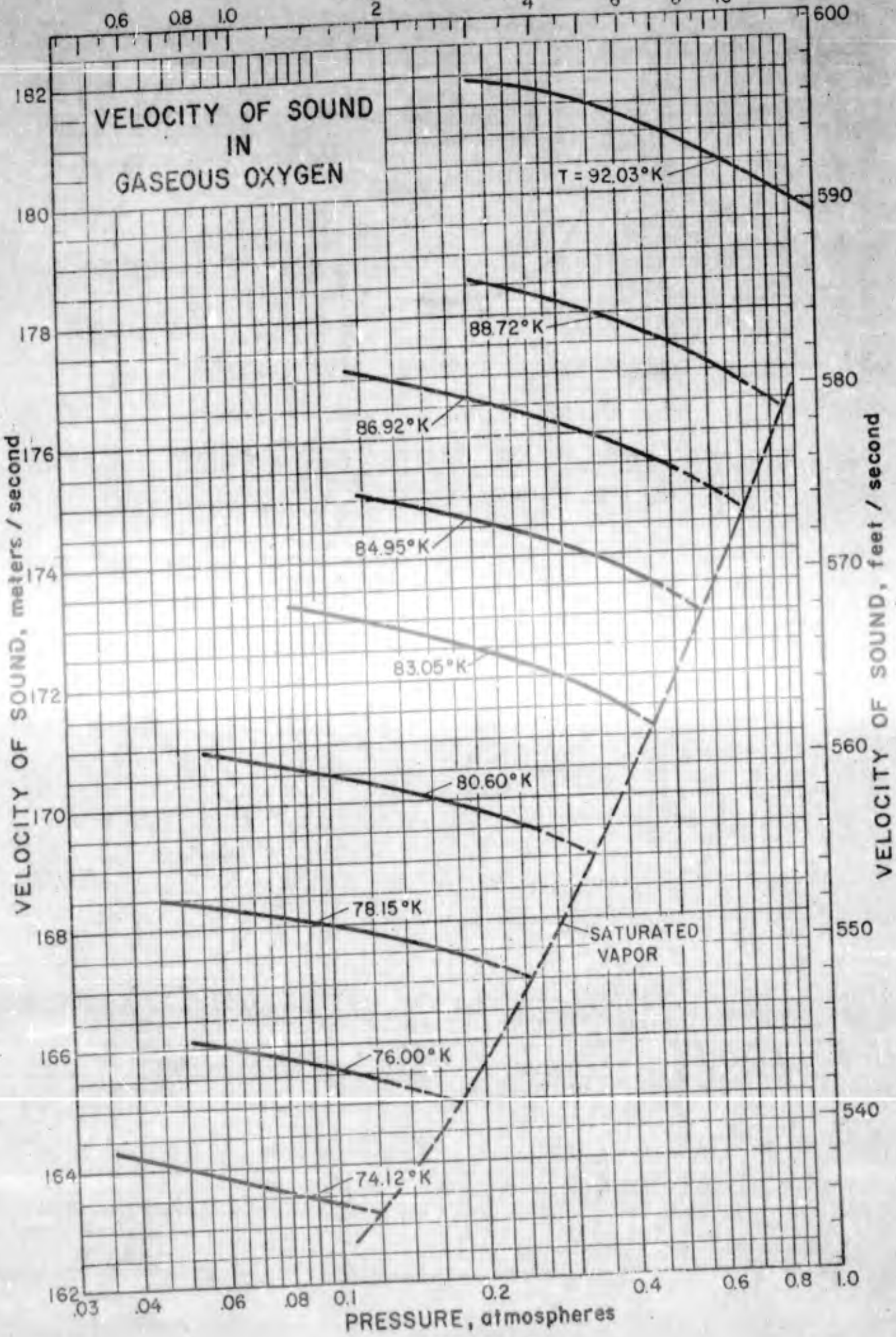
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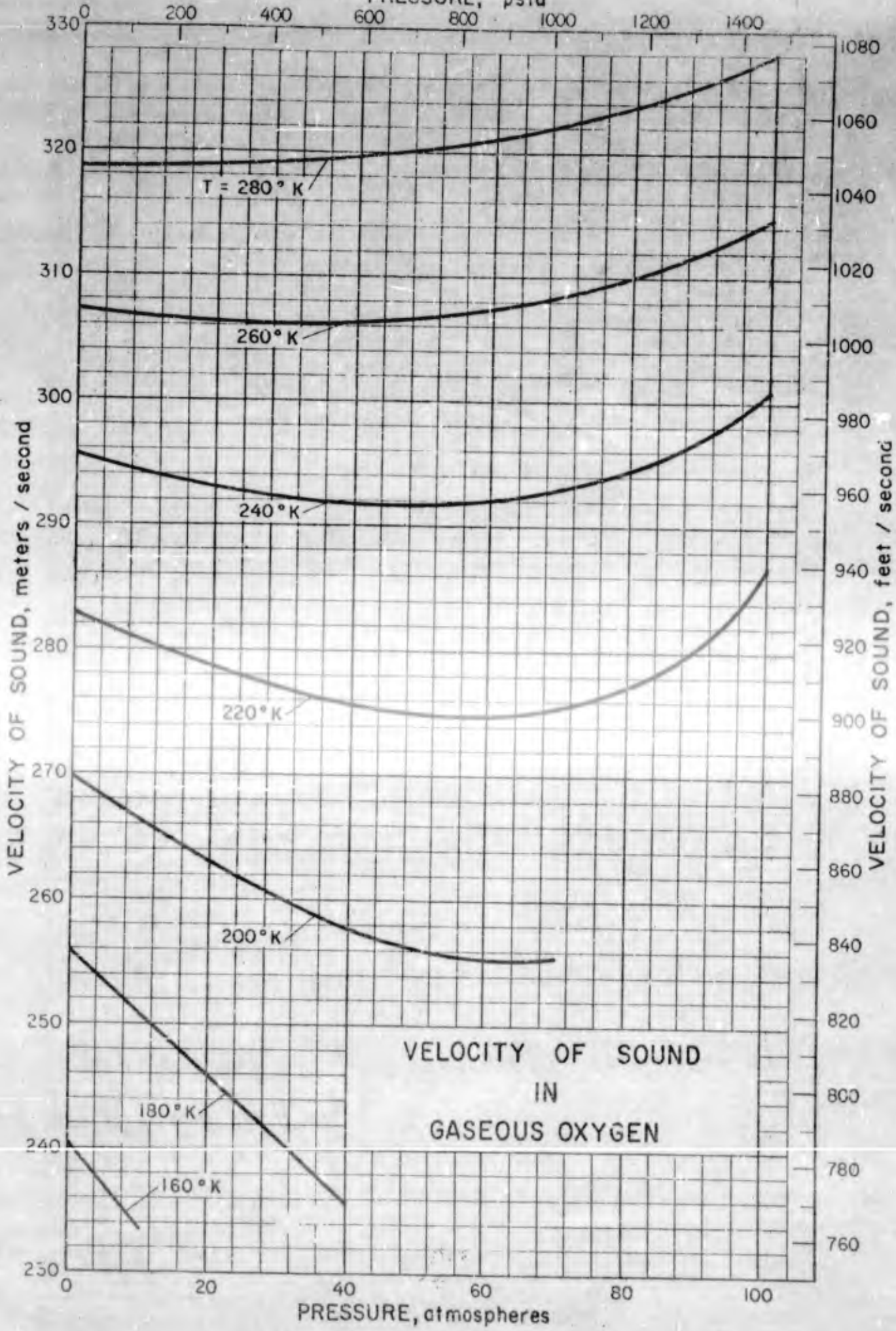
500



15.005  
PRESSURE, psia



15.005  
PRESSURE, psia



## 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); Commun. 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  $a/a_0$ , where  $a$  is the value of the velocity of sound at low frequency at a given temperature and pressure, and  $a_0$  is a datum value ( $a_0 = 331.45$  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 being free 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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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.							
$^{\circ}\text{K}$	.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 (cont.)

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	335.8	244.2	252.3	264.0	275.2	285.9	299.6	316.0	331.46	
10	326.4	236.8	246.4	259.9	272.2	284.2	298.8	316.1	332.3	
20	315.8	229.0	240.8	256.5	270.3	282.9	298.3	316.6	333.4	
30	303.7	221.5	235.4	253.0	268.2	282.3	298.7	317.4	334.7	
40	291.3	214.5	231.0	250.7	267.3	281.9	299.3	318.8	336.4	
50	275.6	211.2	228.8	250.3	267.4	282.5	300.4	320.5	338.3	
60	263.5	221.3	230.3	250.7	268.5	283.9	302.3	322.5	340.5	
70	254.5	253.7	239.4	253.8	270.9	286.2	304.6	325.0	343.0	
80	243.0	294.1	256.5	260.2	274.8	289.5	307.6	327.8	345.8	
90	234.4	330.3	280.1	270.2	280.6	293.5	311.1	331.1	349.1	
100	225.2	361.6	306.5	283.4	288.4	299.3	315.5	334.8	352.4	
150	201.9	475.3	420.3	368.9	346.9	341.7	347.5	359.8	374.3	
200	185.2	553.7	503.5	448.3	414.4	397.3	389.9	393.1	401.7	
250	174.6	615.5	568.6	514.5	476.6	452.6	436.5	430.5	433.1	
300	168.6	(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)	(763.5)	733.5	703.1	674.3	654.4	
650				(792.5)	(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)	(811.2)	780.5	757.3	
850						(835.2)	(835.2)	804.1	780.3	
900								826.6	802.5	
950								848.4	823.8	
1000								(868.9)	844.4	

parenthesis indicate extrapolated values

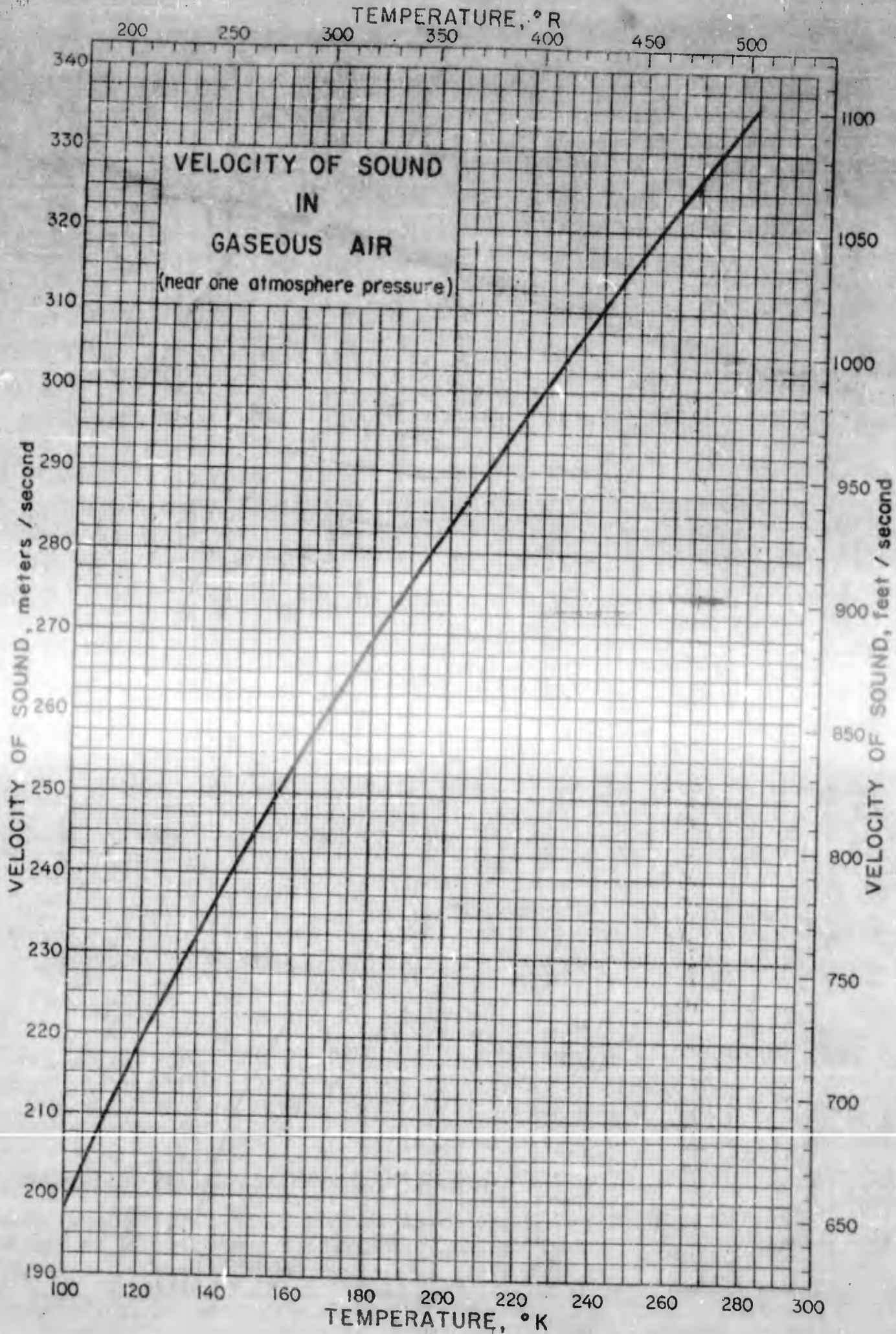
## VELOCITY of SOUND in GASEOUS AIR (Cont.)

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

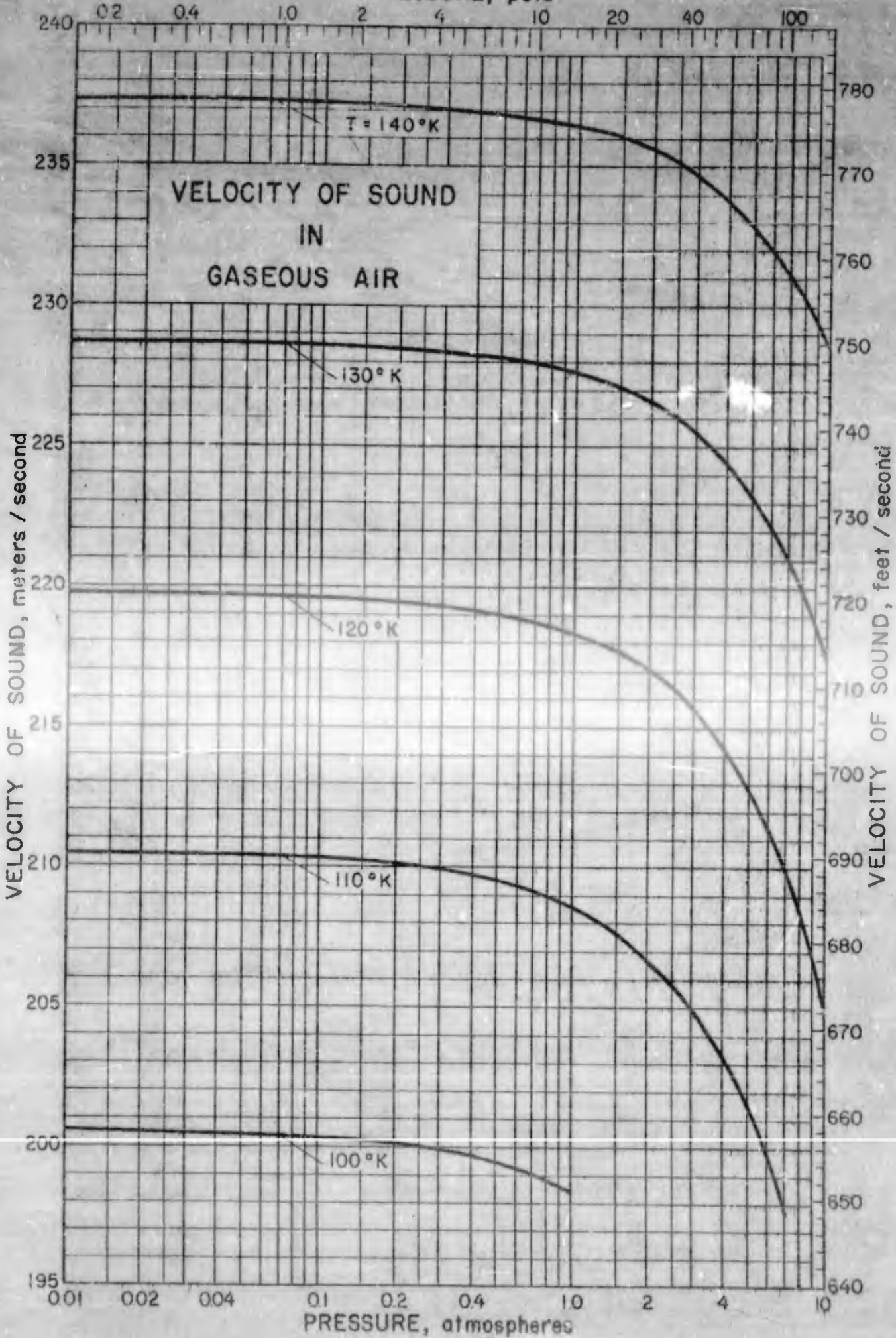
\* Values are from Hilsenrath, et al.

15.006

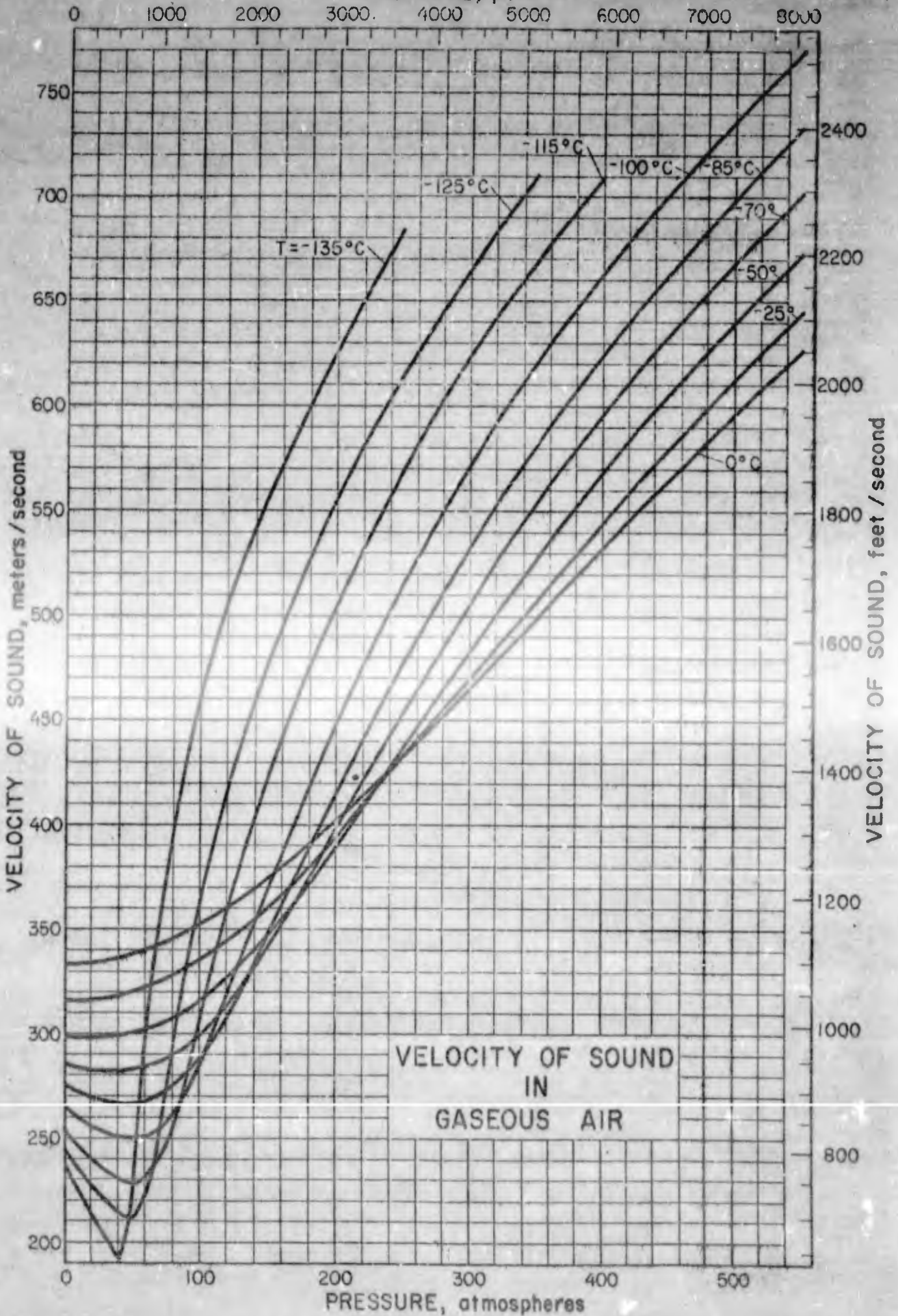


15.006

PRESSURE, psia



15.006  
PRESSURE, psia



VELOCITY OF SOUND  
IN  
GASEOUS AIR



## 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  $a/a_0$ , where  $a$  is the value of the velocity of low frequency sound at a given temperature and pressure, and  $a_0$  ( $a_0 = 336.93$  m/sec) is the velocity of sound at 0°C and 1 atmosphere of pressure. The value of  $a_0$  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  $\gamma$  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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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)

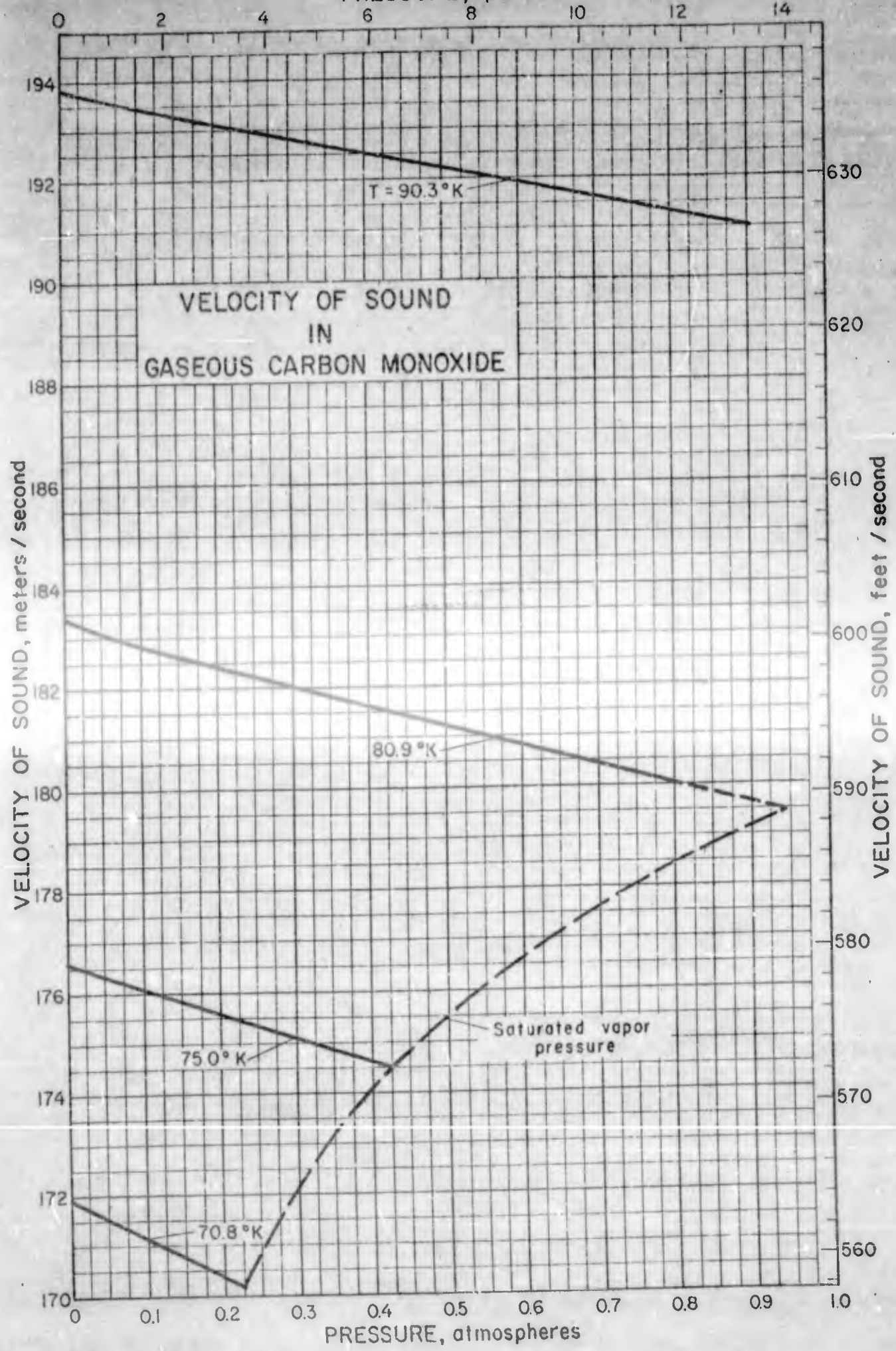
Hilsenrath, et al.			
Temp. $^{\circ}\text{K}$	Velocity m/sec	Temp. $^{\circ}\text{K}$	Velocity m/sec
200	288.08	250	322.44
210	295.15	260	328.84
220	302.23	270	334.91
230	308.96	280	341.31
240	315.70		

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 $^{\circ}\text{K}$		75 $^{\circ}\text{K}$	
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 $^{\circ}\text{K}$	
80.9 $^{\circ}\text{K}$		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)

15.007  
PRESSURE, psia

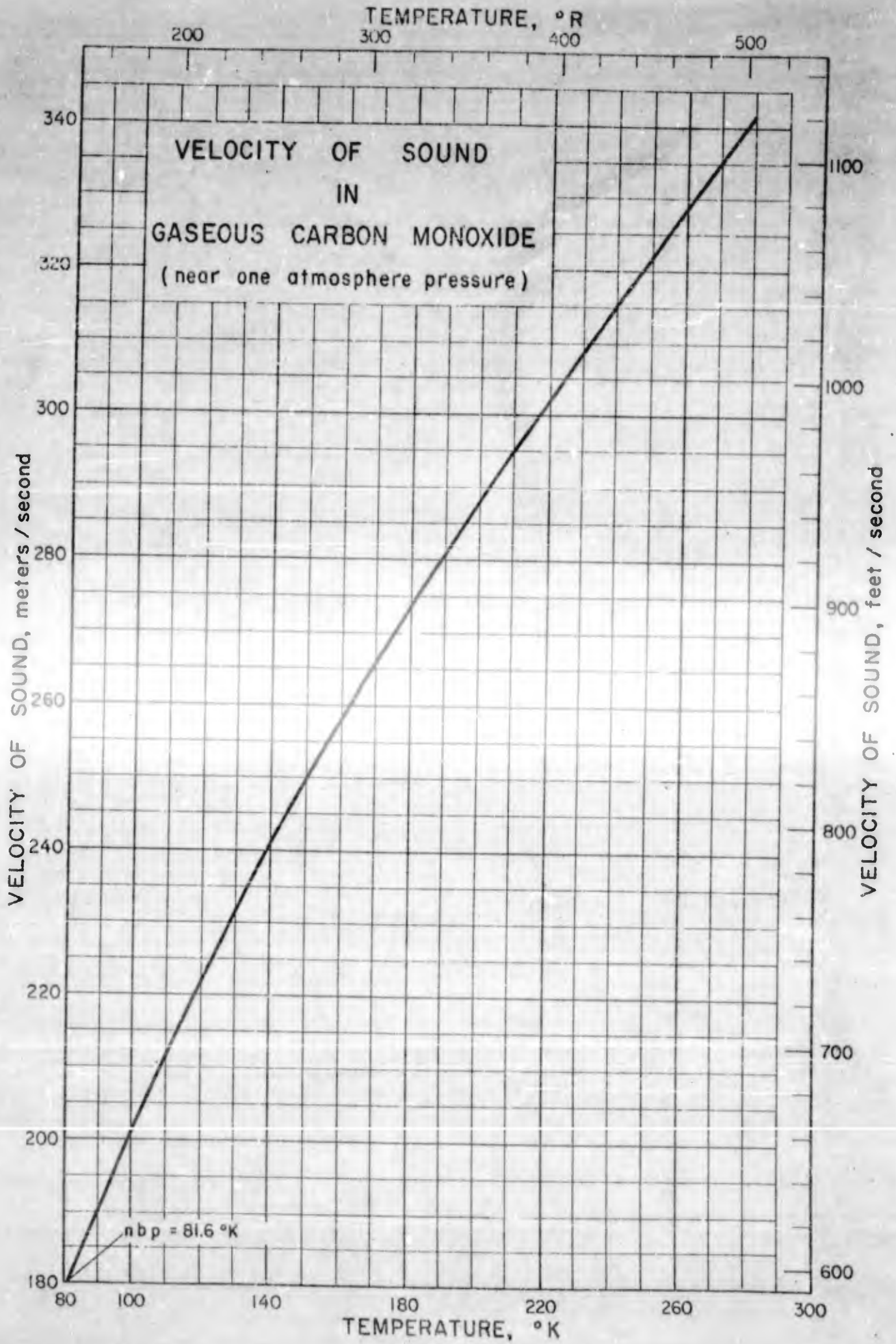


## VELOCITY of SOUND in GASEOUS CARBON MONOXIDE (Cont.)

Comments: (cont.)

In 1829 Dalong 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. Willner, 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.



## 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  $\pm 0.01$  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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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. $^{\circ}\text{K}$	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.)

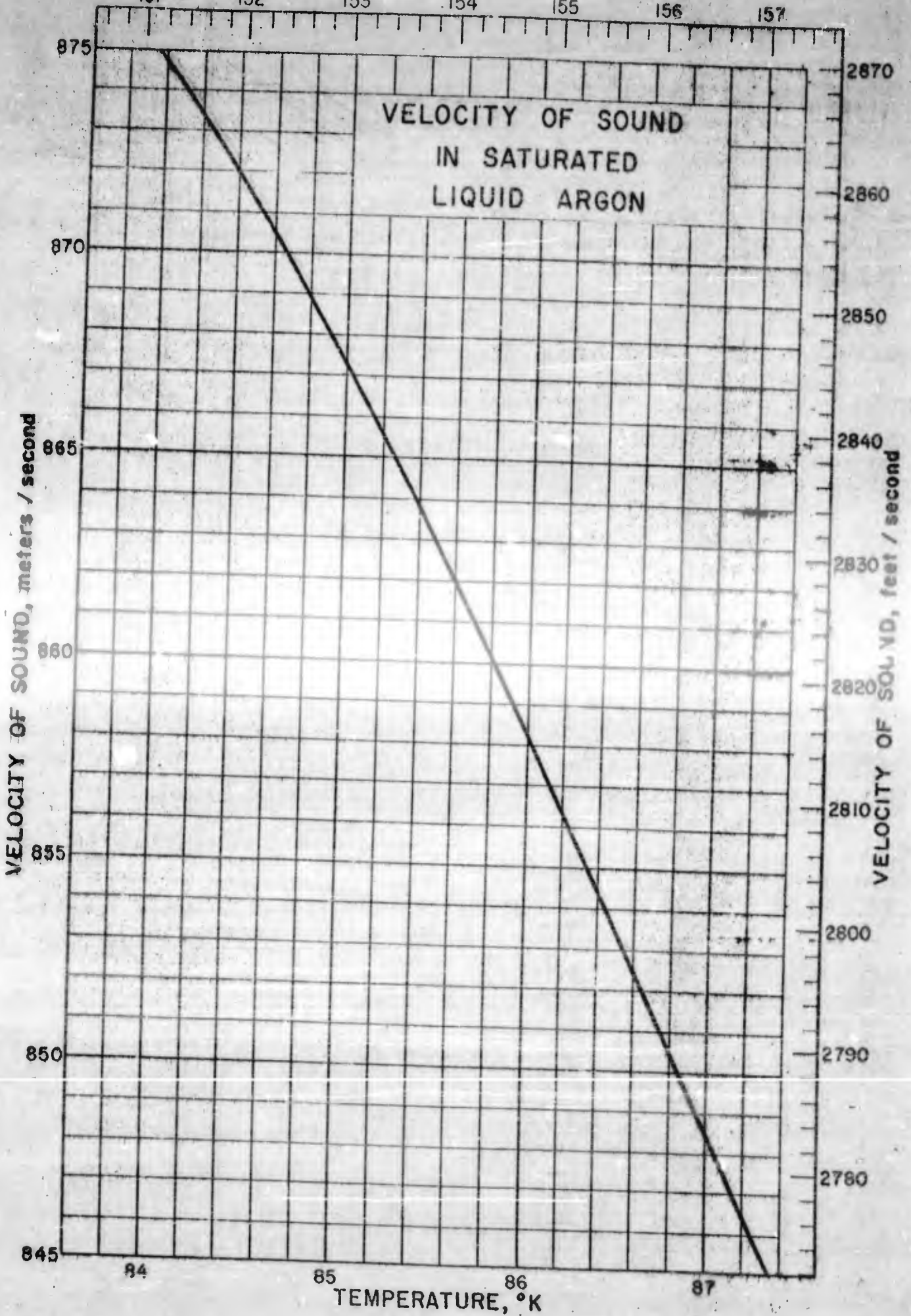
Comments: (cont.)

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



TEMPERATURE, °K

84

85

86

87

## 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 ( $a/a_0$ ), where  $a$  is the value of the velocity of sound at a given pressure and temperature, and  $a_0$  is the velocity of sound at 0°C and 1 atmosphere pressure. The datum value ( $a_0 = 307.88$  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  $\gamma$  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 argon in the tabulations below and on the graphs are: temperature in degrees Kelvin ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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	90.25	0.143	167.9	80.85	0.0730	172.1	
	0.214	177.3		0.671	174.6		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		78.93	0.173	166.4
	0.568	176.2		0.228	176.0			0.107	166.8
	0.334	176.9	0.143	176.3	0.314	163.8			
90.20	0.205	177.3	85.73	0.0842	176.4	0.245	164.0		
	0.428	176.5		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.

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## VELOCITY of SOUND in GASEOUS ARGON (Cont.)

Comments: (cont.)Velocity of Sound in Gaseous Argon  
as a Function of Temperature

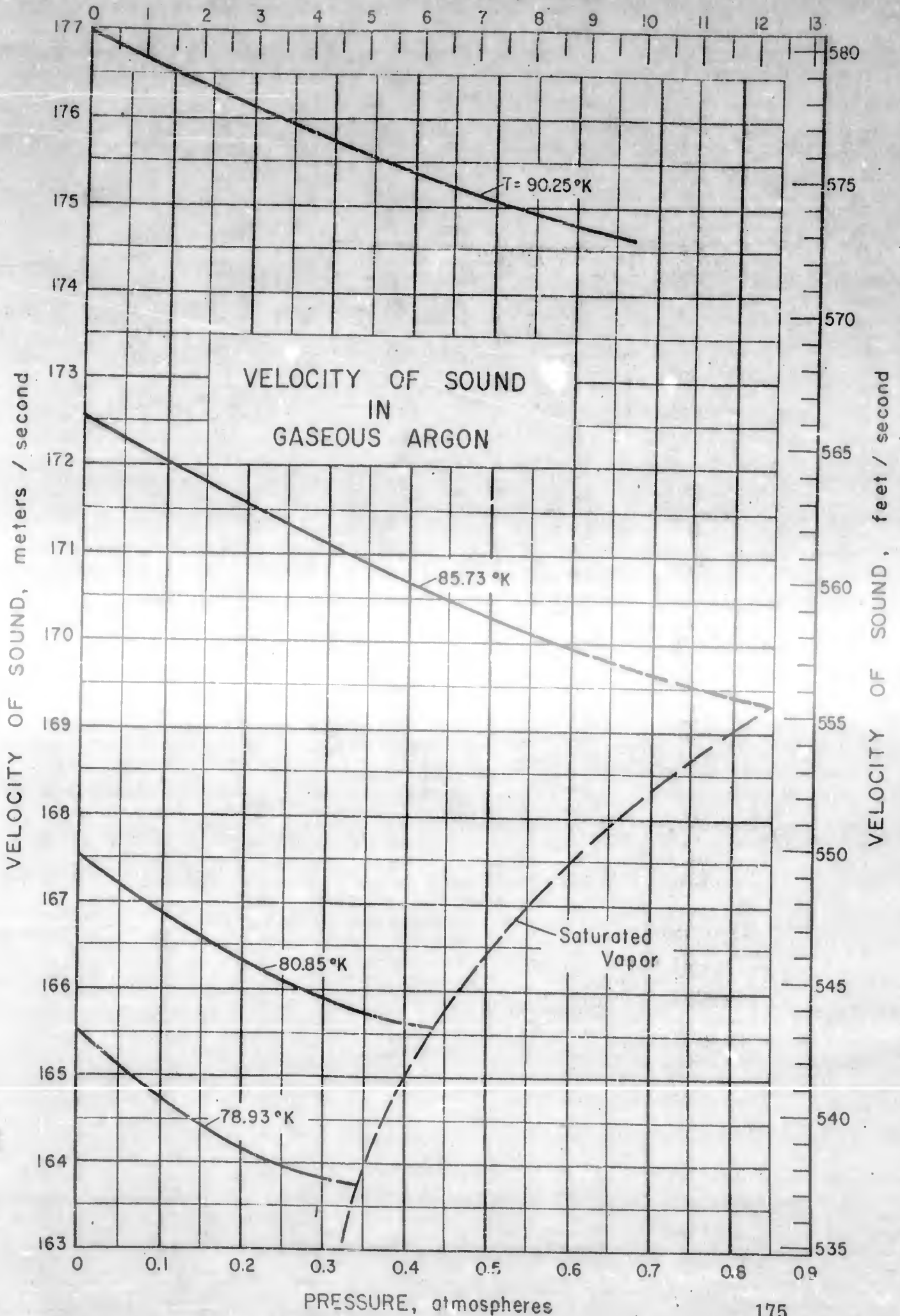
Hilsenrath, et al.	
Pressure, 1 atm.	
Temp. °K	Velocity m/sec
100	184.42
120	202.89
140	219.52
160	235.22
180	249.69
200	263.24
220	276.17
240	288.48
260	300.49
280	311.57

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.

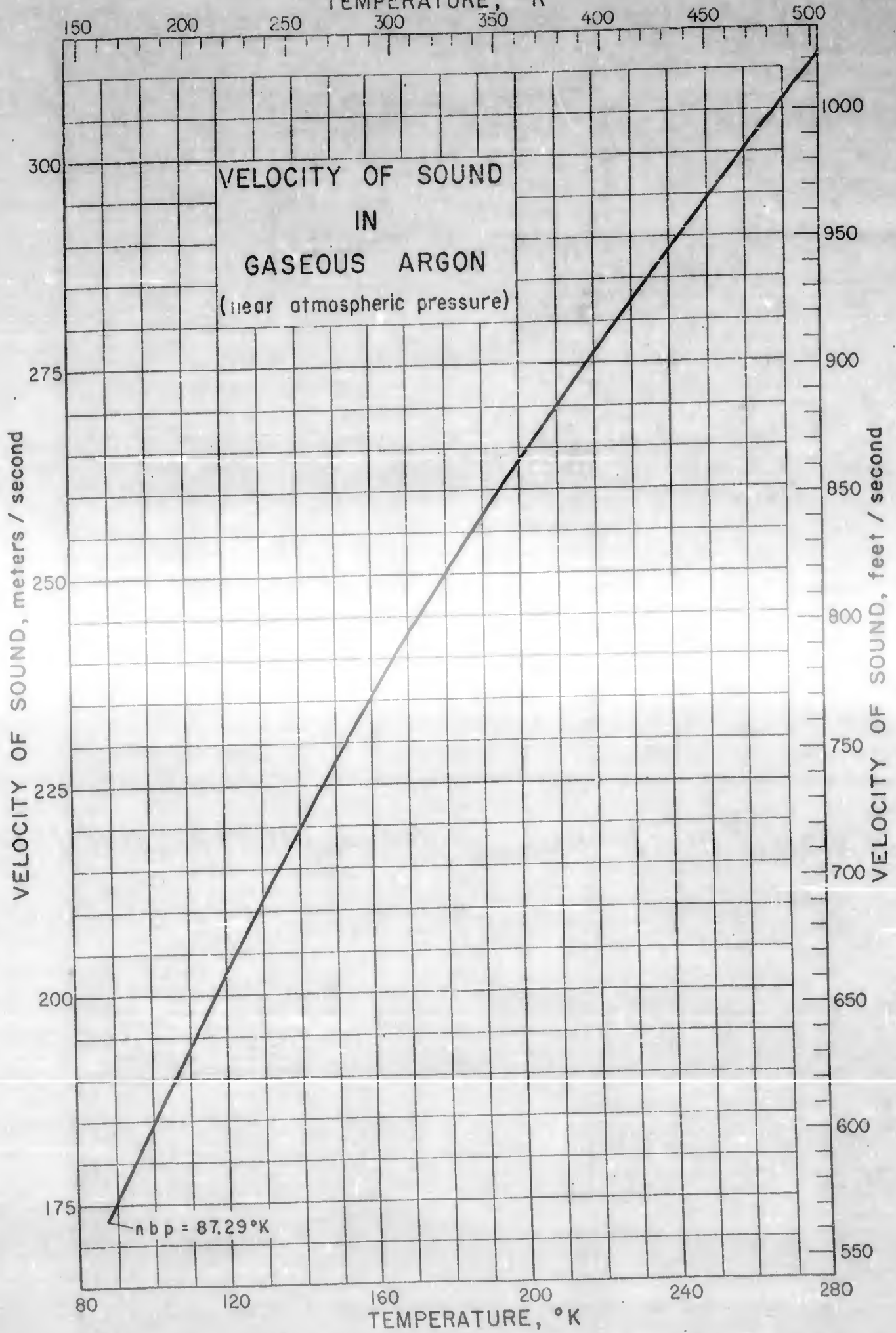
Greenspan determined the attenuation of sound at 11 mc in helium, neon, argon, krypton and xenon at various pressures between atmospheric and a few mm Hg, and compared the results with existing theories.

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.

VELOCITY OF SOUND IN GASEOUS ARGON



15.009  
TEMPERATURE, °R



## 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 ( $0^{\circ}\text{C} = 273.16^{\circ}\text{K}$ ), 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

15.010

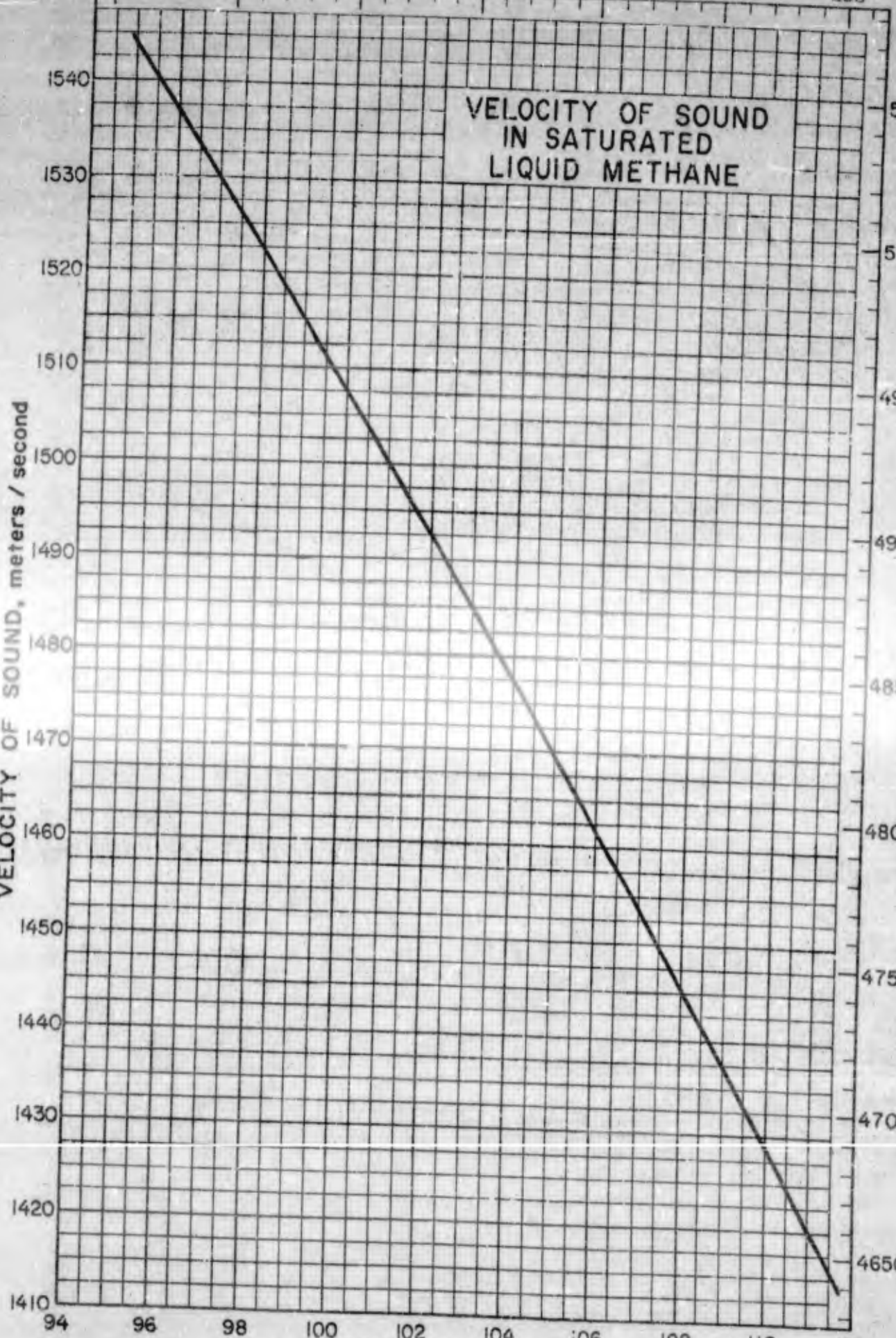
TEMPERATURE, °R

1550 170 175 180 185 190 195 200

VELOCITY OF SOUND  
IN SATURATED  
LIQUID METHANE

VELOCITY OF SOUND, meters / second

VELOCITY OF SOUND, feet / second



TEMPERATURE, °K

1410 94 96 98 100 102 104 106 108 110 112

## 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)

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

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

Noury, J. and Lacame, 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 ( $\rho = 980.665$ ), 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	410.63
		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.

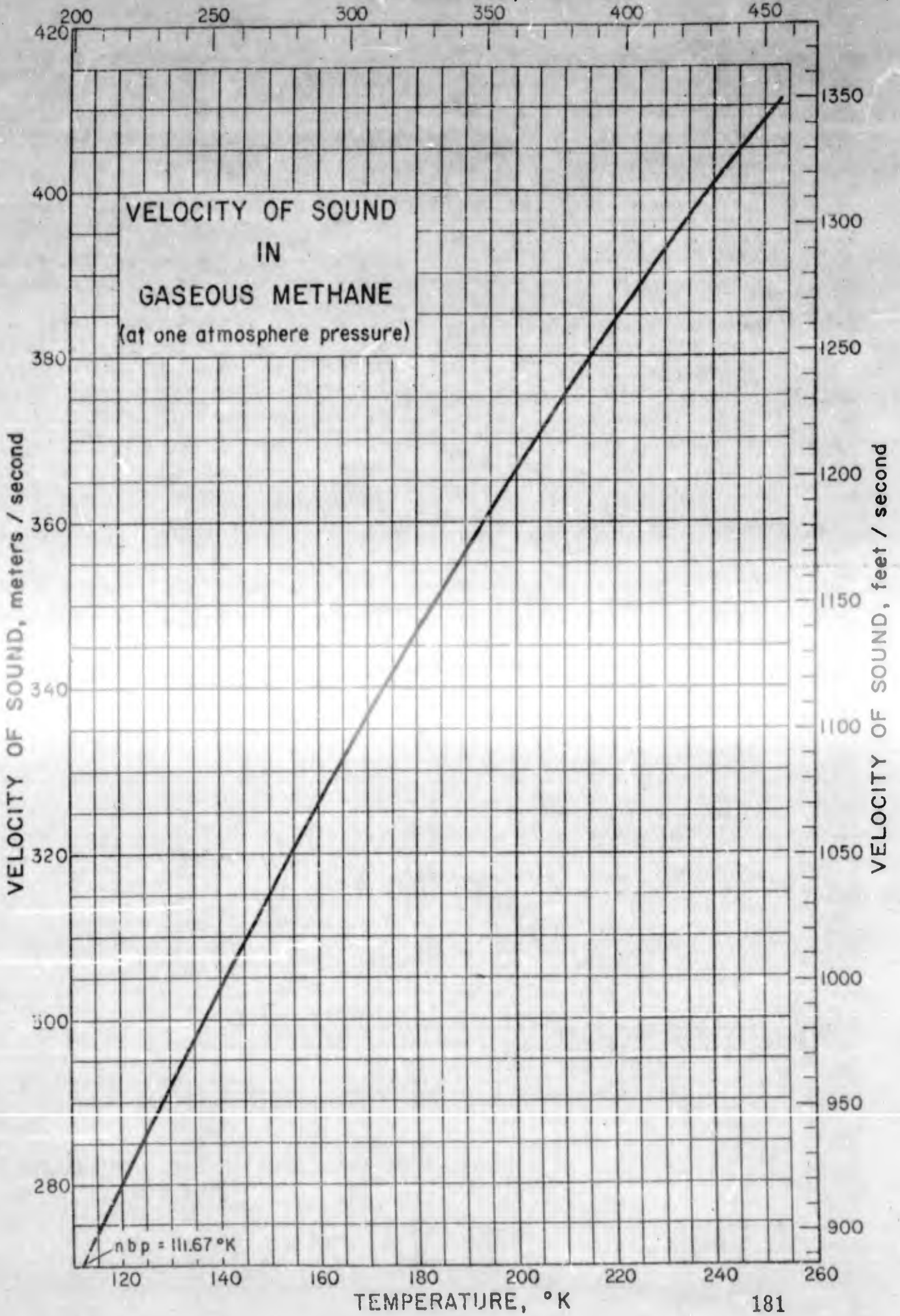
Lacam worked at temperatures of 25 and 50°C, and at pressures between 100 and 900 atmospheres and observed that below 220 atmospheres the velocity increases as the temperature increases, at a given pressure. Above 220 atmospheres the velocity decreases as the temperature increases at a fixed pressure. 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.

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FEEG/RDM/RS      Issued: 4/20/61

15.010  
TEMPERATURE, °R



## 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
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Equilibrium Concentrations of Nitrogen-Oxygen Mixtures .....	16.004/5
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## EQUILIBRIUM CONCENTRATIONS of HELIUM-HYDROGEN MIXTURES

Source of Data:

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

Comments:

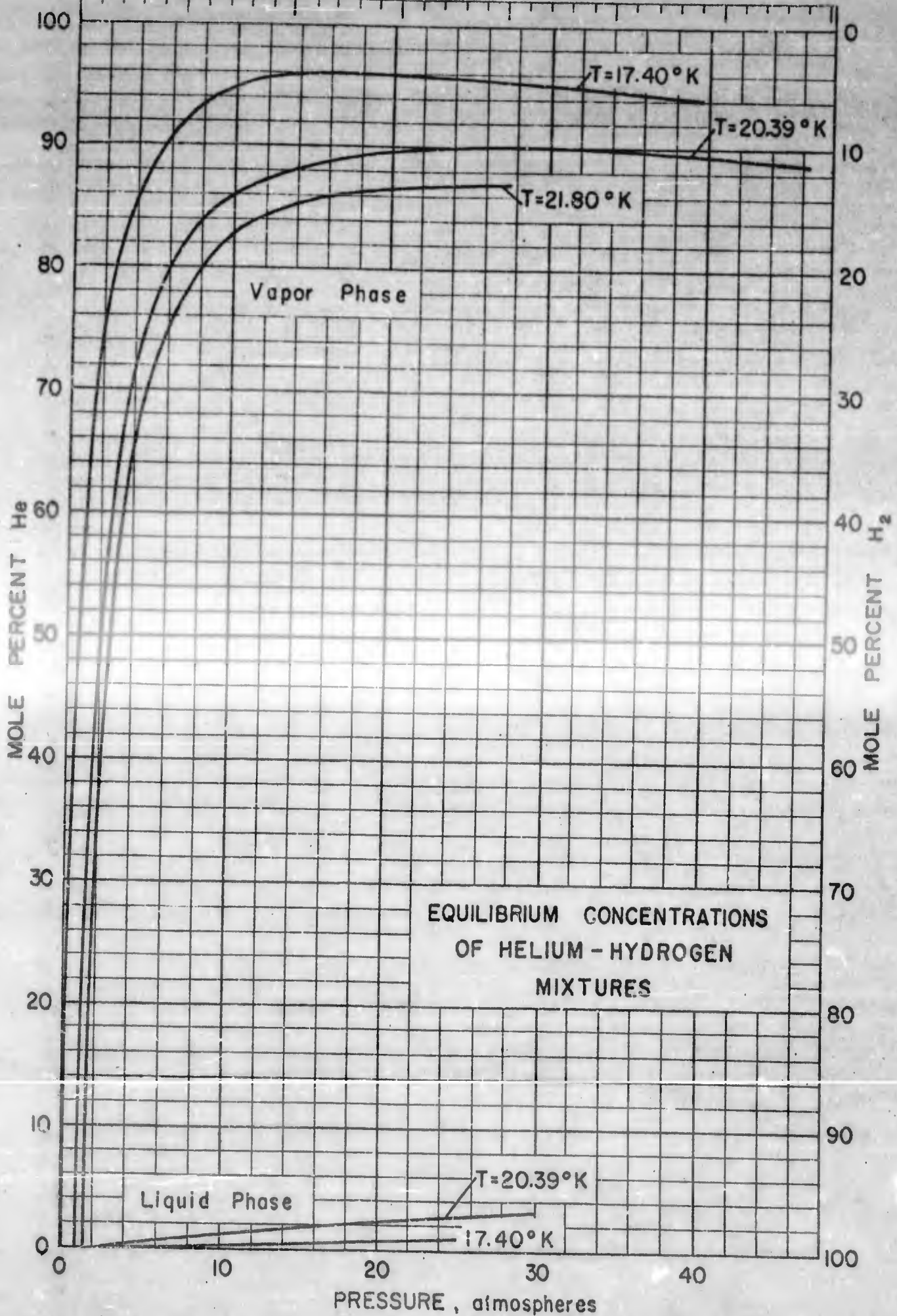
The following tabular data from the dissertation by S. R. Smith, describe the liquid-vapor equilibrium for hydrogen-helium mixtures. These measurements were made at 17.40°, 20.39° and 21.80°K for pressures to about 500 psia where an inversion in the densities of the phases prevented an extension of the 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.

16.001/2

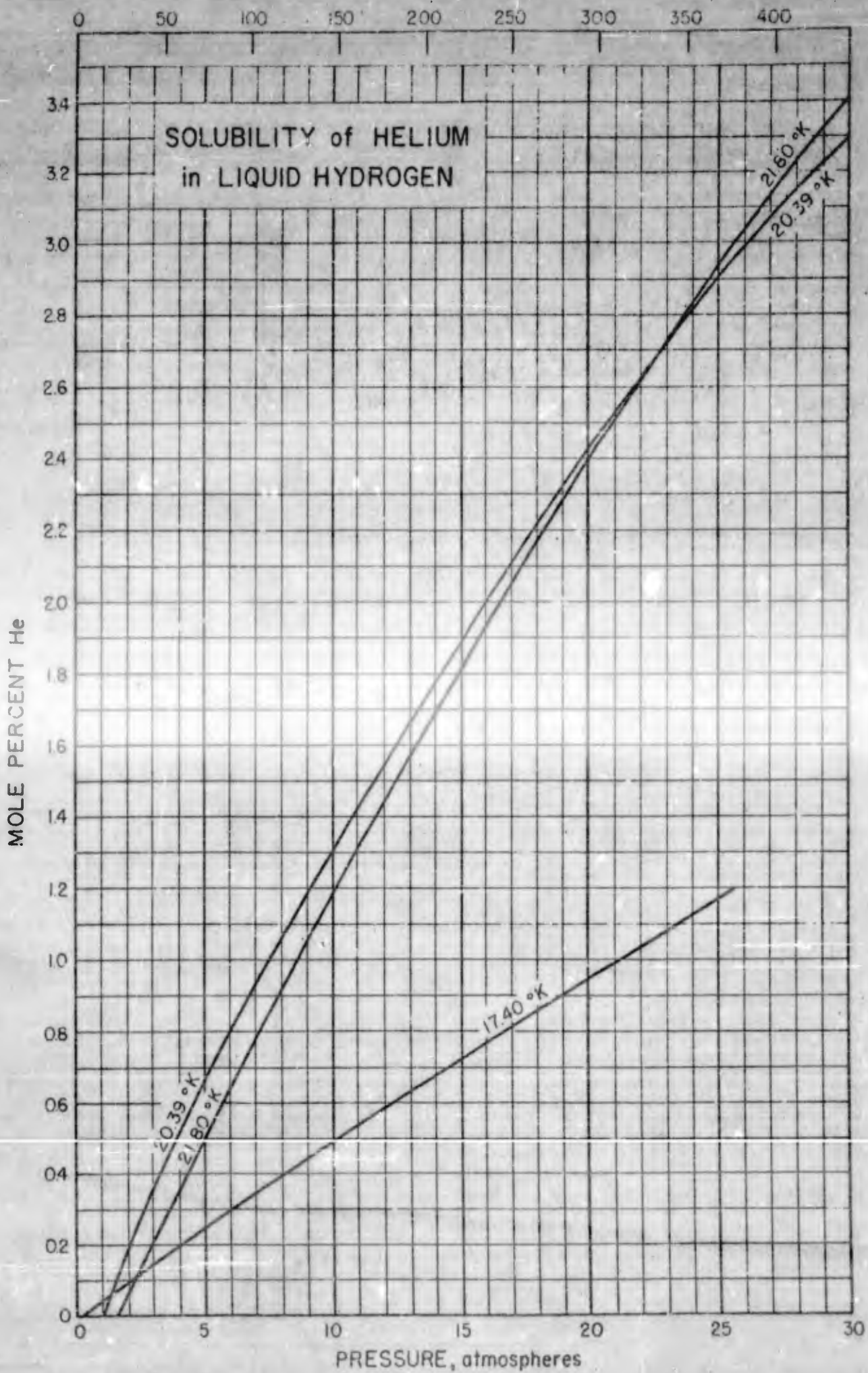
PRESSURE, psic

0 100 200 300 400 500 600 700



EQUILIBRIUM CONCENTRATIONS OF HELIUM - HYDROGEN MIXTURES

16.001/2  
PRESSURE, psia



16.001/2

EQUILIBRIUM CONCENTRATIONS of HELIUM-HYDROGEN MIXTURES  
(Liquid and Vapor Phases)

Press. psia	mole % He		Press. psia	mole % He		Press. psia	mole % He	
	Liquid	Vapor		Liquid	Vapor		Liquid	Vapor
17.40°K			69	--	74.4	396	2.95	--
			69	--	74.0	405	--	90.2
48	0.19	83.4	102	--	82.5	406	3.05	--
48	0.20	83.5	102	0.87	82.6	167	--	88.6
83	0.22	90.1	177	1.53	87.2	475	3.44	--
83	0.28	90.8	177	--	87.3	564	--	89.7
95	0.27	91.8	197	1.63	--	564	--	89.7
95	0.31	91.8	197	1.70	--	629	--	88.3
141	0.45	93.5	222	2.04	--	682	--	88.7
141	0.51	93.4	222	1.98	--	682	--	88.9
157	--	95.5	256	2.16	89.0	852	--	90.9
157	--	95.3	256	2.17	89.3	852	--	90.7
196	--	96.1	256	2.25	--	21.80°K		
196	--	96.2	257	2.16	--	43	0.18	--
207	0.67	94.3	257	2.18	--	43	0.20	--
207	0.74	94.4	291	2.47	90.2	55	--	65.8
236	--	96.3	291	--	90.1	55	--	65.9
236	--	96.2	306	2.53	--	76	--	71.5
267	--	96.3	306	2.48	--	76	--	71.8
267	--	96.3	311	2.55	--	76	--	71.9
316	1.05	95.0	317	2.66	--	82	0.29	--
316	1.08	95.0	317	2.56	--	82	0.21	--
358	1.11	95.2	344	2.82	--	157	1.21	83.6
358	1.15	95.2	350	2.78	--	157	1.36	83.7
473	--	93.6	350	2.77	--	189	--	82.2
473	--	93.6	350	2.58	--	189	--	82.1
525	--	94.4	351	--	89.5	189	--	82.2
525	--	94.3	358	2.77	--	227	1.49	--
579	--	94.2	358	2.64	--	227	1.46	--
579	--	94.2	365	2.95	90.2	306	2.44	--
20.39°K			365	2.97	90.2	306	2.44	--
28	--	61.0	375	2.94	--	386	3.06	87.4
28	--	61.0	375	2.89	--	386	3.13	87.2
63	--	72.9	376	--	90.0	447	--	88.9
63	0.59	72.6	395	--	89.7	447	--	88.7
			395	--	89.8	447	--	88.9
			396	3.01	--			

## 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:

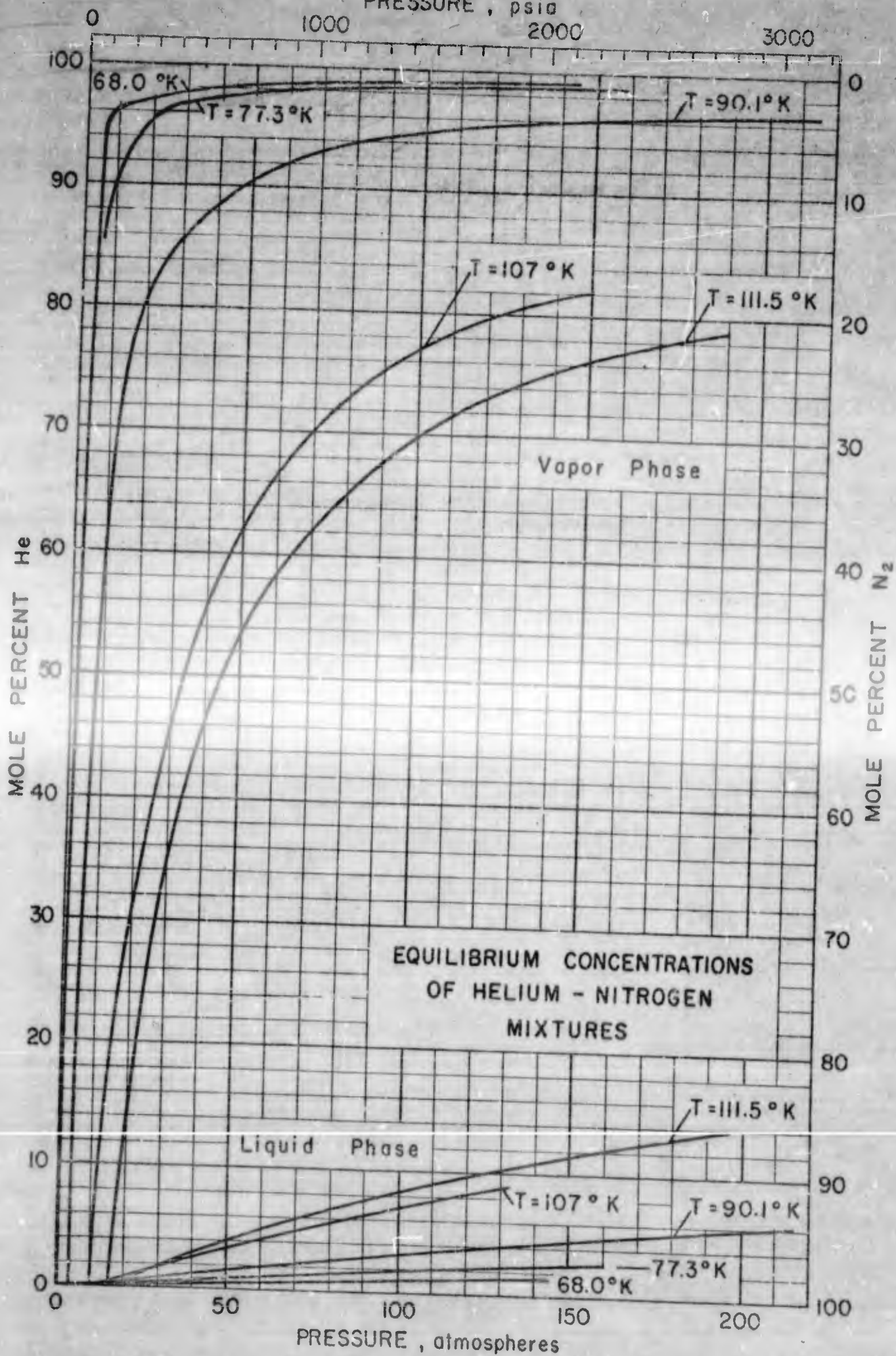
The following tabular data from the reference by Kharakhorin, describe the liquid-vapor equilibrium for helium-nitrogen mixtures. Additional values for this mixture are also reported by Gonikberg and Fastowsky for temperatures of 78°, 90.1° and 109°K and are in fair agreement with the data presented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

VJJ/RS Issued: 9-30-60

16.001/4

PRESSURE, psia

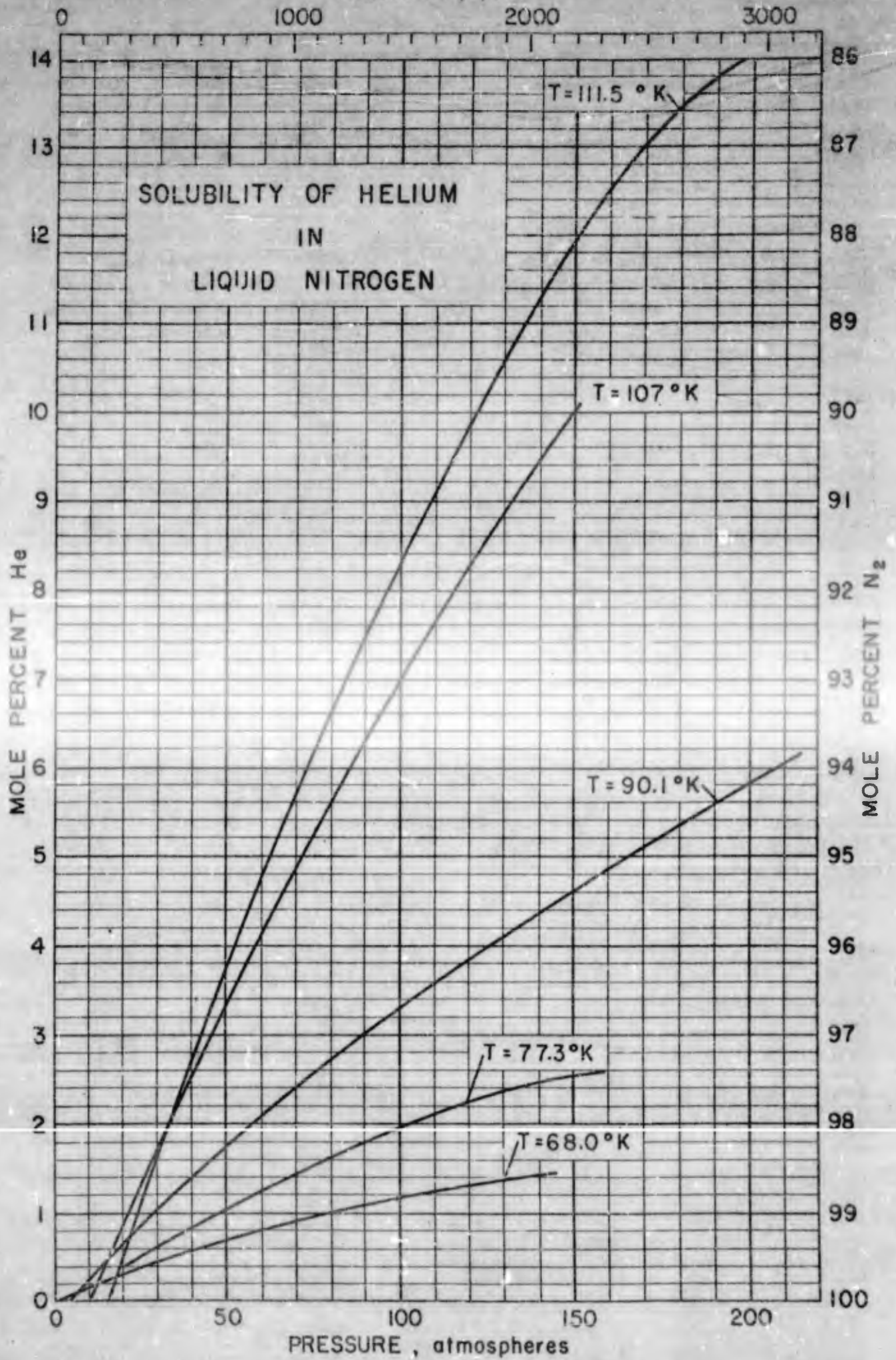


EQUILIBRIUM CONCENTRATIONS OF HELIUM - NITROGEN MIXTURES

PRESSURE, atmospheres

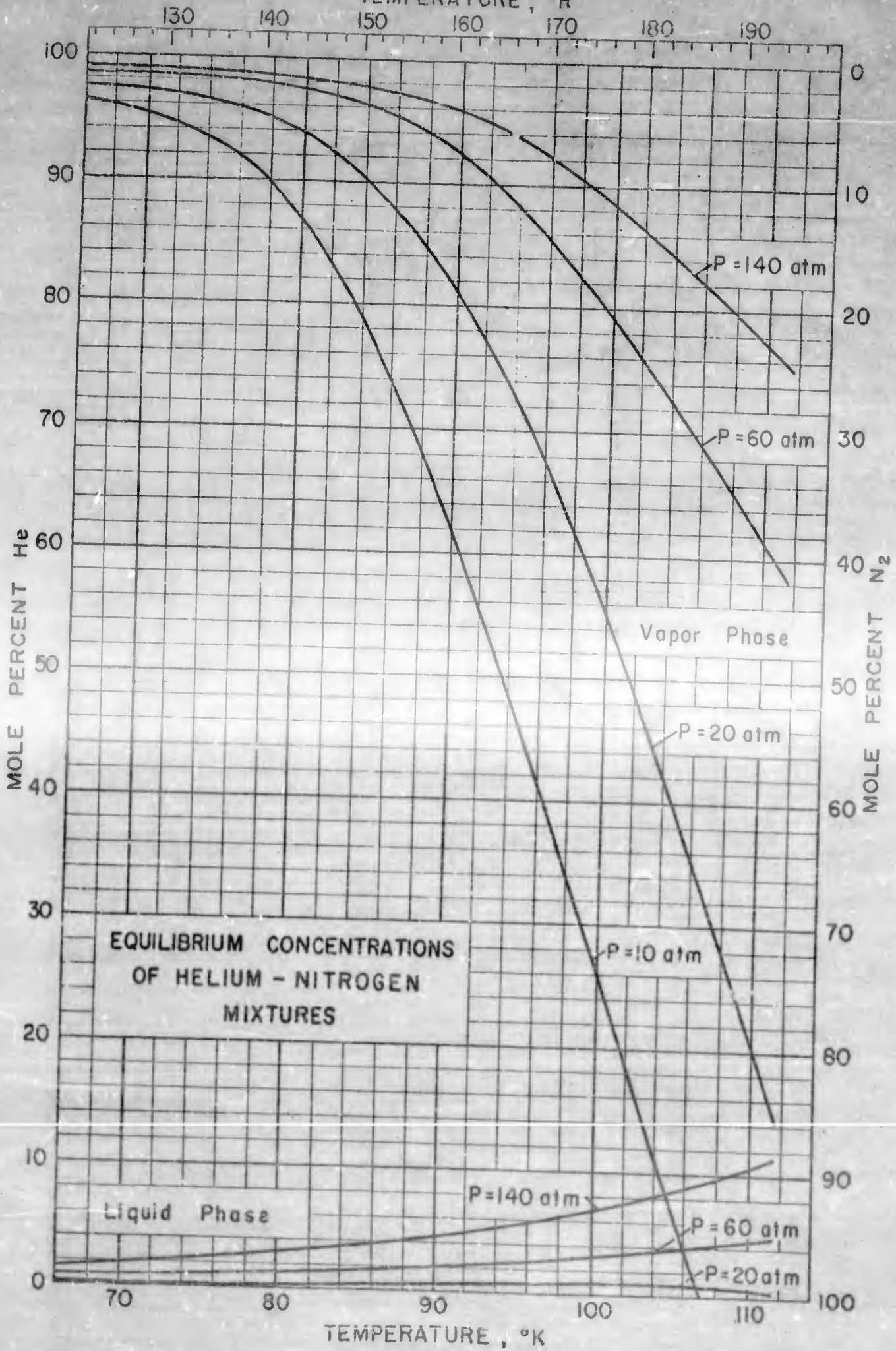
16.001/4

PRESSURE, psia



16.001 / 4

TEMPERATURE, °R



## EQUILIBRIUM CONCENTRATIONS OF HELIUM-NITROGEN MIXTURES

Table of Selected Values  
(Liquid and Vapor Phases)

Press. atm.	Mole % He		Press. atm.	Mole % He		Press. atm.	Mole % He	
	liquid	vapor		liquid	vapor		liquid	vapor
T = 68.0°K			T = 90.1°K			T = 111.5°K		
0.326	0	0	3.60	0	0	23.100	0.85	-
4.480	0.107	83.25	4.84	0.03	15.75	35.000	2.20	52.25
11.620	0.195	96.48	11.65	0.38	62.30	49.800	3.30	61.65
22.300	0.370	97.45	18.50	0.52	80.25	73.800	5.35	71.60
48.500	0.885	98.22	19.10	0.54	80.70	97.000	6.82	76.85
92.750	1.145	98.60	22.30	0.84	81.70	114.000	7.96	79.00
95.700	1.160	98.65	29.00	1.10	85.00	151.000	10.12	82.35
108.000	1.240	98.80	30.00	1.12	85.40	T = 111.5°K		
144.500	1.480	98.96	34.00	1.30	86.95	15.37	0	0
T = 77.3°K			41.00	1.35	88.45	19.40	0.33	13.90
1.00	0	0	48.50	1.62	90.45	20.20	0.37	15.10
4.85	0.098	80.69	58.00	2.08	91.65	22.20	0.65	19.25
11.60	0.300	91.90	67.75	2.27	92.80	24.30	0.80	-
22.30	0.460	96.00	74.00	2.34	92.95	28.30	1.40	-
33.90	0.730	96.59	83.50	2.83	93.80	38.52	2.75	-
48.50	0.960	97.75	87.50	-	94.15	44.80	3.29	50.70
58.60	1.125	98.00	101.50	3.72	94.45	56.25	4.49	56.55
71.25	1.520	98.15	106.50	3.82	95.70	69.00	5.75	61.20
78.00	1.585	98.20	136.00	4.37	95.85	72.50	6.12	61.55
97.30	2.030	98.22	165.50	5.00	95.95	91.00	7.65	68.00
111.40	2.100	-	178.70	5.05	96.10	116.50	9.45	71.95
121.00	2.325	98.30	192.70	5.63	96.27	120.50	9.98	73.15
145.00	2.545	98.47	204.50	6.00	96.21	125.50	10.40	73.95
146.50	2.550	98.53	214.50	6.18	96.53	134.00	10.80	73.75
158.20	2.715	98.60	T = 107°K			140.50	11.45	75.40
158.50	2.740	98.74	10.205	0	0	174.70	13.10	78.05
						195.00	13.95	79.00

## 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:

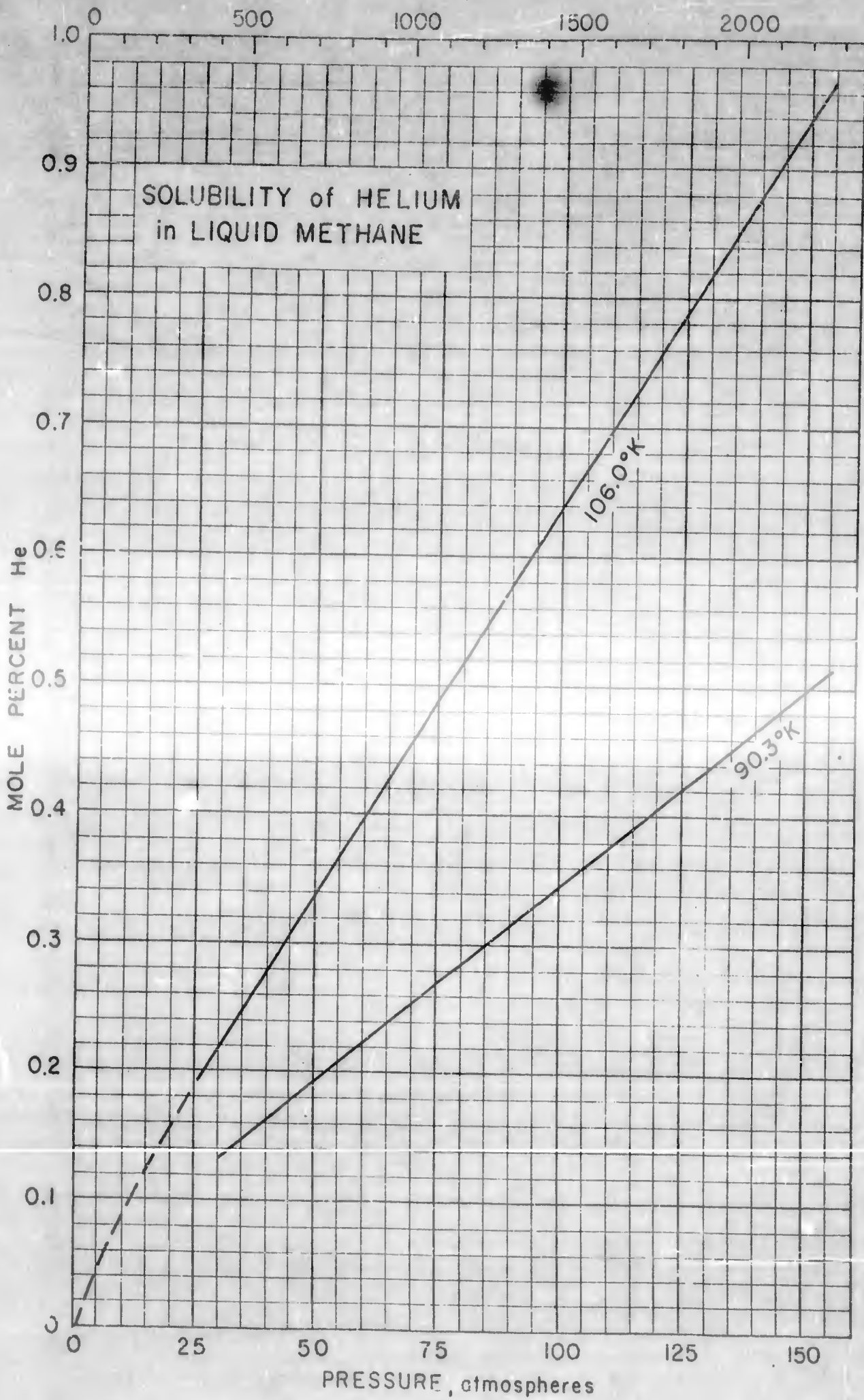
The data for the solubility of helium in liquid methane are from the experimental results of Gonikberg and Fastowsky. The value of the vapor pressure of methane at 106°K ( $P = 0.61$  atm. at 0% He), however, was determined from values listed by Matthew and Hurd.

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

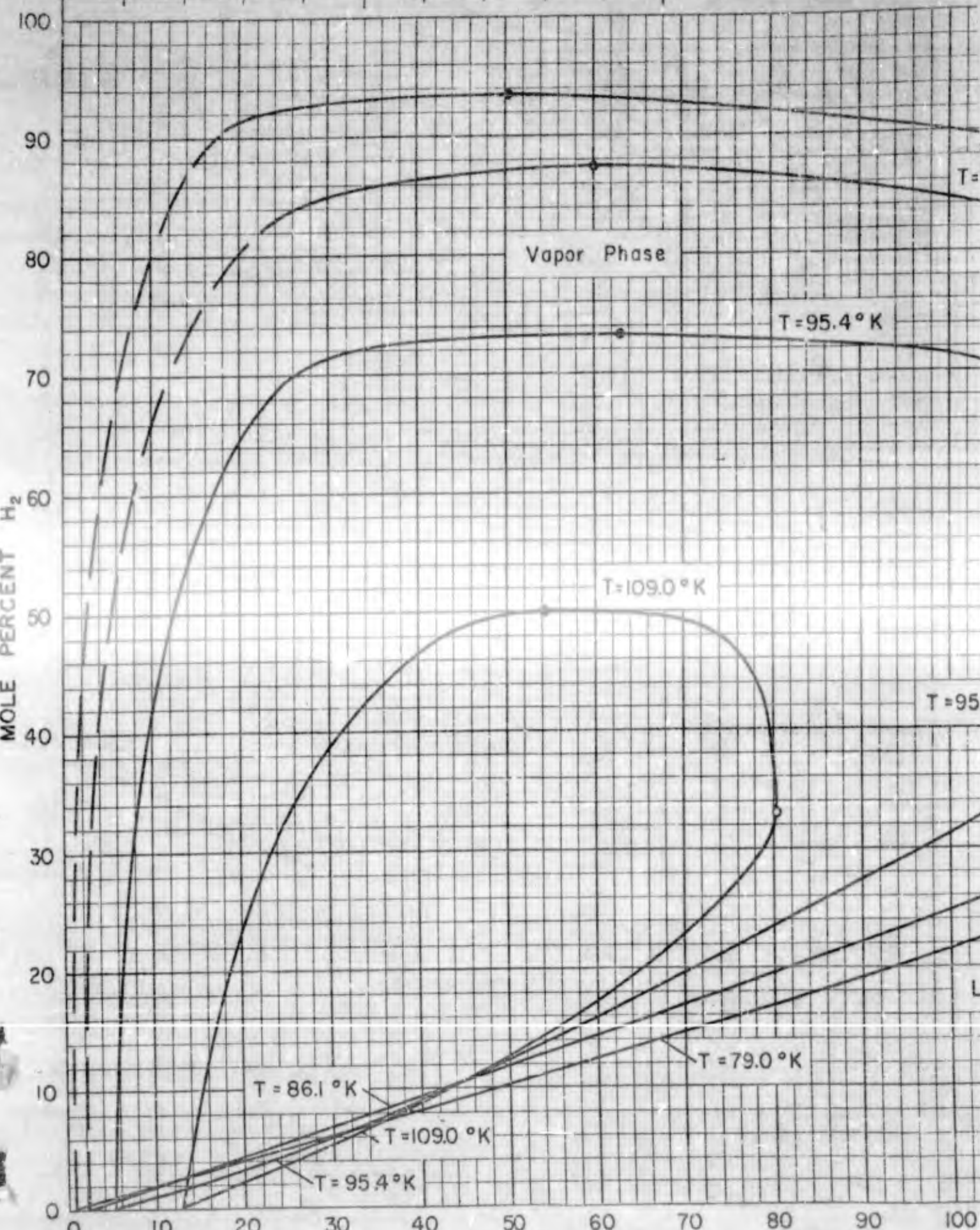
Pressure		Mole % He in liq. CH <sub>4</sub>	Pressure		Mole % He in liq. CH <sub>4</sub>
atm.	kg/cm <sup>2</sup>		atm.	kg/cm <sup>2</sup>	
T = 90.3°K			T = 106.0°K		
29.0	30	0.13	25.2	26	0.19
75.5	78	0.27	59.0	61	0.39
94.8	98	0.32	96.8	100	0.63
112	116	0.37	144	149	0.90
135	139	0.46	155	160	0.97
157	162	0.52			

16.001 / 10  
PRESSURE, psia

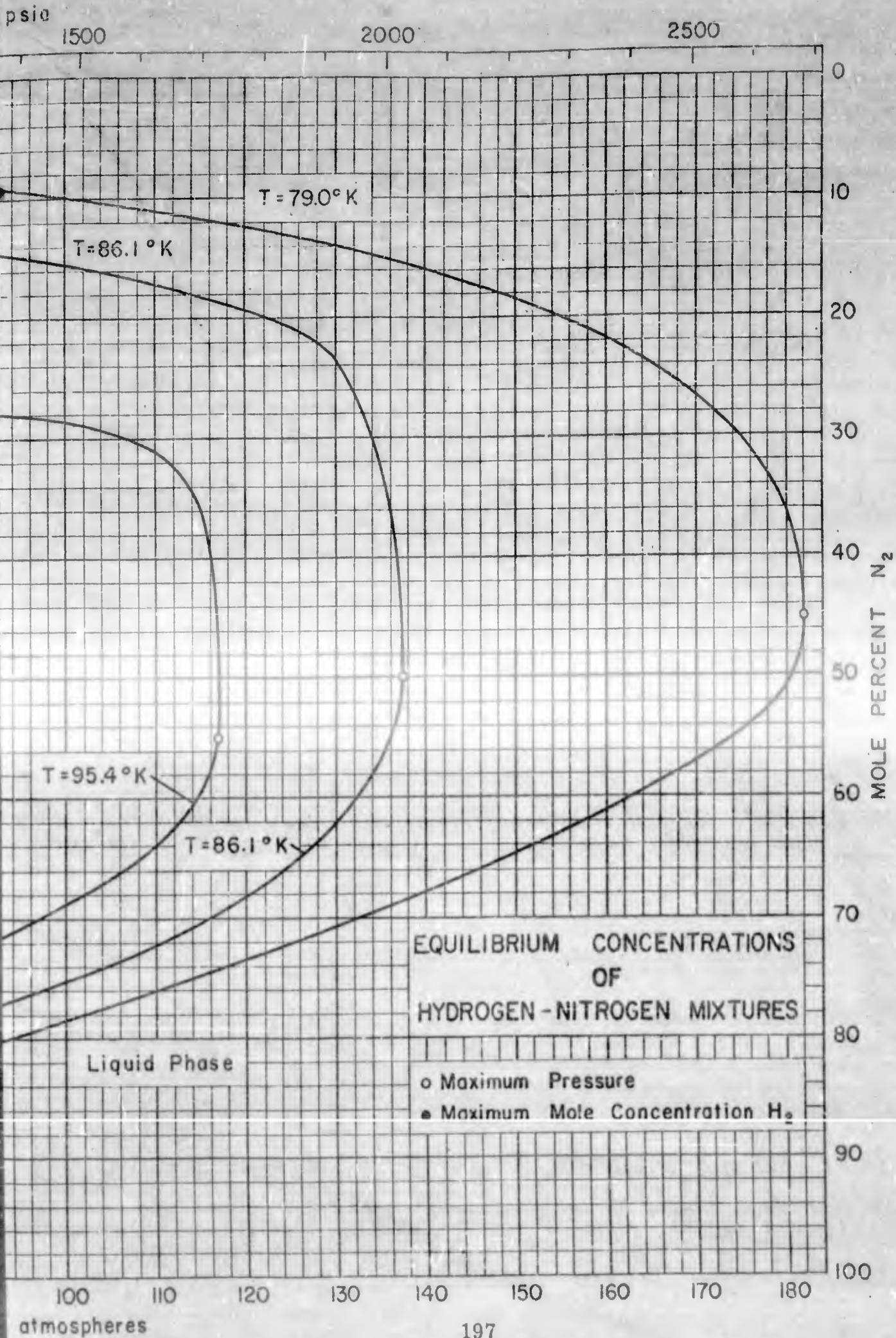


0 500 1000 1500

MOLE PERCENT H<sub>2</sub>



PRESSURE, 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)
- Verschöyle, 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:

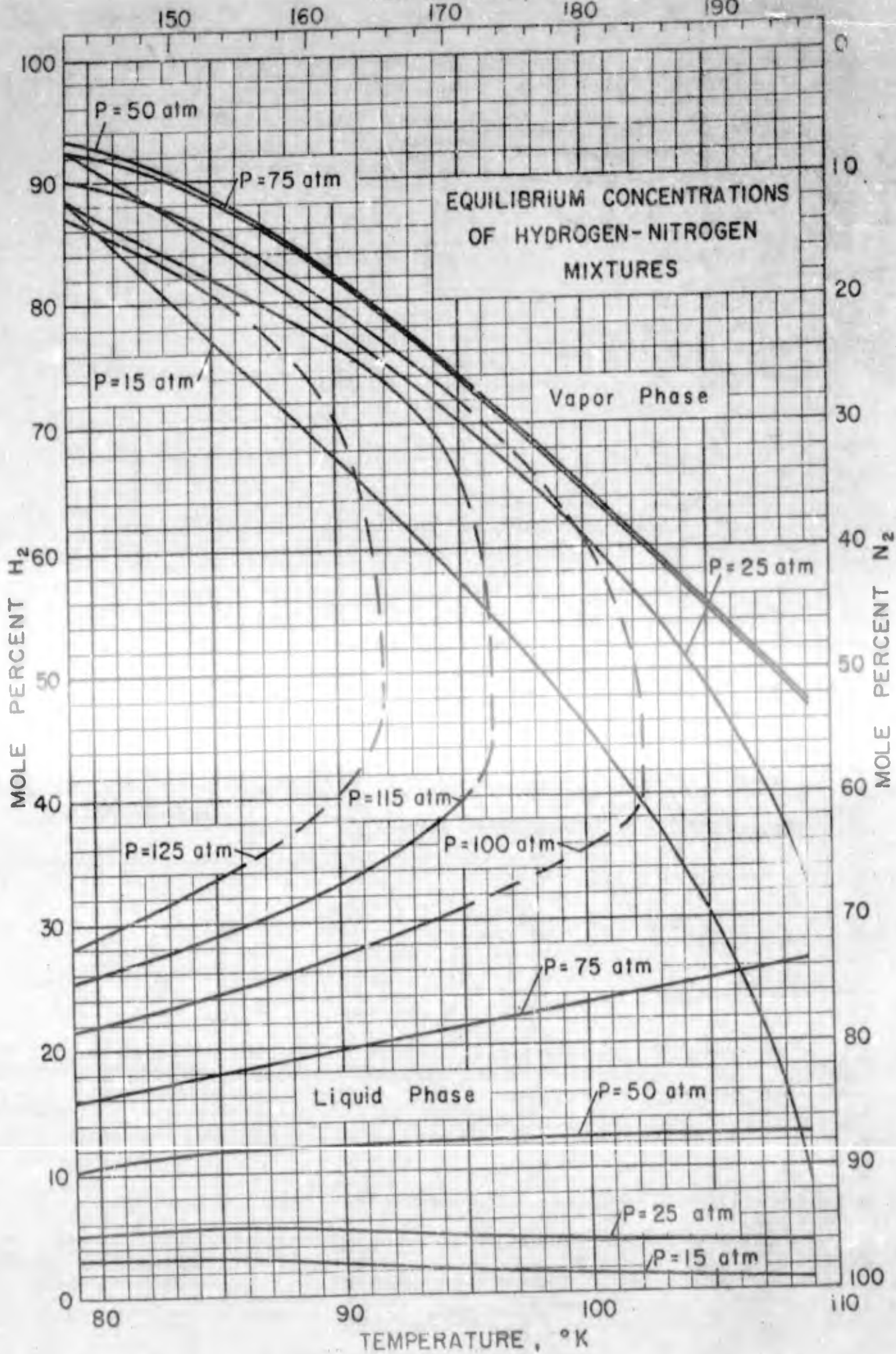
The following tables of data from the paper by Gonikberg, Fastowsky and Gurwitsch, describe the liquid-vapor equilibrium for hydrogen-nitrogen mixtures: The following graphs have been constructed from this data; the first presents the data for the liquid and vapor phases as isotherms ( $T = C$ ) on coordinates 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  $90^\circ$  and  $95^\circ\text{K}$  with pressures to 660 psia and Eubanks reports values at  $-310^\circ$ ,  $-280^\circ$  and a few points at  $-240^\circ\text{F}$  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.

Comparison of Equilibrium Concentrations as reported by Gonikberg and Eubanks (X = mole percent hydrogen)					
Press. atm.	$X_{\text{Gon.}} - X_{\text{Eub.}}$		Press. atm.	$X_{\text{Gon.}} - X_{\text{Eub.}}$	
	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.	$X_{\text{Gon.}} - X_{\text{M.-B.}}$		Press. atm.	$X_{\text{Gon.}} - X_{\text{M.-B.}}$	
	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



## EQUILIBRIUM CONCENTRATION OF HYDROGEN-NITROGEN MIXTURES

Table of Selected Values

Pressure		Mole % H <sub>2</sub>		Pressure		Mole % H <sub>2</sub>	
atm.	kg/cm <sup>2</sup>	liquid	vapor	atm.	kg/cm <sup>2</sup>	liquid	vapor
T = 79.0°K				122.1	126	33.7	80.1
1.16	1.2	0	0	129.8	134	37.5	77.0
18.3	18.9	4.2	91.0	136.6	141	43.0	56.6
33.3	34.4	6.9	-	137.4 †	142 †	50	50
50.3	52	-	93.5*	T = 95.4°K			
51.3	53	10.7	93.6	5.33	5.5	0	0
66.8	69	15.8	92.2	13.08	13.5	2.7	51.6
78.5	81	17.3	91.3	24.9	25.7	4.2	69.2
94.9	98	19.9	91.5	42.4	43.8	10.2	73.0
99.8	103	21.3	90.2	61.0	63	16.2	73.3
107.5	111	22.4	88.9	62.9	65	-	73.2*
120.2	124	26.6	-	76.5	79	22.1	72.7
120.1	126	27.1	-	91.1	94	27.7	72.2
143.4	148	33.7	82.0	109.5	113	39.4	69.1
153.1	158	36.4	80.5	115.3	119	41.7	63.5
175.3	181	45.7	69.7	116.2	120	43.2	47.3
182.0 †	188 †	55	55	117.1 †	121 †	45	45
T = 86.1°K				T = 109°K			
2.42	2.5	0	0	12.9	13.3	0	0
23.34	24.1	5.2	83.0	19.0	19.6	1.8	20.7
43.6	45.0	9.8	86.5	33.9	35.0	-	42.3
60.0	62	-	87.5*	44.9	46.4	10.3	48.9
66.8	69	16.0	-	54.2	56	-	50.2*
77.5	80	-	87.0	57.2	59	15.6	50.0
102.7	106	25.5	84.1	77.5	80	28.4	45.7
109.5	113	26.9	-	80.3 †	83 †	33	33

\*maximum mole concentration  
† maximum pressure

## EQUILIBRIUM CONCENTRATIONS of HYDROGEN-CARBON MONOXIDE MIXTURES

Sources of Data:

Verschoye, 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 Verschoye and by Eubanks. The data reported by Verschoye 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, Verschoye lists the points of maximum pressure and of maximum mole concentration, H<sub>2</sub>, 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.

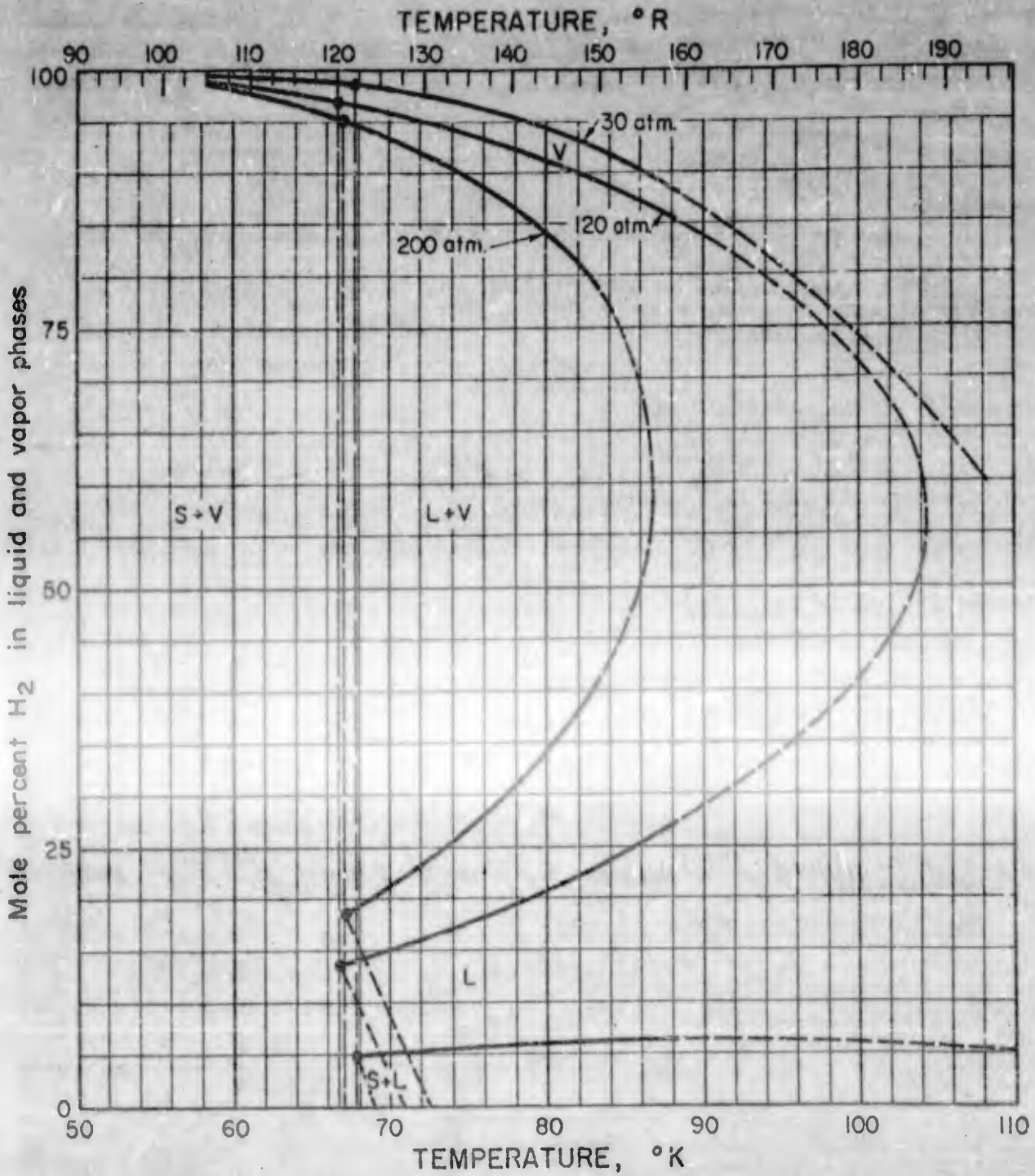
The lack of agreement of the data from these two references is indicated by the values reported by both sources for 83.15°K which was the only temperature common to both. These data may be compared on the following P - X graph. It should also be noted that Verschoye's data for the liquid and the vapor 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 Verschoye's paper, and give H<sub>2</sub>-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.

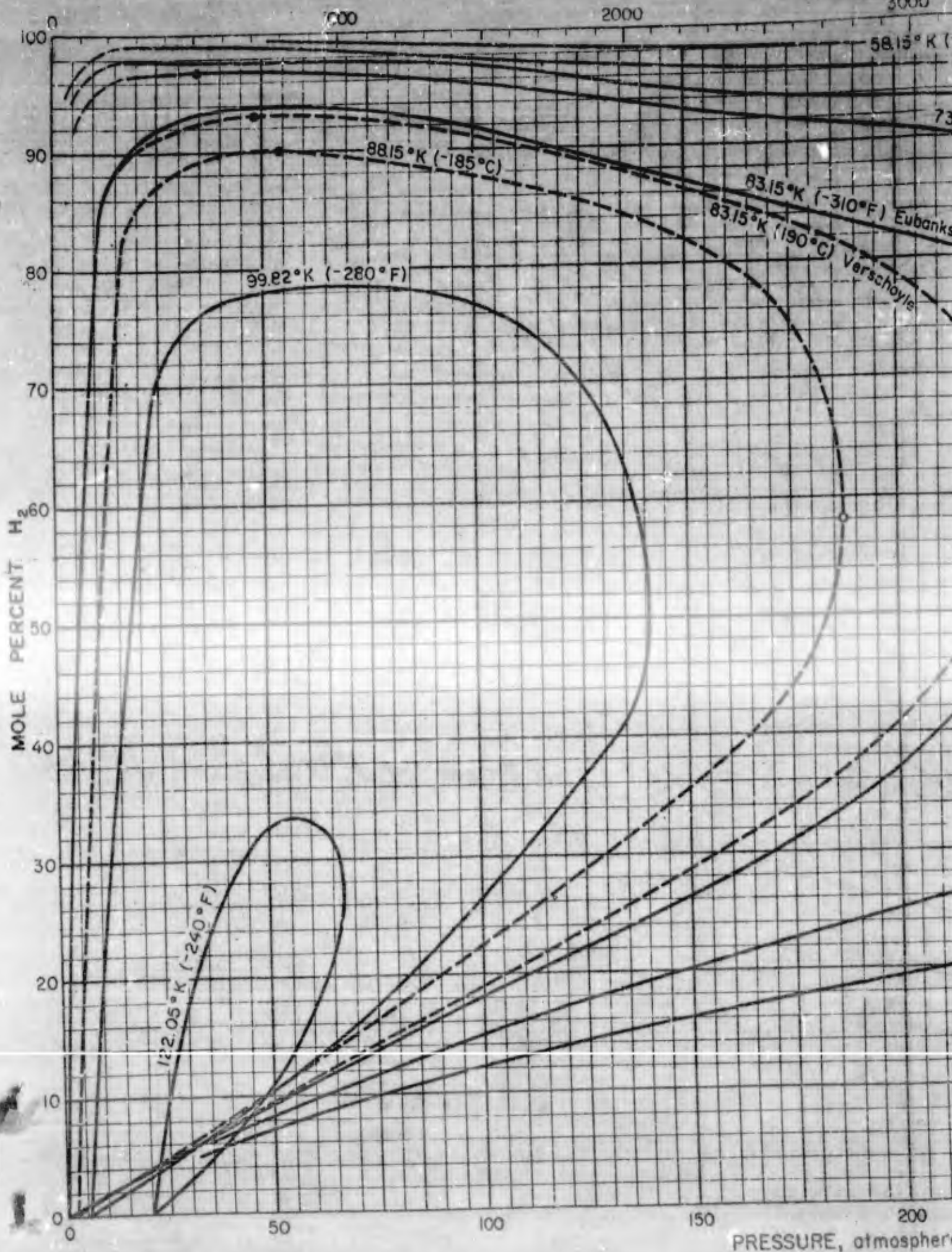
Selected Values of the H<sub>2</sub>-CO, Three-Phase Curve

Pressure atm.	Temperature °C
55.2	-206.12
104.1	-206.59
147.4	-206.67
205.5	-206.39

EQUILIBRIUM CONCENTRATIONS of HYDROGEN-CARBON MONOXIDE MIXTURES



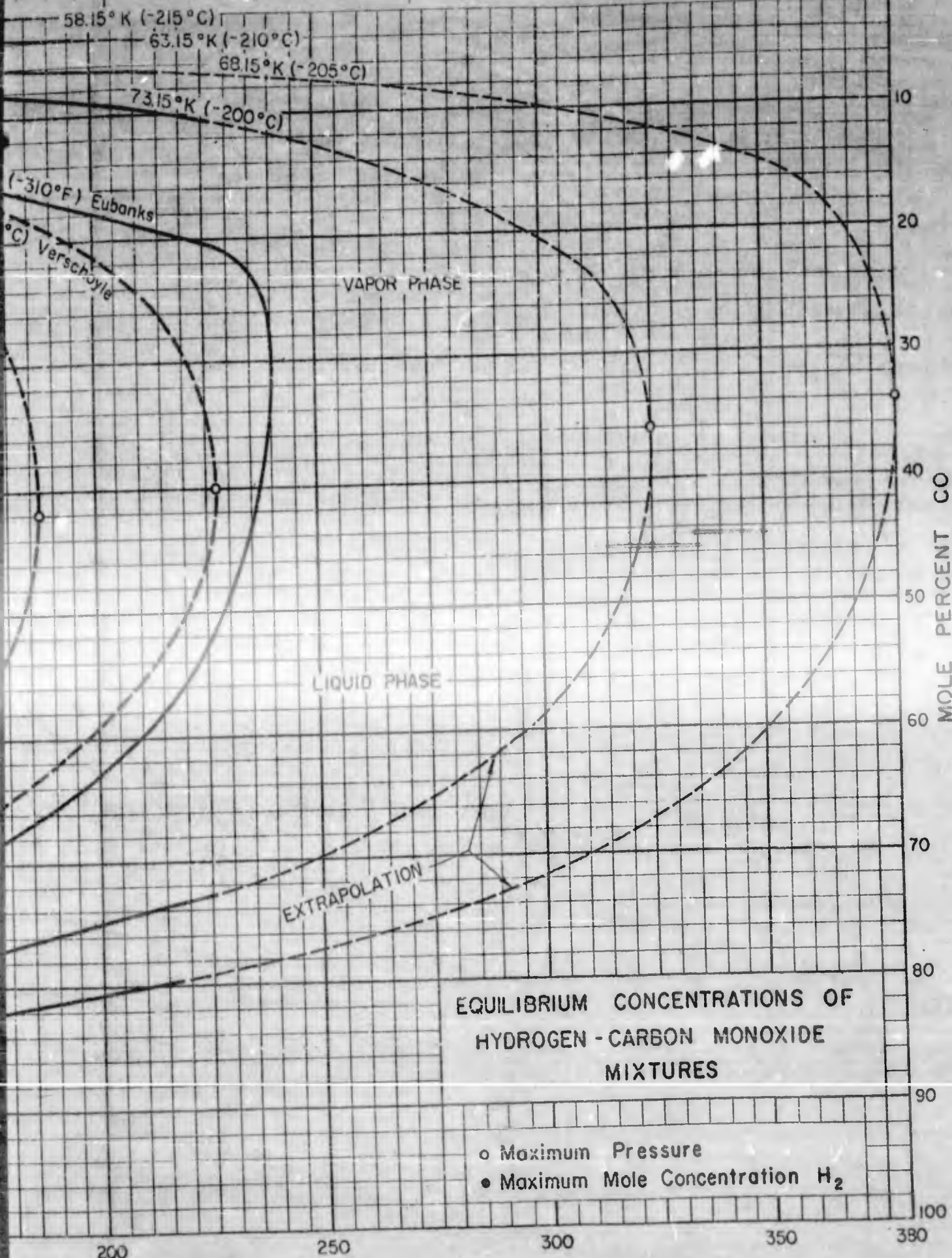
PRESSURE, psia  
3000



PRESSURE, atmospheres

002/7

PRESSURE, psia  
3000 4000 5000



EQUILIBRIUM CONCENTRATIONS OF  
HYDROGEN - CARBON MONOXIDE  
MIXTURES



## EQUILIBRIUM CONCENTRATIONS of HYDROGEN-CARBON MONOXIDE MIXTURES

## Tables of Selected Values

Verschoyle		Verschoyle (cont.)			Verschoyle (cont.)		
Press. atm.	Mole % H <sub>2</sub> in Vapor	Press. atm.	Mole % H <sub>2</sub>		Press. atm.	Mole % H <sub>2</sub>	
			in Liq.	in Vapor		in Liq.	in Vapor
-215°C (58.15°K) ±.06°		-205°C (68.15°K) ±.04°			-190°C (83.15°K) ±.04°		
(0.018)	(0.0)	(0.15)	(0.0)	(0.0)	1.18	0.00	0.0
51.37	99.47	17.02	3.0	97.9	17.2	2.7	89.9
89.52	98.90	21.69	3.3	98.2	†48.	---	†93.
		26.61	4.2	97.6	51.2	12.5	93.2
128.05	98.50				89.3	17.0	92.0
157.03	98.08	31.67	4.9	98.6	109.8	21.0	90.7
176.37	98.18	41.45	6.3	97.5	128.1	25.4	88.8
		79.89	10.2	97.7	166.8	32.9	84.3
		118.38	13.8	96.5	176.4	34.4	83.1
		152.33	16.3	94.6	186.1	36.8	80.8
-210°C (63.15°K) ±.03°		190.97	18.8	93.9	190.9	38.1	80.5
(0.052)	(0.0)	215.16	20.2	93.4	195.8	40.1	79.5
16.81	99.22	380*	66	66	200.6	41.5	77.7
21.85	99.12	-200°C (73.15°K) ±.04°			205.4	43.5	76.6
		0.33	0.0	0.0	210.4	44.8	75.9
32.03	99.18	17.3	3.3	96.7	215.1	47.0	73.7
65.74	98.76	22.2	---	95.4	220.9	48.6	69.4
79.80	97.42	31.5	---	96.4	224.8	54.1	66.3
		31.8	5.6	97.5	228*	60	60
104.01	97.80	†34.	---	†97.5	-185°C (88.15°K) ±.03°		
137.76	97.03	50.9	---	97.0	2.18	0.0	0.0
147.39	96.88	51.0	8.4	96.7	17.2	3.6	84.0
		79.7	---	96.3	22.1	5.2	86.6
176.41	96.53	80.2	12.7	95.9	31.4	7.1	88.8
195.75	96.31	113.9	16.6	95.1	†54.	---	†90.
		128.0	---	94.2	55.9	13.4	90.2
		142.5	---	93.5	89.6	21.7	88.7
		152.4	20.6	93.0	128.2	30.3	84.8
		176.4	23.0	92.0	166.7	41.0	77.1
		186.2	23.6	91.4	181.3	45.4	70.4
		205.6	25.0	91.2	187*	58	58
		224.9	27.5	89.0			
		325*	64	64			

† Maximum mole % H<sub>2</sub>

\* Maximum pressure

WIDE MIXTURES

Perchoyle (cont.)

Eubanks

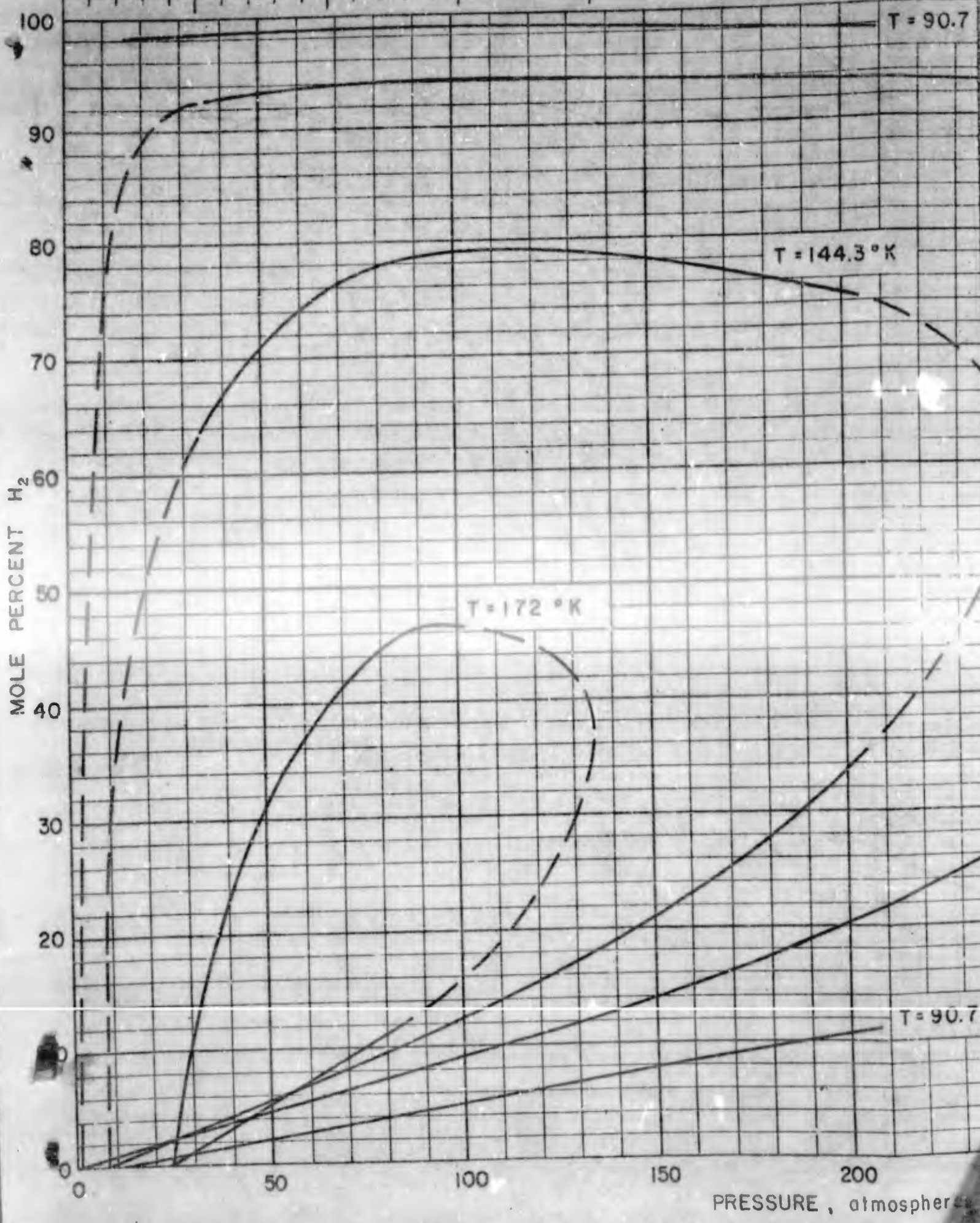
	Mole % H <sub>2</sub>	
	in Liq.	in Vapor
0°C (83.15°K) ±.04°		
8	0.00	0.0
	2.7	89.9
	---	*93.
	12.5	93.2
	17.0	92.0
	21.0	90.7
	25.4	88.8
	32.9	84.3
	34.4	83.1
	36.8	80.8
	38.1	80.5
	40.1	79.5
	41.5	77.7
	43.5	76.6
	44.8	75.9
	47.0	73.7
	48.6	69.4
	54.1	66.3
	60	60
5°C (88.15°K) ±.03°		
	0.0	0.0
	3.6	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
	45.1	70.1
	58	58

Pressure		Mole % H <sub>2</sub>	
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

10.000.717  
PRESSURE, psia

0 500 1000 1500 2000 2500 3000



PRESSURE, atmospheres

sia

3500 4000 4500 5000 5500 6000

T = 90.7 ° K

T = 116.5 ° K

Vapor Phase

K

0  
10  
20  
30  
40  
50  
60  
70  
80  
90  
100  
MOLE PERCENT CH<sub>4</sub>

Liquid Phase

T = 90.7 ° K

EQUILIBRIUM CONCENTRATIONS  
OF  
HYDROGEN - METHANE MIXTURES

250 300 350 400

pheres

205

7

## 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, 427-2 (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, 236-241 (1957)

Comments:

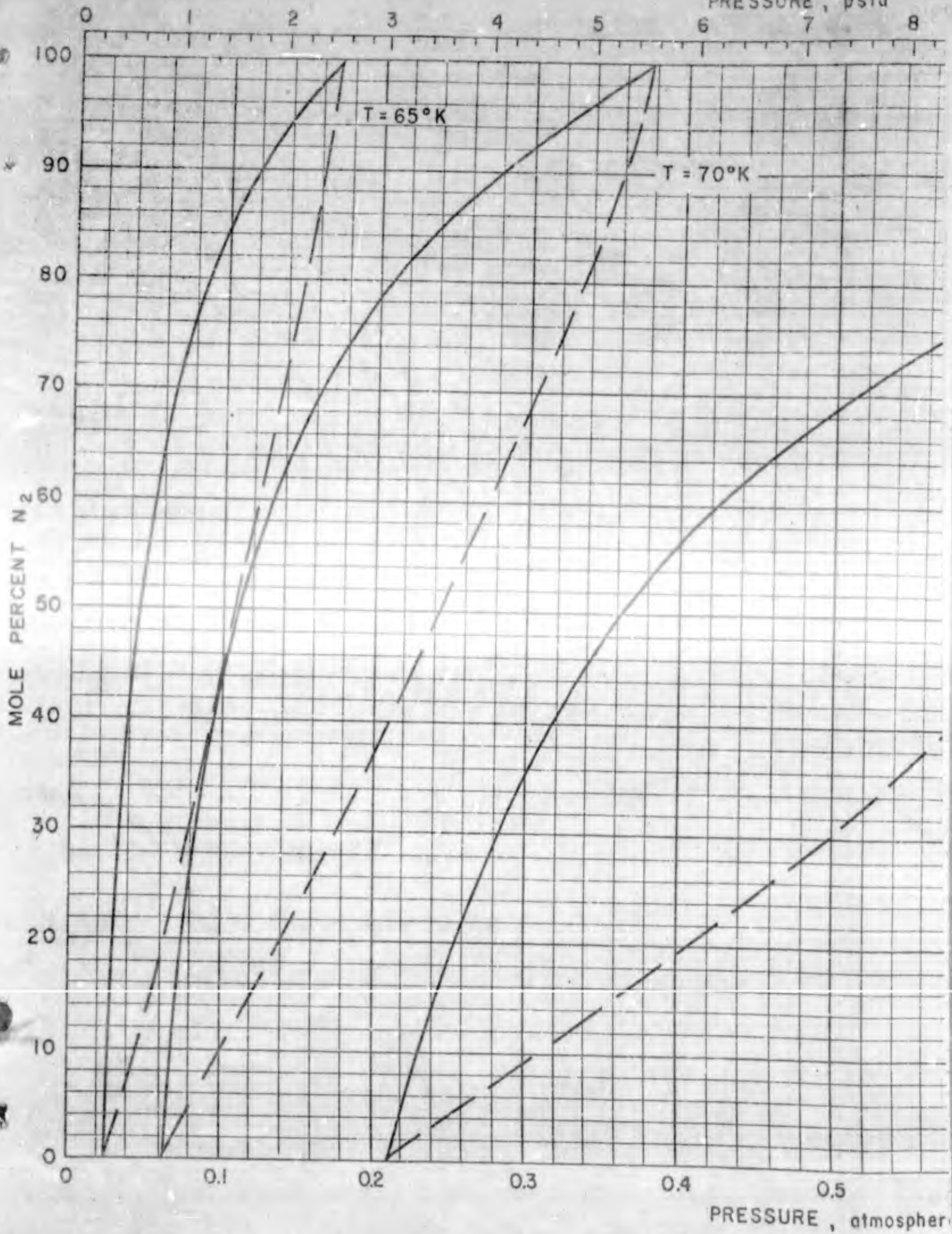
The following tabular data from the references listed above as sources of data, are for the liquid-vapor equilibrium of hydrogen-methane mixtures. The data reported by Benham and Katz are pressure-concentration data for temperatures of 116.5°, 144.3°, 172°K. The data for 90.7°K are from the paper by 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

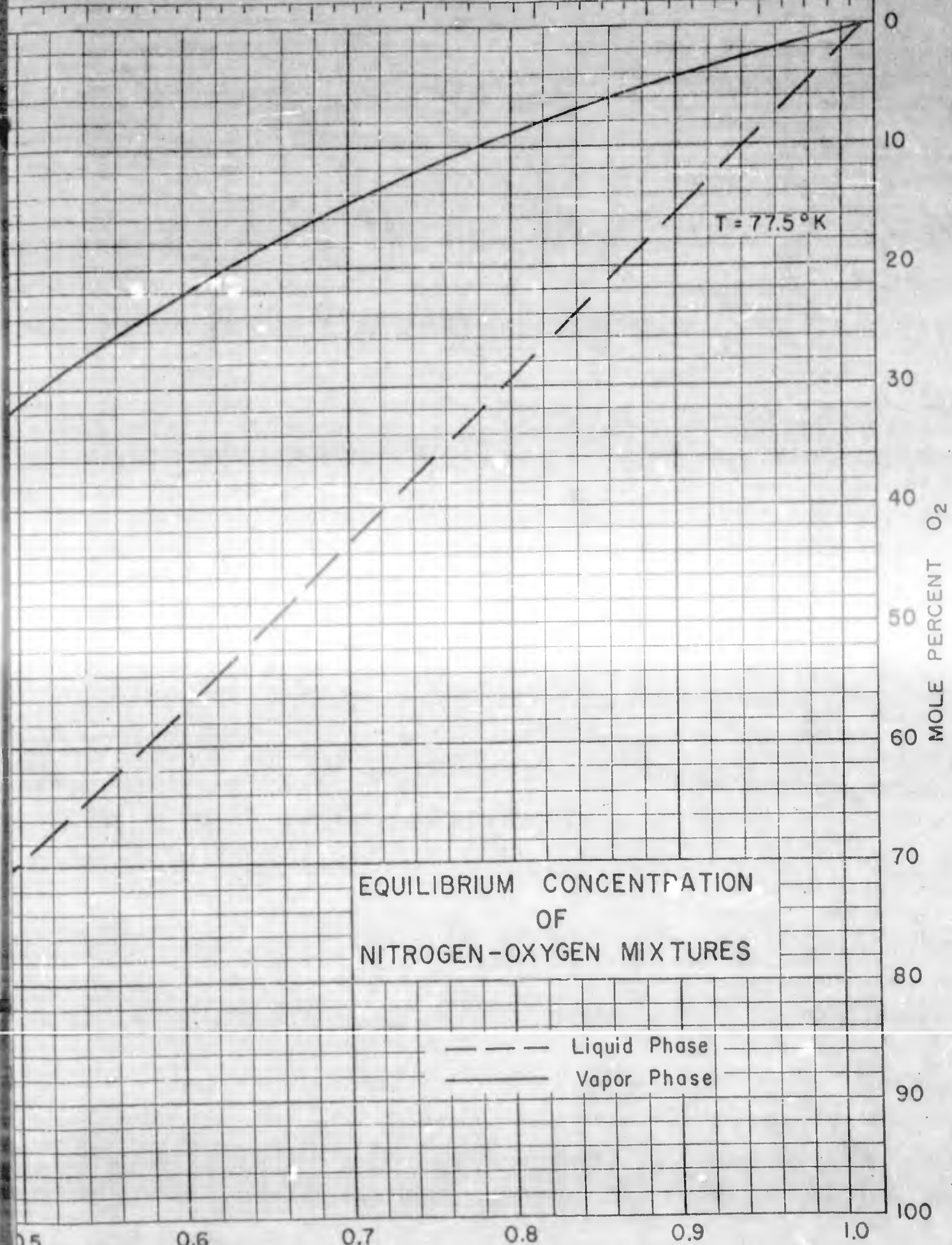
Benham and Katz					
Press. atm.	Mole % H <sub>2</sub>		Press. atm.	Mole % H <sub>2</sub>	
	liquid	vapor		liquid	vapor
T = 172°K					
34.0	1.70	15.83	101.-	13.10	79.31
68.0	8.77	40.60	135.-	18.05	78.23
87.1	12.55	46.31	204.1	3-.99	74.57
102.1	16.22	46.76	T = 116.5°K		
T = 144.3°K					
34.0	3.43	63.92	33.3	3.16	92.79
68.0	7.81	76.18	101.-	9.50	9-.66
			156.5	13.9-	93.83
			272.2	31.70	92.89

Equilibrium Concentration of Hydrogen-Methane Mixtures

Freeth and Verschoyle			
Temperature °C	Pressure atm.	Mole % H <sub>2</sub>	
		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



5  
psia 8 9 10 11 12 13 14 15



EQUILIBRIUM CONCENTRATION  
OF  
NITROGEN-OXYGEN MIXTURES

--- Liquid Phase  
— Vapor Phase

0.5 0.6 0.7 0.8 0.9 1.0  
atmospheres 207

2

## 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., Pennsylvania State College, O.S.R.D. Report 4493 (1944)

Other References:

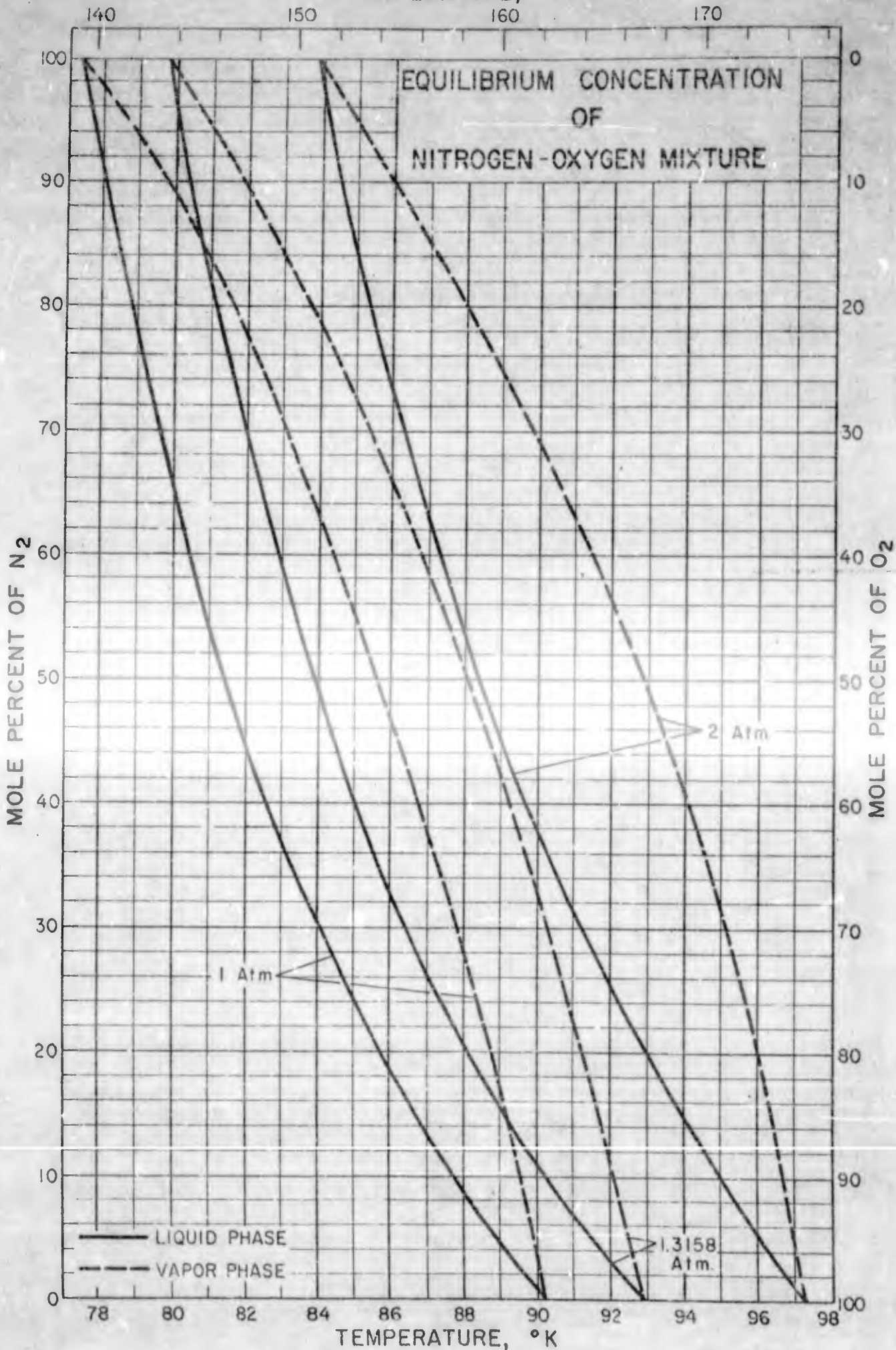
- Inglis, J. K. H., Phil. Mag. 11, 640-658 (1906)
- Komarov, P., Likhter, A. and Ruhemann, M., Zhur. Tekh. Fiz. 5, 1723-8 (1935)
- Kritschewsky, I. R. and Torotscheschnikow, N. S., Z. physik. Chem. (Leipzig) A176, 338-46 (1936)
- Kuenen, J. P., Verschoyle, T. and Van Urk, A. Th., Koninkl. Ned. Akad. 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.

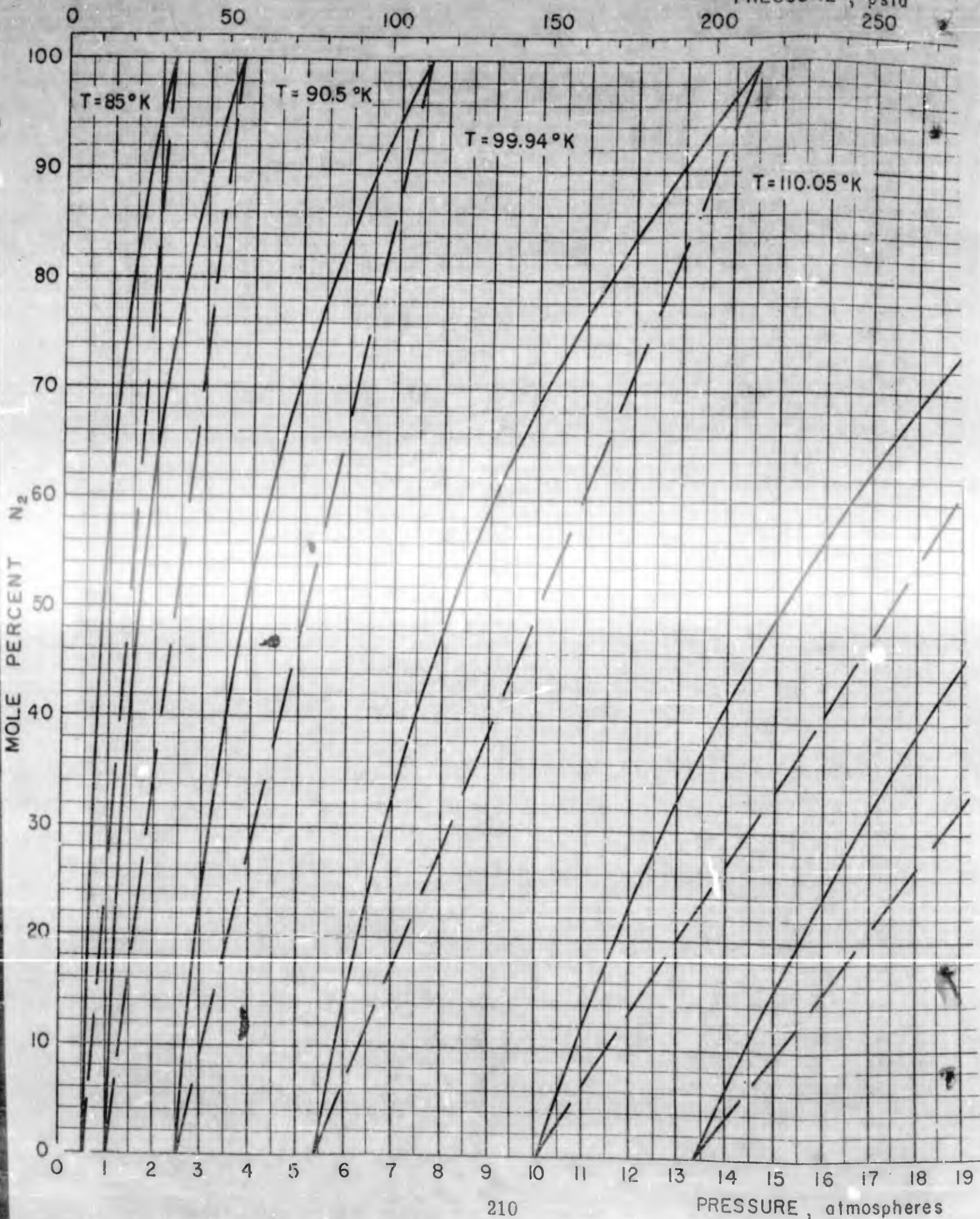
16.004 / 5

TEMPERATURE, °R



16.004 / 5

PRESSURE, psia  
250



16.004 / 5

PRESSURE, psia  
250

300

350

400

450

$T=110.05^\circ\text{K}$

$T=119.92^\circ\text{K}$

$T=125.00^\circ\text{K}$

0

10

20

30

40

50

60

70

80

90

100

MOLE PERCENT  $\text{O}_2$

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

PRESSURE, atmospheres

7

EQUILIBRIUM CONCENTRATIONS OF NITROGEN - OXYGEN MIXTURES

Table of Selected Values

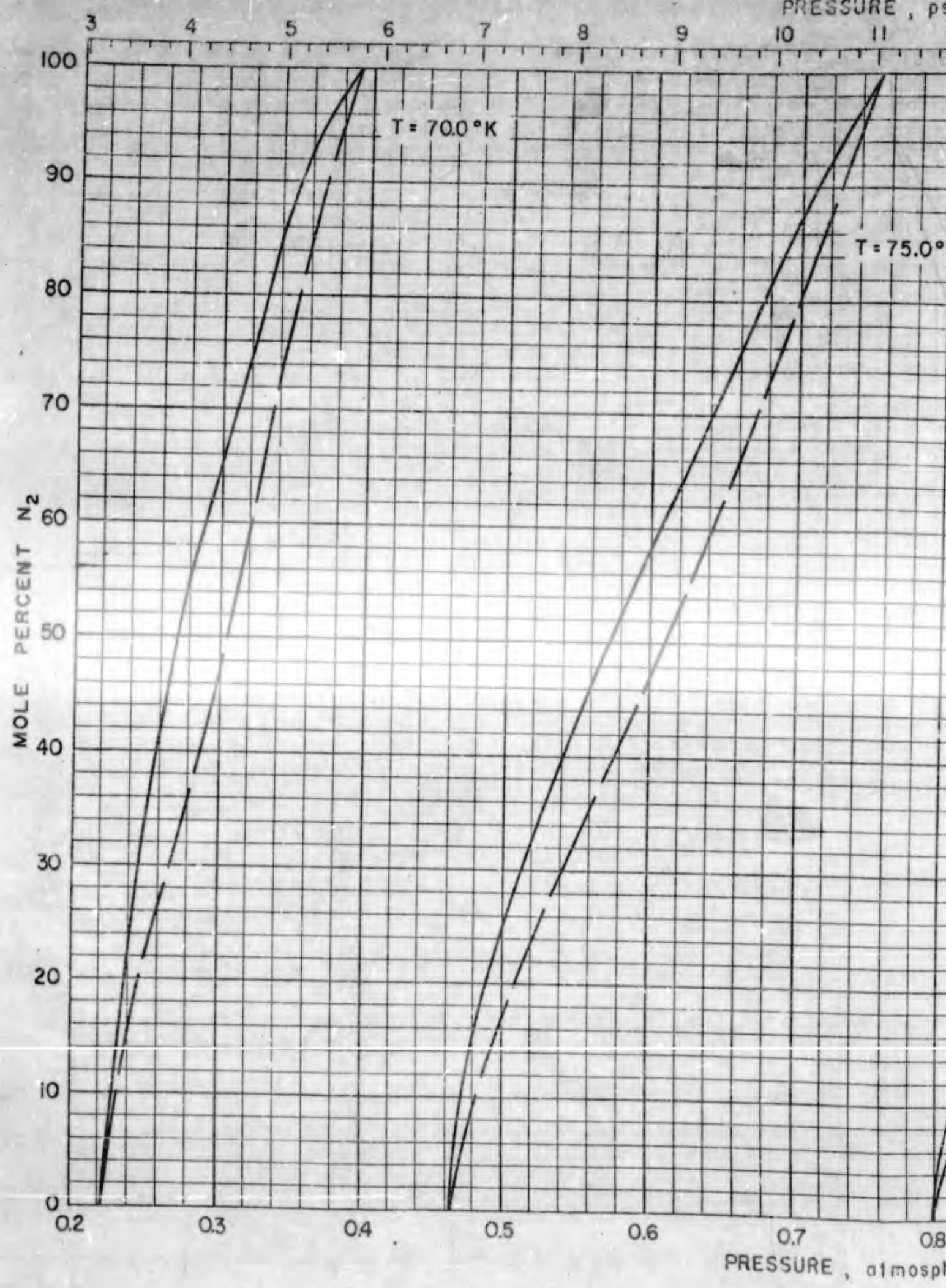
Press. atm.	Mole % N <sub>2</sub>		Press. atm.	Mole % N <sub>2</sub>		Press. atm.	Mole % N <sub>2</sub>	
	liquid	vapor		liquid	vapor		liquid	vapor
55°K								
0.023	0	0	1.540	11.00	12.00	10.771	10.00	10.00
.040	7.20	44.0	1.531	12.00	13.00	11.113	10.00	10.00
.050	16.0	55.0	1.523	13.00	14.00	11.455	10.00	10.00
.080	30.9	75.3	1.515	14.00	15.00	11.797	10.00	10.00
.100	44.5	84.9	1.508	15.00	16.00	12.139	10.00	10.00
.12	58.4	90.3	1.502	16.00	17.00	12.481	10.00	10.00
.140	82.4	94.9	1.497	17.00	18.00	12.823	10.00	10.00
.150	88.0	98.2	1.493	18.00	19.00	13.165	10.00	10.00
.172	100	100	1.490	19.00	20.00	13.507	100	100
70°K								
0.072	0	0	2.457	0.00	0	10.771	0	0
.10	9.7	15.3	2.457	1.00	13.00	11.113	10.00	21.66
.15	42.2	57.7	2.457	2.00	14.00	11.455	10.00	22.77
.20	52.4	70.7	2.457	3.00	15.00	11.797	10.00	23.88
.25	58.0	81.4	2.457	4.00	16.00	12.139	10.00	24.99
.30	68.2	92.5	2.457	5.00	17.00	12.481	10.00	26.10
.35	85.4	97.4	2.457	6.00	18.00	12.823	10.00	27.21
.378	100	100	2.457	7.00	19.00	13.165	100	100
99.90°K								
0.462	0	0	3.891	0	0	21.452	0	0
.10	3.00	13.00	3.891	1.00	15.00	22.951	0	0
.15	7.01	18.00	3.891	2.00	16.00	24.71	100	100
.20	9.95	24.55	3.891	3.00	17.00			
.25	13.00	31.29	3.891	4.00	18.00			
.30	17.91	38.94	3.891	5.00	19.00			
.35	25.12	49.08	3.891	6.00	20.00			
.40	42.48	60.00	3.891	7.00	21.00			
.50	48.75	71.29	3.891	8.00	22.00			
.60	58.97	78.52	3.891	9.00	23.00			
.70	63.78	81.63	3.891	10.00	24.00			
.80	80.55	90.77	3.891	11.00	25.00			
.90	90.80	95.78	3.891	12.00	26.00			
1.07	100	100	3.891	13.00	27.00			
125.00°K								
13.315	0	0	4.700	42.48	60.00	13.315	0	0
15.531	10.93	20.24	5.043	48.75	71.29	15.531	10.93	20.24
16.857	19.50	30.95	5.323	58.97	78.52	16.857	19.50	30.95
20.450	40.37	53.71	5.841	63.78	81.63	20.450	40.37	53.71
22.992	54.08	---	6.240	80.55	90.77	22.992	54.08	---
24.298	62.25	71.95	7.180	90.80	95.78	24.298	62.25	71.95
27.549	78.28	83.85	7.07	100	100	27.549	78.28	83.85
29.332	88.00	90.89	110.05°K					
31.71	100	100	5.378	0	0	85°K		
90.5°K								
0.5597	0	0	6.033	0.52	15.17	0.5597	0	0
0.558	4.09	17.37	6.000	12.00	20.26	0.658	4.09	17.37
1.218	36.27	70.20	7.280	20.17	39.50	1.218	36.27	70.20
1.421	49.02	79.16	9.231	41.09	61.44	1.421	49.02	79.16
1.563	60.01	87.00	85°K					
2.243	100	100	90.5°K			1.563	60.01	87.00

Table of Selected Values

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

2

10.000 1.1  
PRESSURE, ps

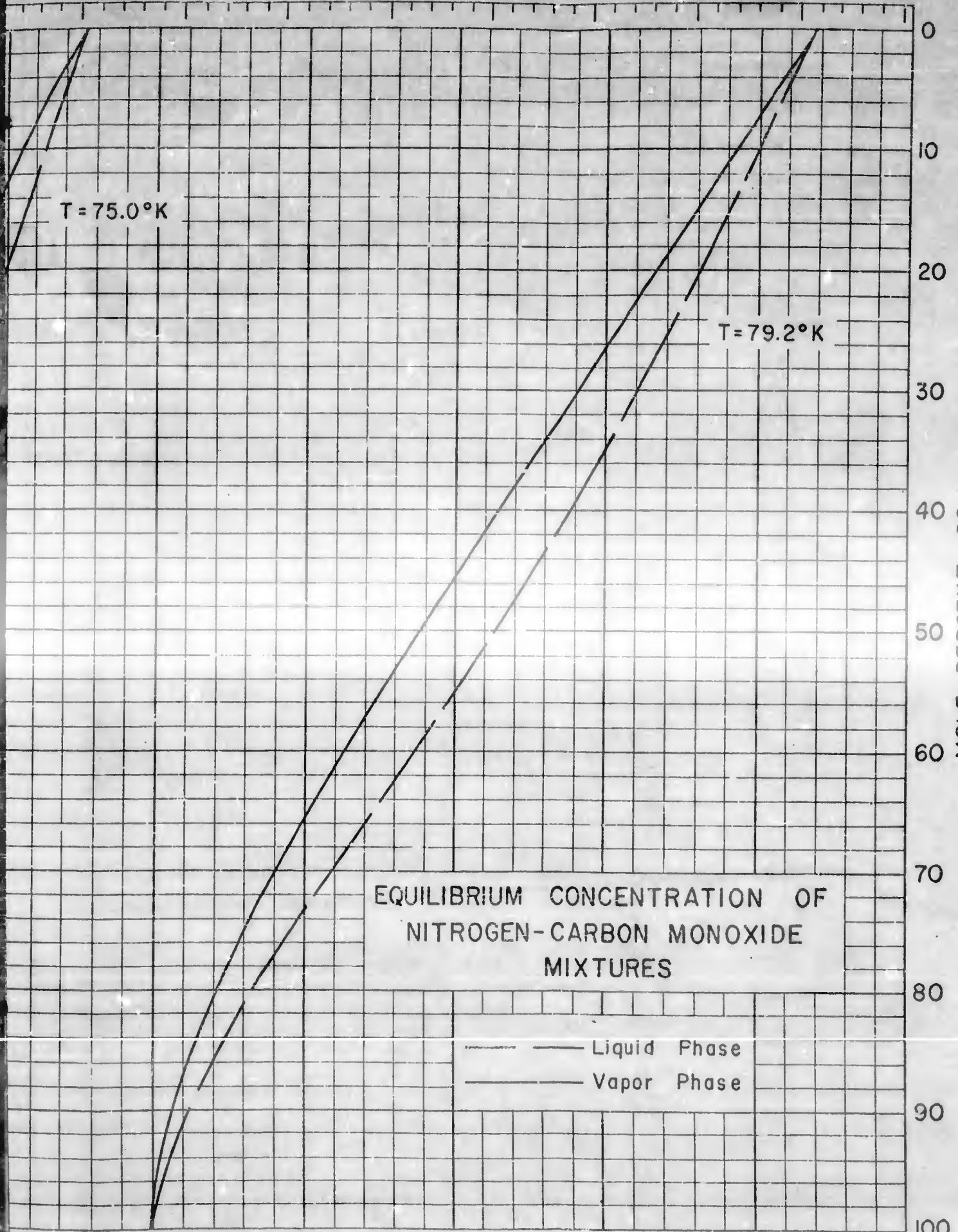


PRESSURE, atmosph

16.004 / 7

PRESSURE, psia

11 12 13 14 15 16 17 18 19



EQUILIBRIUM CONCENTRATION OF NITROGEN-CARBON MONOXIDE MIXTURES

— Liquid Phase  
- - - Vapor Phase

PRESSURE, atmospheres

24

## EQUILIBRIUM CONCENTRATION of NITROGEN-CARBON MONOXIDE MIXTURES

Sources of Data:

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

Verschoye, 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 2, 337 (1935)

Komarov, P., Likhter, A. and Ruhemann, M.; Zhur. Tekh. Fiz. 2, 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 Verschoye'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)

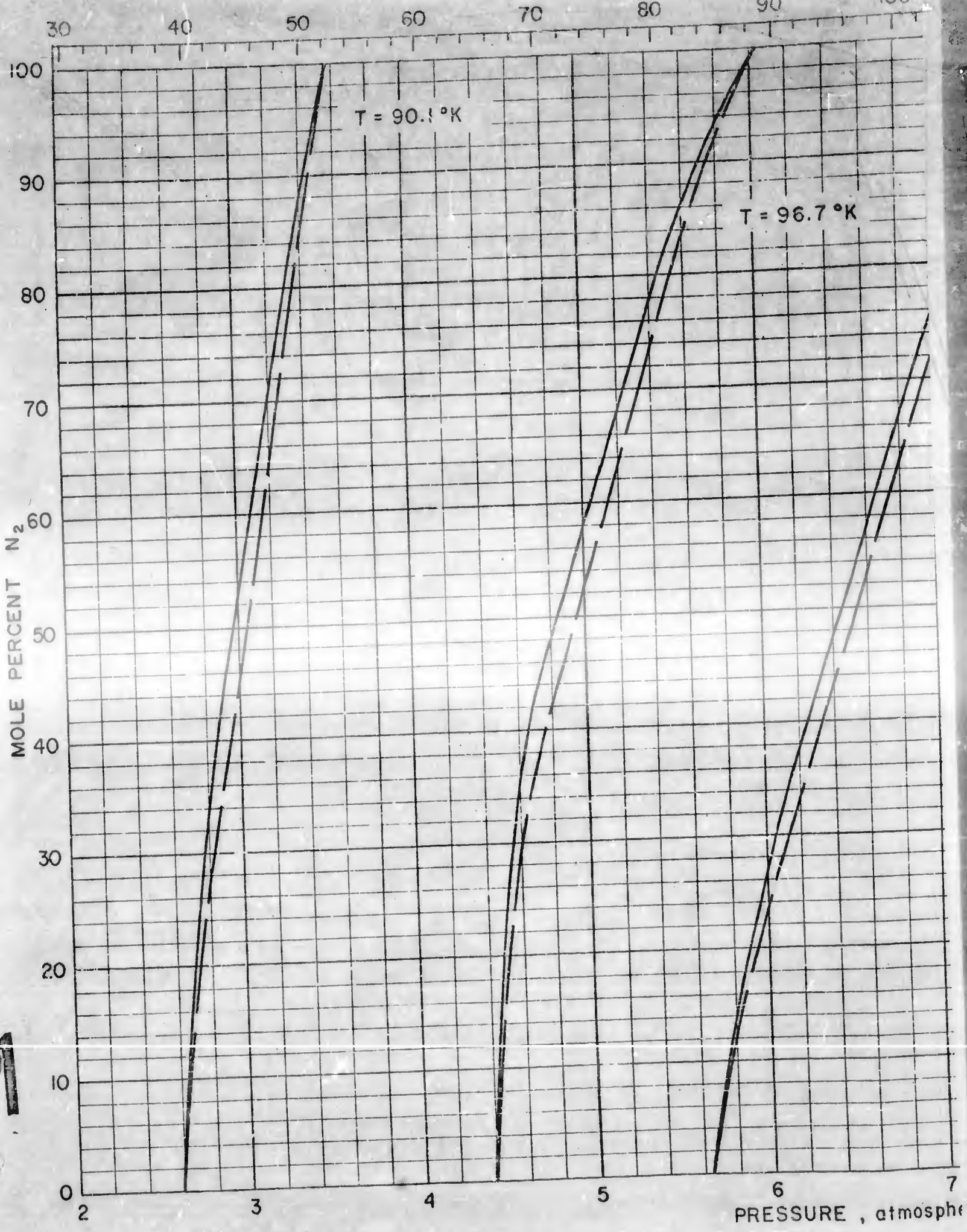
Temp. °C	Press. cm.	Temp. °C	Press. cm.	Temp. °C	Press. cm.	Temp. °C	Press. cm.
Mole % N <sub>2</sub> = 80.1		Mole % N <sub>2</sub> = 59.95		Mole % N <sub>2</sub> = 40.0		Mole % N <sub>2</sub> = 20.05	
-193.88	88.41	-193.90	81.87	-193.90	74.20	-193.90	65.82
-193.88	88.38	-193.90	81.89	-193.90	74.29	-193.90	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

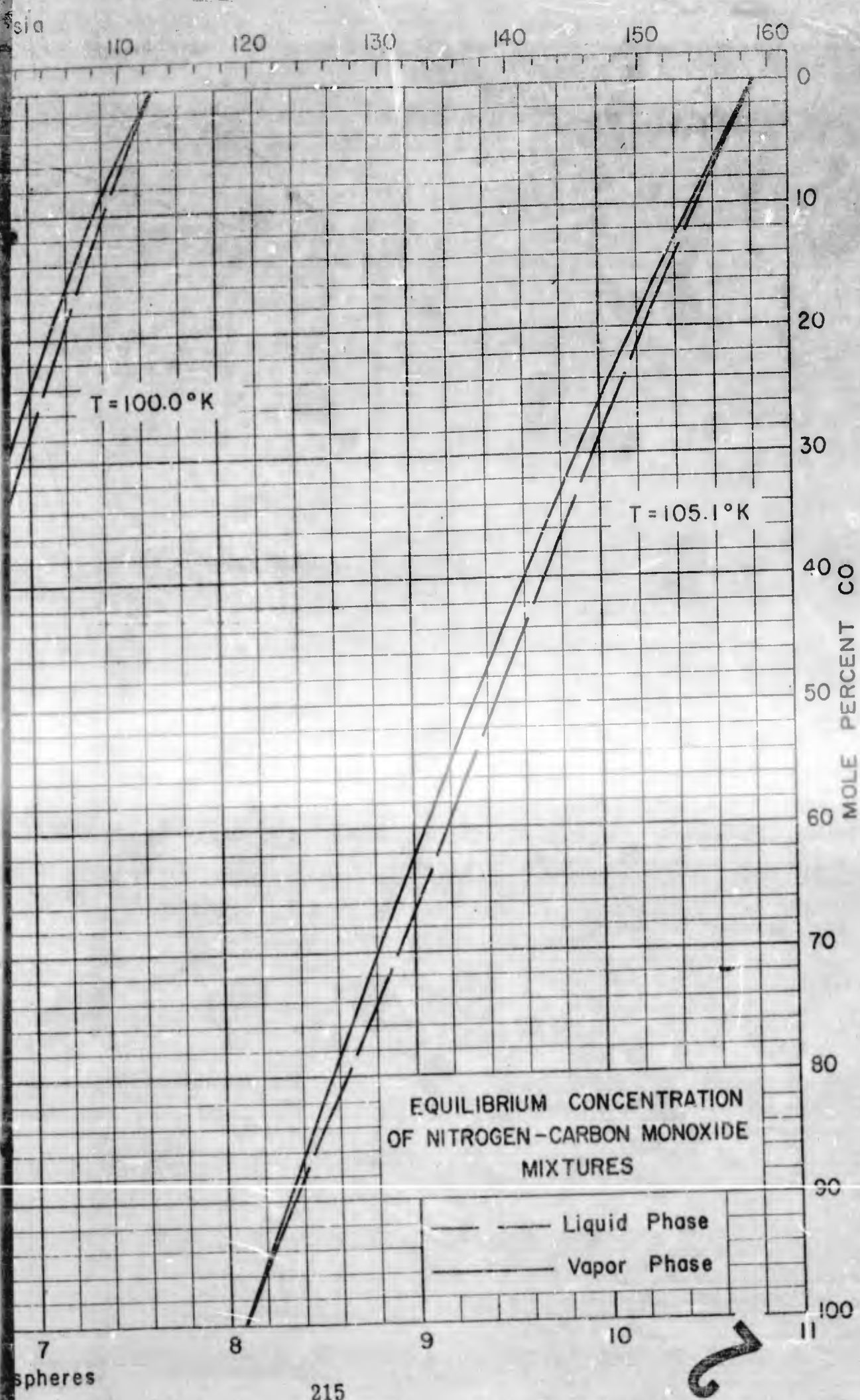
FEFG/RS Issued: 3-28-61

Equilibrium Concentrations - Liquid and Vapor Phases

(Yushkevich and Torocheshnikov)

Press. Atm.	Mole % N <sub>2</sub>		Press. Atm.	Mole % N <sub>2</sub>		Press. Atm.	Mole % N <sub>2</sub>	
	Liq.	Vap.		Liq.	Vap.		Liq.	Vap.
70.0°K			2.762	0.224	0.288	8.60	0.190	0.216
0.393	1.000	1.000	2.68	0.135	0.162	88.06	0.000	0.000
0.355	0.810	0.910	2.591	0.000	0.000	110.0°K		
0.323	0.600	0.728	96.7°K			14.5	1.000	1.000
0.290	0.400	0.600	6.04	1.000	1.000	13.14	0.680	0.718
0.249	0.201	0.310	5.57	0.822	0.856	13.07	0.660	0.700
0.223	0.000	0.000	5.34	0.693	0.745	12.68	0.534	0.580
75.0°K			5.30	0.666	0.721	12.49	0.485	0.530
0.754	1.000	1.000	4.62	0.328	0.384	12.34	0.440	0.487
0.700	0.801	0.875	4.53	0.206	0.260	12.20	0.397	0.443
0.643	0.600	0.700	4.45	0.107	0.135	12.00	0.350	0.393
0.578	0.400	0.520	4.39	0.000	0.000	11.62	0.246	0.280
0.510	0.201	0.290	100.0°K			11.52	0.215	0.245
0.463	0.000	0.000	7.68	1.000	1.000	11.26	0.149	0.170
79.2°K			6.97	0.718	0.755	10.99	0.000	0.000
1.236	1.000	1.000	6.87	0.660	0.700	116.6°K		
1.163	0.860	0.860	6.24	0.348	0.395	21.03	1.000	1.000
1.077	0.600	0.690	6.15	0.302	0.355	18.54	0.587	0.620
0.976	0.400	0.500	6.06	0.260	0.300	18.40	0.565	0.600
0.866	0.201	0.270	5.88	0.170	0.198	17.81	0.416	0.457
0.798	0.000	0.000	5.82	0.136	0.160	17.76	0.410	0.445
90.1°K			5.61	0.000	0.000	17.52	0.360	0.392
3.566	1.000	1.000	105.1°K			16.94	0.244	0.278
3.341	0.792	0.831	10.80	1.000	1.000	16.13	0.000	0.000
3.323	0.759	0.803	9.70	0.600	0.640	121.8°K		
3.22	0.650	0.710	9.66	0.584	0.627	27.42	1.000	1.000
2.914	0.375	0.452	9.44	0.475	0.520	23.96	0.542	0.570
			8.73	0.228	0.256	22.33	0.280	0.300
						22.07	0.245	0.256
						21.19	0.000	0.000





EQUILIBRIUM CONCENTRATION  
 OF NITROGEN-CARBON MONOXIDE  
 MIXTURES

- - - - - Liquid Phase  
 \_\_\_\_\_ Vapor Phase

7  
 spheres

215



16.004/7

PRESSURE, psia  
260 280

300

160

180

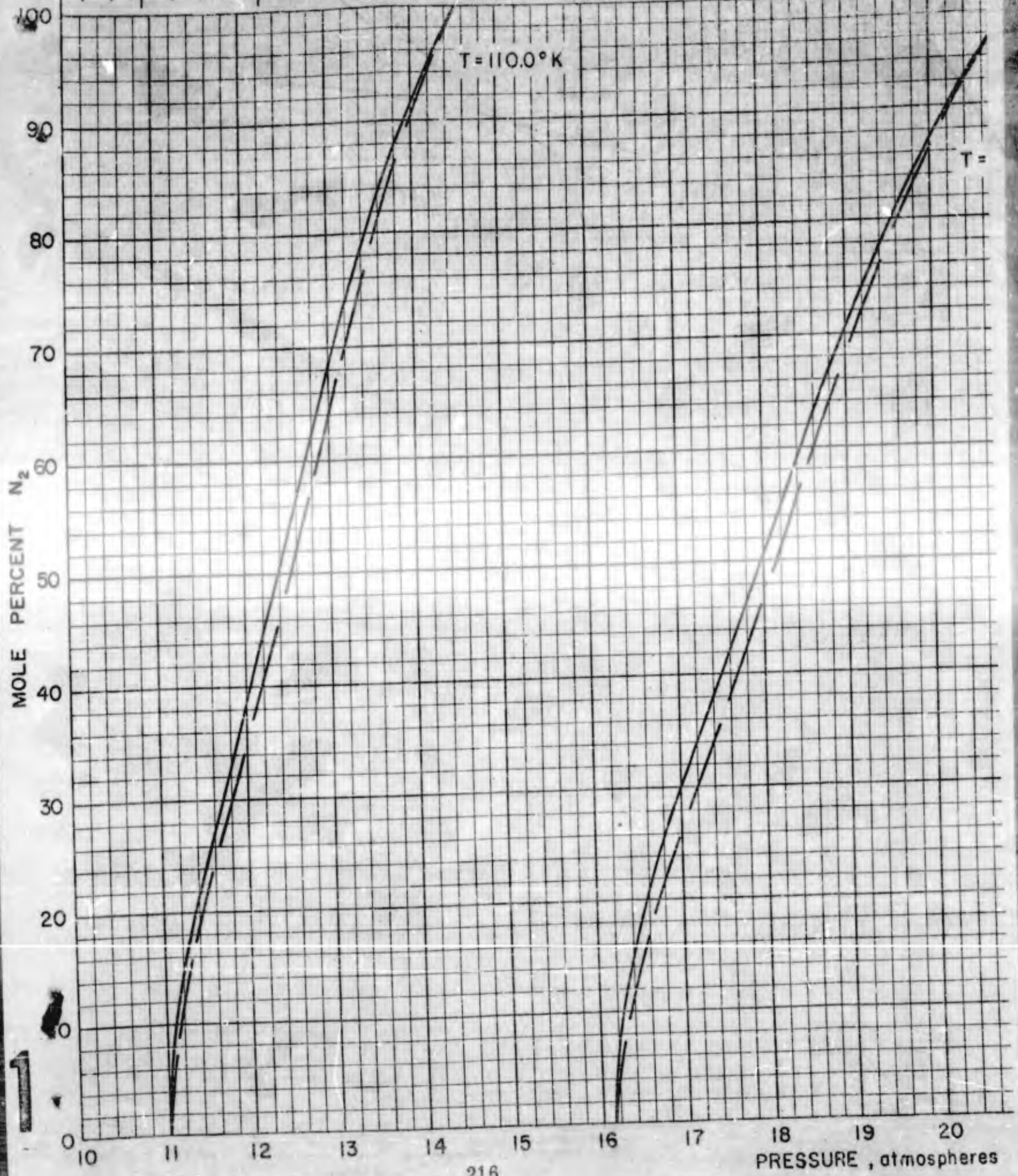
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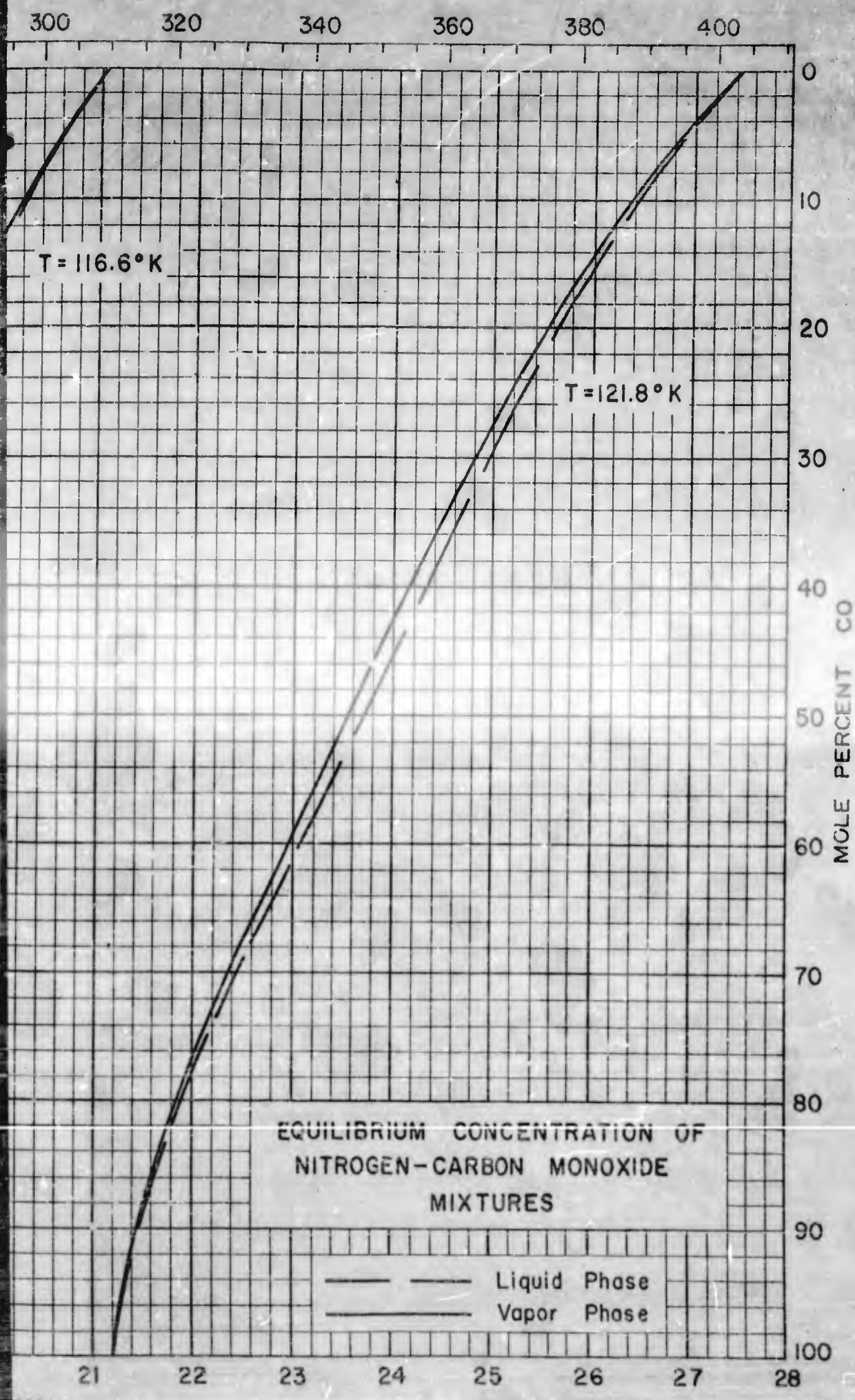
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240

260

280

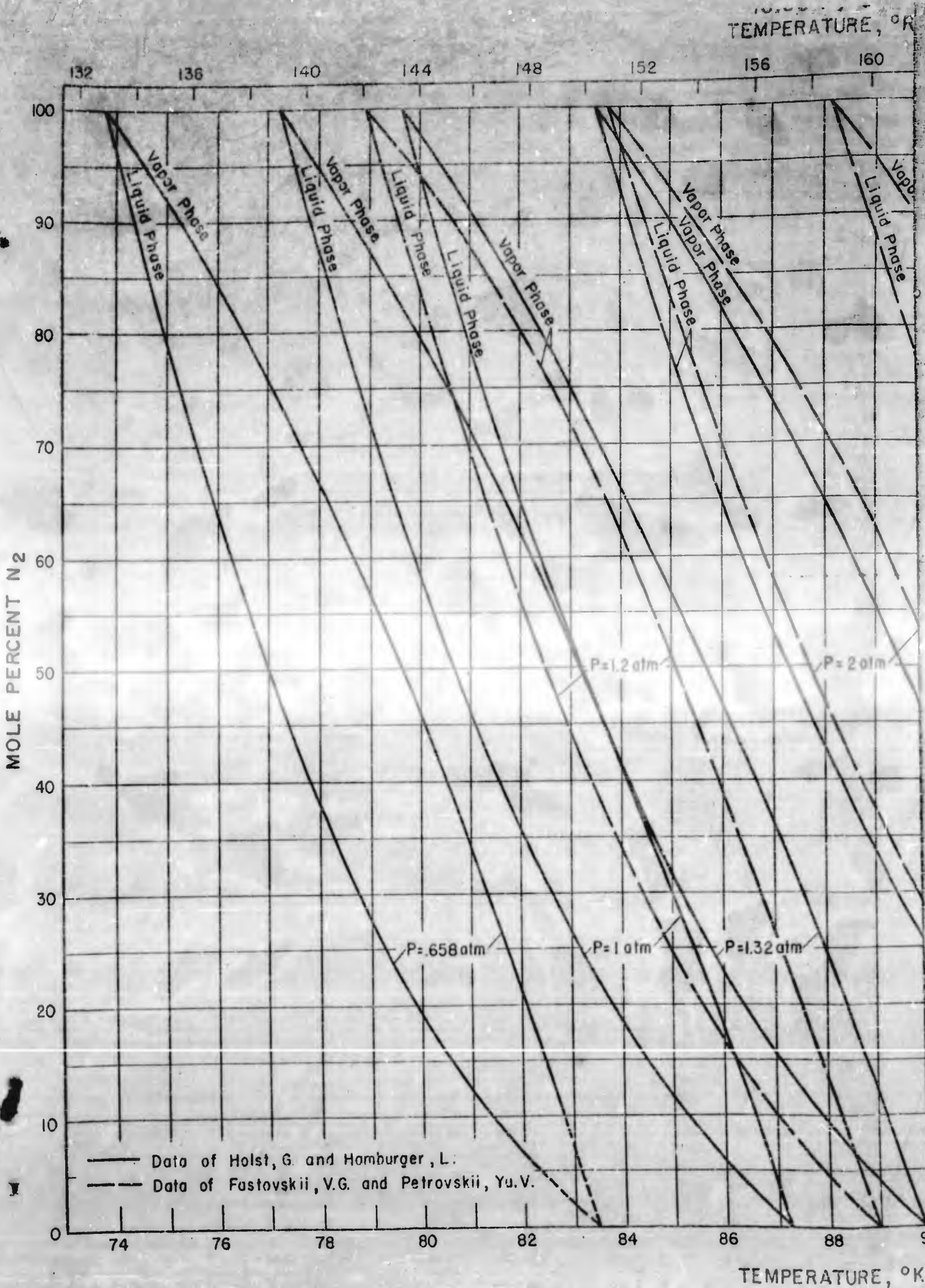




EQUILIBRIUM CONCENTRATION OF  
NITROGEN-CARBON MONOXIDE  
MIXTURES

— Liquid Phase  
- - - Vapor Phase

2



MOLE PERCENT N<sub>2</sub>

TEMPERATURE, °R

TEMPERATURE, °K

132 136 140 144 148 152 156 160

100  
90  
80  
70  
60  
50  
40  
30  
20  
10  
0

74 76 78 80 82 84 86 88 90

Vapor Phase  
Liquid Phase

P = 0.658 atm  
P = 1 atm  
P = 1.32 atm  
P = 1.2 atm  
P = 2 atm

RE, °R

160

164

168

172

176

180

184

0

10

20

30

40

50

60

70

80

90

100

MOLE PERCENT ARGON

# EQUILIBRIUM CONCENTRATION OF NITROGEN - ARGON MIXTURES

Liquid Phase

Vapor Phase

Liquid Phase

Vapor Phase

2 atm

P = 3 atm

P = 4 atm

P = 197 atm

RE, °K

217

90

92

94

96

98

100

102

2

## 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:

Terocheshnikov, 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.

16.004/9

EQUILIBRIUM CONCENTRATIONS of NITROGEN-ARGON MIXTURES

Tables of Selected Values

Holst and Hamburger

Temp. °K	Mole % N <sub>2</sub>		Temp. °K	Mole % N <sub>2</sub>	
	Liquid	Vapor		Liquid	Vapor
P = 50 cm Hg (0.658 atm.)			P = 100 cm Hg (1.32 atm.)		
73.87	100.0	100.0	79.71	100.0	100.0
73.94	99.0	--	79.78	99.	--
74.82	82.6	--	80.76	82.6	--
75.86	65.3	--	81.95	65.3	--
77.21	--	74.05	83.08	--	74.0
78.65	31.5	--	85.05	31.5	--
79.41	--	52.8	85.40	--	52.8
81.42	10.0	--	87.98	10.0	--
81.79	--	24.3	88.04	---	24.3
83.45	0.0	0.0	89.93	0.0	0.0
P = 76 cm Hg (1.0 atm.)			P = 150 cm Hg (1.97 atm.)		
77.28	100.0	100.0	83.57	0.0	0.0
77.35	99.	--	83.64	99.	--
78.30	82.6	--	84.70	82.6	--
79.41	65.3	--	85.97	65.3	--
80.66	--	74.0	86.93	--	74.0
82.40	31.5	--	89.29	31.5	--
82.97	--	52.8	89.33	--	52.8
85.25	10.0	--	92.15	--	24.3
85.46	--	24.3	92.32	10.0	--
87.26	0.0	0.0	94.18	0.0	0.0

Press. atm.	Press. cm Hg	Mole % N <sub>2</sub>	
		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

92.6

93.5

94.4

Table of Selected Values

Pastovskii and Petrovskii

Temp. °K	Mole % N <sub>2</sub>		Temp. °K	Mole % N <sub>2</sub>	
	Liquid	Vapor		Liquid	Vapor
P = 912 mm Hg (1.2 atm.)			P = 2280 mm Hg (3.0 atm.)		
78.90	100	100	88.11	100	100
79.58	90	96.52	88.84	90	95.90
80.26	80	92.46	89.66	80	91.08
80.96	70	87.74	90.42	70	85.95
81.66	60	82.24	91.26	60	79.71
82.50	50	75.60	92.24	50	72.34
83.50	40	67.15	93.34	40	63.58
84.46	30	56.96	94.56	30	52.78
85.64	20	43.47	95.96	20	39.43
87.00	10	25.80	97.45	10	22.32
87.92	5	14.10	98.32	5	12.00
89.00	0	0	99.22	0	0
P = 1520 mm Hg (2.0 atm.)			P = 3040 mm Hg (4.0 atm.)		
83.80	100	100	91.40	100	100
84.44	90	90.16	92.16	90	95.33
85.24	80	91.73	92.98	80	91.76
86.00	70	86.63	93.18	70	85.57
86.80	60	80.68	94.80	60	79.07
87.72	50	73.47	95.86	50	71.50
88.76	40	64.91	97.05	40	62.41
89.88	30	54.34	98.21	30	51.69
91.08	20	40.87	99.68	20	37.97
92.64	10	23.36	101.13	10	21.22
93.56	5	12.53	102.00	5	19.30
94.43	0	0	102.88	0	0

2

16.004/9

EQUILIBRIUM CONCENTRATIONS of NITROGEN-ARGON MIXTURES

Tables of Selected Values

Holst and Hamburger

Temp. °K	Mole % N <sub>2</sub>		Temp. °K	Mole % N <sub>2</sub>	
	Liquid	Vapor		Liquid	Vapor
P = 50 cm Hg (0.658 atm.)			P = 100 cm Hg (1.32 atm.)		
73.87	100.0	100.0	79.71	100.0	100.0
73.94	99.0	--	79.78	99.	--
74.82	82.6	--	80.76	82.6	--
75.86	65.3	--	81.95	65.3	--
77.21	--	74.05	83.08	--	74.0
78.65	31.5	--	85.05	31.5	--
79.41	--	52.8	85.40	--	52.8
81.42	10.0	--	87.98	10.0	--
81.79	--	24.3	88.04	---	24.3
83.45	0.0	0.0	89.93	0.0	0.0
P = 76 cm Hg (1.0 atm.)			P = 150 cm Hg (1.97 atm.)		
77.26	100.0	100.0	83.57	0.0	0.0
77.35	99.	--	83.64	99.	--
78.30	82.6	--	84.70	82.6	--
79.41	65.3	--	85.97	65.3	--
80.66	--	74.0	86.93	--	74.0
82.40	31.5	--	89.29	31.5	--
82.97	--	52.8	89.33	--	52.8
85.25	10.0	--	92.15	--	24.3
85.46	--	24.3	92.32	10.0	--
87.26	0.0	0.0	94.18	0.0	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
92.6
93.5
94.4

Press. atm.	Press. cm Hg	Mole % N <sub>2</sub>	
		Liq.	Vep.
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

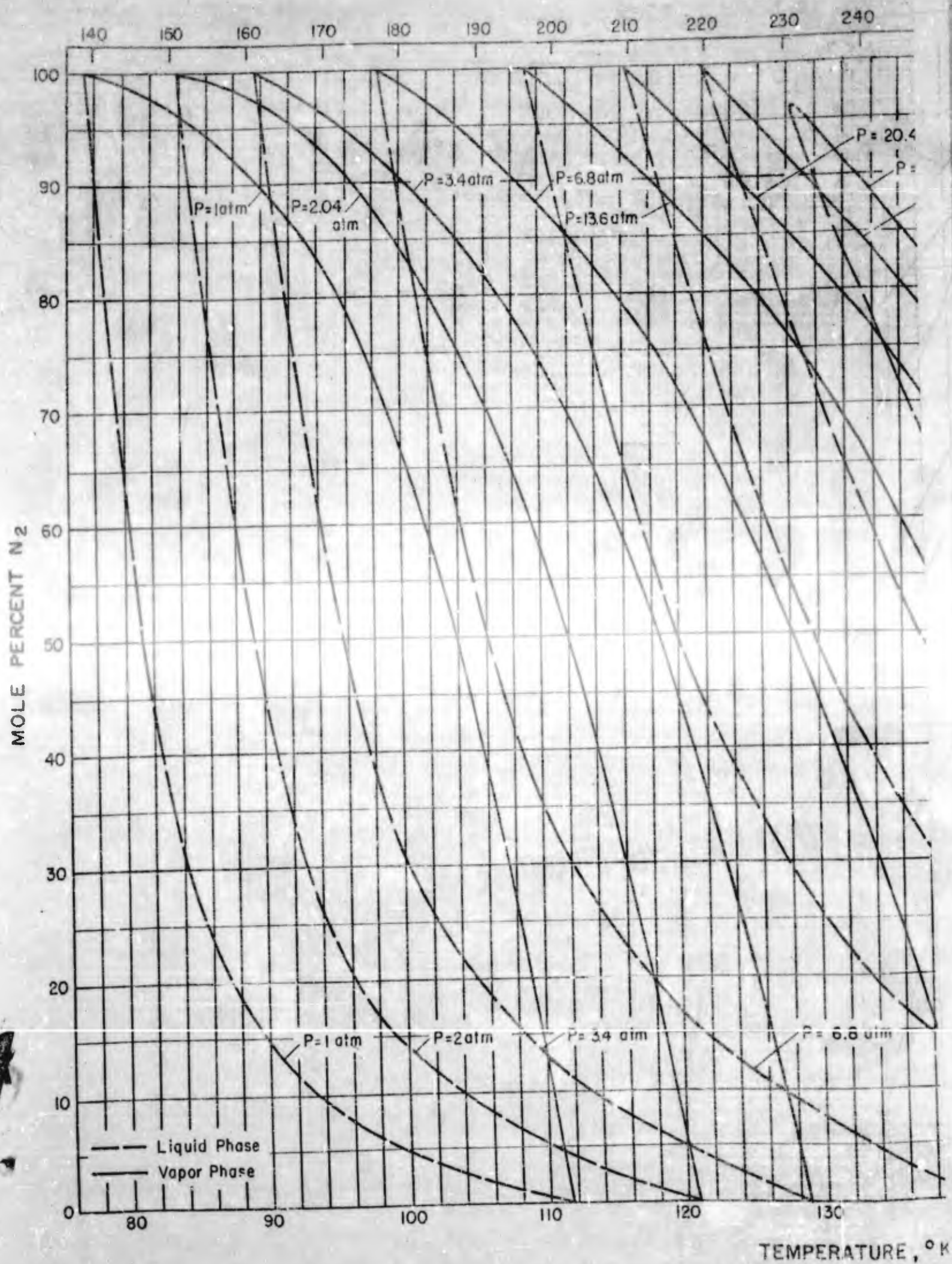
Table of Selected Values

Fastovskii and Petrovskii

Temp. °K	Mole % N <sub>2</sub>		Temp. °K	Mole % N <sub>2</sub>	
	Liquid	Vapor		Liquid	Vapor
P = 912 mm Hg (1.2 atm.)			P = 2280 mm Hg (3.0 atm.)		
78.90	100	100	88.11	100	100
79.58	90	96.52	88.84	90	95.90
80.26	80	92.46	89.66	80	91.08
80.96	70	87.74	90.42	70	85.95
81.66	60	82.24	91.26	60	79.71
82.50	50	75.60	92.24	50	72.34
83.50	40	67.15	93.34	40	63.58
84.46	30	56.96	94.56	30	52.78
85.64	20	43.47	95.96	20	39.43
87.00	10	25.80	97.45	10	22.32
87.92	5	14.10	98.32	5	12.00
89.00	0	0	99.22	0	0
P = 1520 mm Hg (2.0 atm.)			P = 3040 mm Hg (4.0 atm.)		
83.80	100	100	91.40	100	100
84.44	90	96.16	92.16	90	95.83
85.24	80	91.73	92.98	80	91.06
86.00	70	86.63	93.18	70	85.57
86.80	60	80.68	94.80	60	79.07
87.72	50	73.47	95.86	50	71.50
88.76	40	64.91	97.05	40	62.41
89.88	30	54.34	98.21	30	51.69
91.08	20	40.87	99.68	20	37.97
92.64	10	23.36	101.13	10	21.22
93.56	5	12.53	102.00	5	19.30
94.43	0	0	102.88	0	0

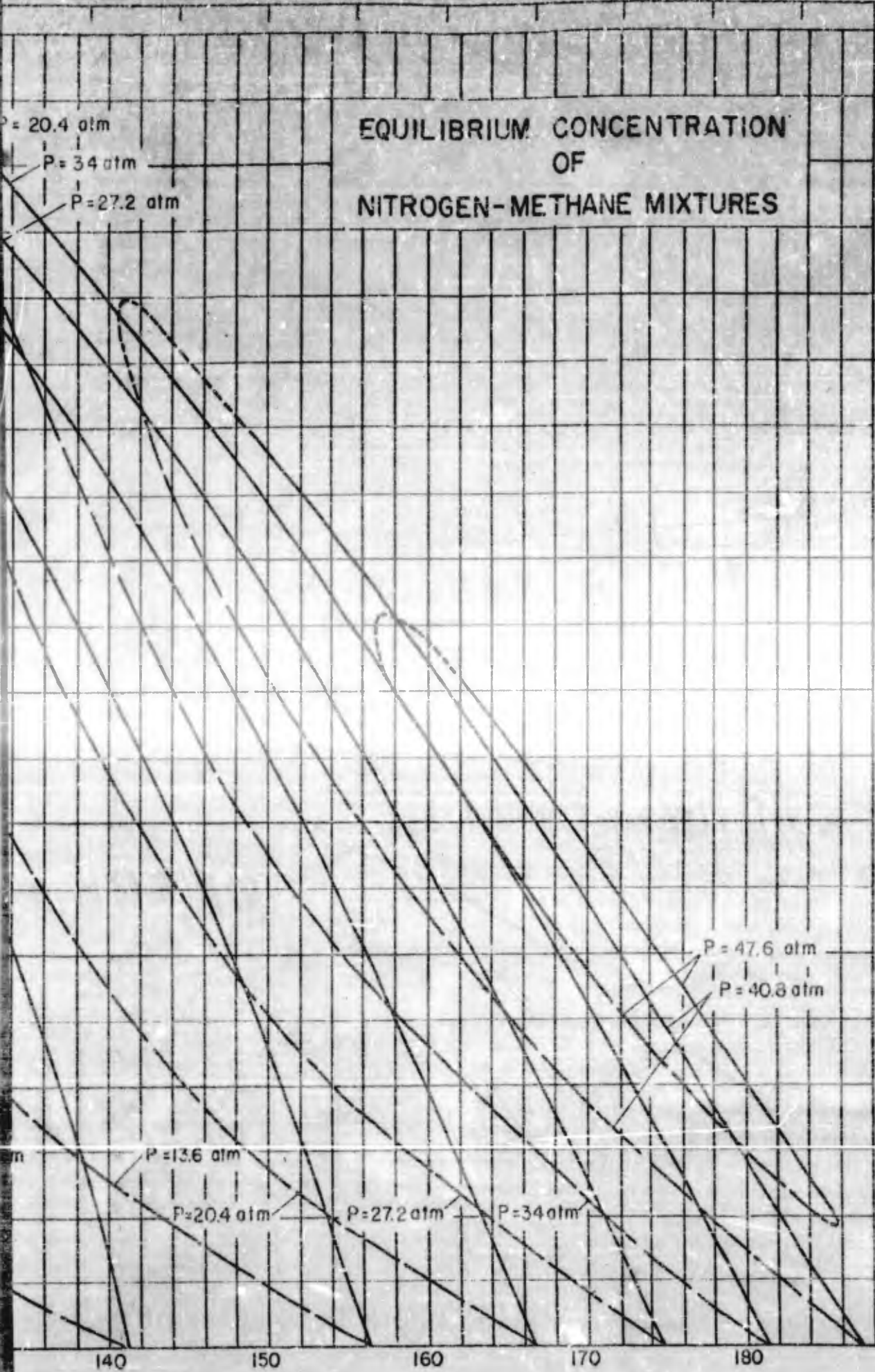
2

16.004 / 10  
TEMPERATURE, °



RE, °R

0 250 260 270 280 290 300 310 320 330



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, 1-22 (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  $-295^{\circ}$  to  $-116.7^{\circ}\text{F}$  with pressures from 14.7 to 700 psia and the data from Cines, et al. are for temperatures from  $-280^{\circ}$  to  $-150^{\circ}\text{F}$  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,  $\pm 0.05\%$
- high-pressure dew points,  $\pm 2$  psi or  $\pm 0.1^{\circ}\text{F}$ , whichever is larger
- high-pressured bubble points,  $\pm 1$  psi
- low-pressure dew and bubble points,  $\pm 0.1$  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.

16.004 / 10  
EQUILIBRIUM CONCENTRATIONS OF NITROGEN - METHANE MIXTURES  
Tables of selected values

Values from Bloomer and Parent

Pressure		Mole Percent Nitrogen																										
		Temperature, °K																										
		0%			5.11%			10.02%			28.88%			50.88%			69.70%			84.22%			95.15%			100%		
psia	atm.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	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	110.2	95.28	111.8	89.06	106.4	85.93	100.1	85.26	--	--	--	--	--	--	--	--	--	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	89.56	89.56	89.56	89.56	89.56	89.56	89.56			
100	6.8	141.3	140.1	131.7	139.3	126.3	134.6	132.9	127.8	127.8	105.9	121.1	102.7	112.9	100.7	104.0	99.11	98.44	98.44	98.44	98.44	98.44	98.44	98.44	98.44			
200	13.6	156.3	154.9	148.1	153.7	143.2	148.1	148.1	139.8	139.8	119.6	131.6	115.0	122.7	112.2	113.8	110.1	108.9	108.9	108.9	108.9	108.9	108.9	108.9	108.9			
300	20.4	166.8	164.7	159.0	163.4	154.7	156.7	149.3	147.7	147.7	129.2	138.1	123.6	128.9	120.1	120.2	117.5	116.3	116.3	116.3	116.3	116.3	116.3	116.3	116.3			
400	27.2	174.8	172.4	167.8	171.1	163.6	163.6	147.9	153.4	153.4	136.6	143.3	130.6	133.6	126.4	125.4	123.4	122.9	122.9	122.9	122.9	122.9	122.9	122.9	122.9			
500	34.0	181.5	178.8	174.9	177.2	171.0	169.9	158.6	157.7	157.7	143.8	146.8	136.8	136.9	131.9	129.5	128.5	128.5	128.5	128.5	128.5	128.5	128.5	128.5	128.5			
600	40.8	187.2	183.9	181.2	182.1	177.4	172.8	162.8	160.9	160.9	150.1	149.0	142.7	--	--	--	--	--	--	--	--	--	--	--	--			
700	47.6	--	--	--	185.5	184.4	175.3	169.3	162.1	162.1	157.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--			

\* The vapor pressures of Nitrogen (Mole % N<sub>2</sub> = 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.	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	86.8	40.6	78.9	20.6	59.2	8.9	33.4	18.5	47.9	1.8	7.9	--	--	--	--	--	--
400	27.2	--	--	--	--	98.9	99.7	85.4	95.2	62.1	86.0	35.2	69.2	18.5	56.5	29.5	56.5	8.2	22.6	--	--	--	--	--	--
500	40.8	--	--	--	--	--	--	--	--	82.2	91.2	50.9	75.2	29.5	62.0	41.5	62.0	15.1	31.8	--	--	--	--	--	--
600	47.6	--	--	--	--	--	--	--	--	--	--	66.8	78.3	41.5	62.0	15.1	31.8	--	--	--	--	--	--	--	--

## 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,  $\rho/\rho_{273}$ , 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  $\rho_{273}$  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  $\rho$ , or values of resistivity ratio,  $\rho/\rho_T$ , 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  $\rho_{273}$  is used in the calculation of the ratio. Where the original data are values of resistivity ratios, the value of  $\rho_{273}$  indicated on the graph sheet for calculation of resistivity is either the value of  $\rho_{273}$  from the original data in those instances where it was given, or the most probable value of  $\rho_{273}$  from another source when it is not available from the original experimenters. Where the original data are resistivity ratios,  $\rho/\rho_T$ , and  $T$  is not 273°K, a suitable correction has been used to convert the ratio to  $\rho/\rho_{273}$ .

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,

$$\rho = \rho_1 + \rho_0$$

where  $\rho_1$  is the intrinsic resistivity (the electron-lattice interaction) and

## PREFACE to the ELECTRICAL RESISTIVITY of METALLIC ELEMENTS (Cont.)

is a function of temperature, and  $\rho_0$  is the imperfectness 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  $\rho_0$  is much greater than  $\rho_i$  so that temperature change has little effect on the resistivity, while at high temperatures  $\rho_i$  is much greater than  $\rho_0$ , 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  $\rho_0$  is much less than  $\rho_i$  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:

$$H_c = H_0 \left[ 1 - (T/T_c)^2 \right]$$

where  $H_0$  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  $H_0$  are given in Table 2.

## PREFACE to the ELECTRICAL RESISTIVITY OF METALLIC ELEMENTS (Cont.)

Table 1

## Conversion Factors for Electrical Resistivity

$\rho$	ohm-cm	ohm-in	ohm-cir mil/ft.
1 ohm-cm =	1.000	0.3937	$6.015 \times 10^6$
1 ohm-in =	2.540	1.000	$1.528 \times 10^7$
1 ohm-cir mil/ft =	$1.662 \times 10^{-7}$	$6.545 \times 10^{-8}$	1.000

Table 2

## Transition Temperatures for Superconducting Elements \*

Element	Transit on Temp., °K	Critical Magnetic Field $H_0$ , 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 ( $\rho_{273}$ ) for lithium to be used in calculating values of electrical resistivity is  $8.55 \times 10^{-6}$  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  $\rho/\rho_{273}$ .) The actual values of  $\rho_{273}$  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  $\rho_{273}$  from Guntz and Broniewski. The resistivity was determined as the sum of the residual and ideal resistivities,  $\rho = \rho_0 + \rho_1$  using the values reported in this paper for a specimen of high purity as follows with  $\rho$  in ohm-cm.  $\rho_0 = 0.0372 \times 10^{-6}$ ,  $\rho_1 = 4.9 \times 10^{-15} T^2$  for  $T < 16^\circ\text{K}$ .

(Continued on following page.)

## ELECTRICAL RESISTIVITY of LITHIUM (Cont.)

Comments: (cont.)

The Landolt-Bornstein 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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

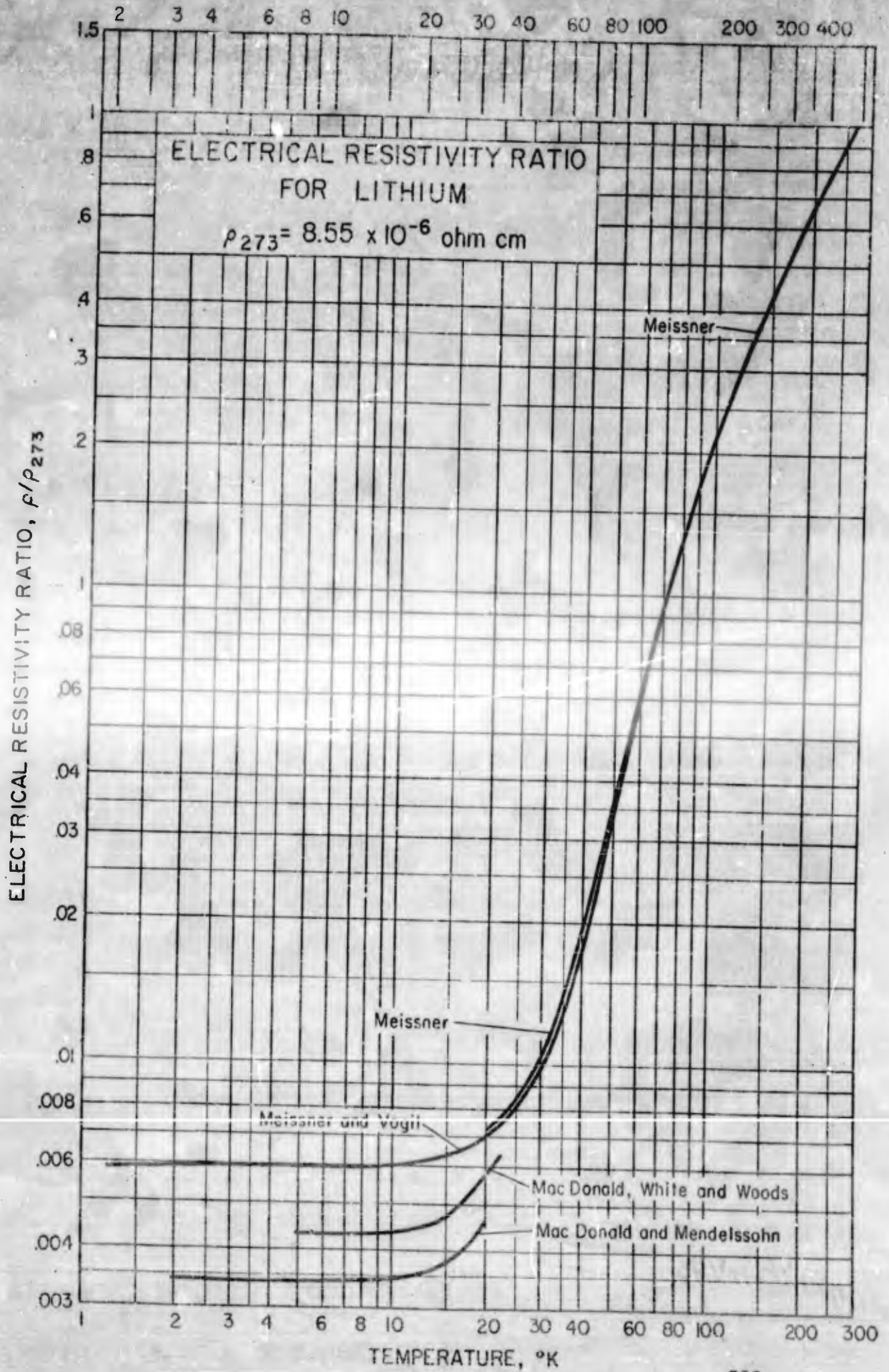
$\rho_{290}$  = Resistivity at 290°K, (ohm-cm)

Meissner and Voigt		MacDonald and Mendelssohn	
Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{290}$
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.

TEMPERATURE, °R



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 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, 358-374 (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.; Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 173a (1924)

Hackspill, L.; Compt. rend. 151, 305 (1910)

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 ( $\rho_{273}$ ) for sodium to be used in calculating electrical resistivity is  $4.28 \times 10^{-6}$  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  $\rho/\rho_{273}$ .) The actual values of  $\rho_{273}$  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  $\rho_{273}$  from L. Hackspill. The resistivity was determined as the sum of the residual and ideal resistivities,  $\rho = \rho_0 + \rho_1$ , using the values reported in this paper for

(Continued on following page.)

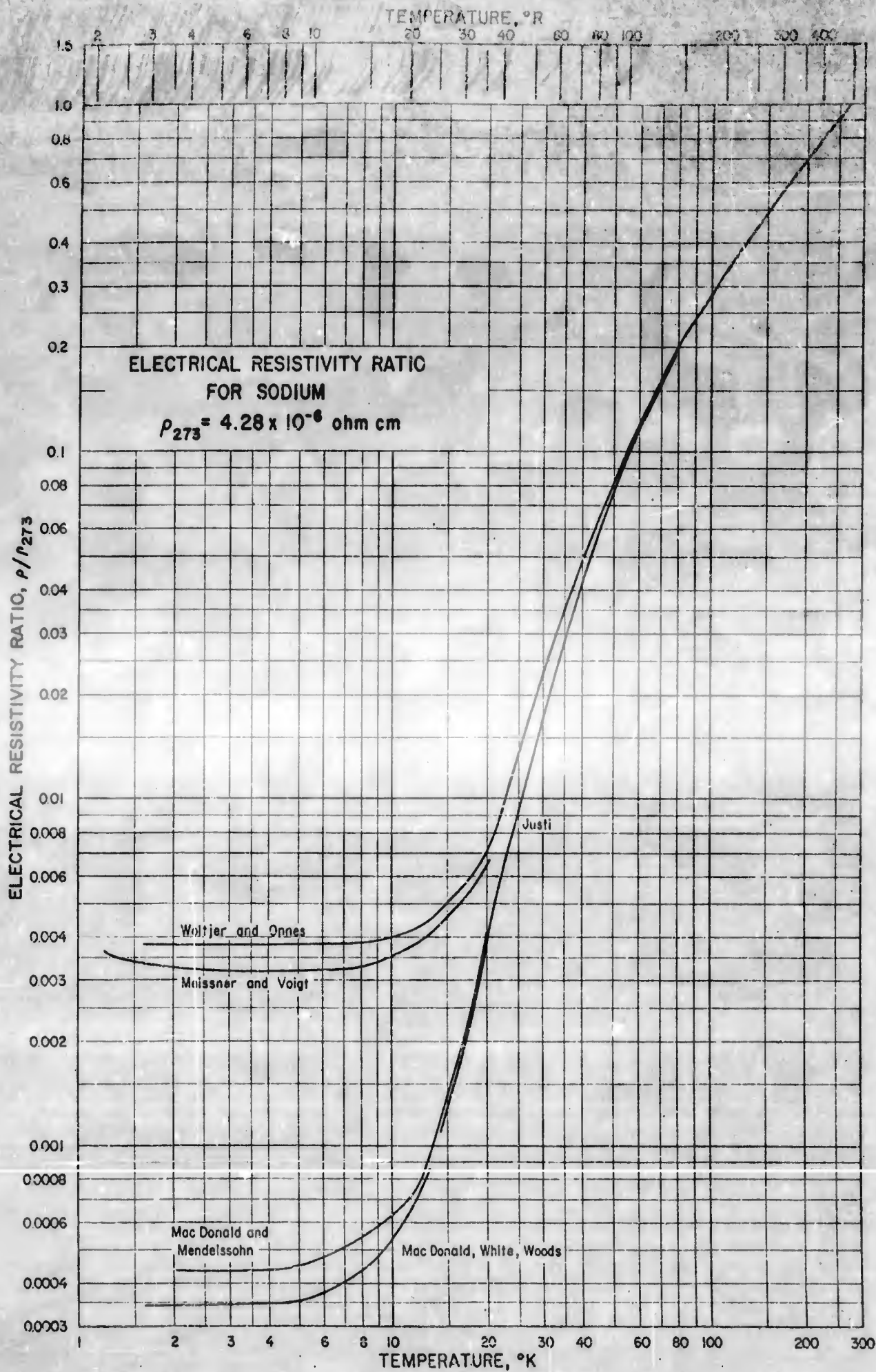
## ELECTRICAL RESISTIVITY of SODIUM (cont.)

Comments: (cont.)

A specimen of high purity as follows with  $\rho$  in ohm-cm,  $\rho_0 = .001472 \times 10^{-6}$ ,  $\rho_1 = 8.6 \times 10^{-16} T^6$  ( $4^\circ\text{K} < T < 9^\circ\text{K}$ ),  $\rho_1 = 8.4 \times 10^{-15} T^5$  ( $8^\circ\text{K} < T < 15^\circ\text{K}$ ).

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			
$\rho$ = Resistivity, (ohm-cm)			
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)			
$\rho_{290}$ = Resistivity at 290°K, (ohm-cm)			
Justi		Woltjer & Onnes	
Temp. °K	$\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
14.0	0.00117	- 80	66.0
20.4	0.00435	-100	57.8
64.0	0.1337	-102.22	56.89
77.6	0.1893		
Mac Donald and Mendelssohn		-120	49.7
		-140	41.7
		-160	33.7
Temp. °K	$\rho/\rho_{290}$	-164.37	31.94
		-180	25.7
		-182.95	24.40
2	0.0004		
4	0.0004	-200	17.6
8	0.0005	-200.96	17.04
12	0.0007	-216.32	10.89
16	0.0016		
20	0.0038	-220	9.4
		-240	3.1
		-260	0.45
Meissner & Voigt		-268.9	0.381
Temp. °K	$\rho/\rho_{273}$	-269.6	0.382
		-270.9	0.382
1.2	0.0037	-271.6	0.382
1.3	0.0035		
4.2	0.0032		
20.4	0.0067		
77.6	0.1875		
87.8	0.2304		



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.; Commun. 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 ( $\rho_{273}$ ) for potassium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $\rho_{273} = 6.1 \times 10^{-6}$  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  $\rho/\rho_{273}$ .) The actual values of  $\rho_{273}$  are not available for the samples used by the several investigators so a datum value

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## 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  $\rho_{273}$  from Hackspill. The electrical resistivity was determined as the sum of the residual and ideal resistivities,  $\rho = \rho_0 + \rho_1$ , using the values reported in this paper for a specimen of high purity as follows with  $\rho$  in ohm-cm,  $\rho_0 = 0.01331 \times 10^{-6}$ ,  $\rho_1 = 2.8 \times 10^{-13} T^5$  ( $T < 8^\circ\text{K}$ ).

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			
$\rho$ = Resistivity, (ohm-cm)			
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)			
$\rho_{290}$ = Resistivity at 290°K, (ohm-cm)			
Justi		MacDonald and Mendelssohn	
Temp. °K	$\rho/\rho_{273}^*$	Temp. °K	$\rho/\rho_{290}^*$
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 fourth 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

 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Van den Berg			
(Group I)		(Group II)	
Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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	$\rho/\rho_{273}$
- 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

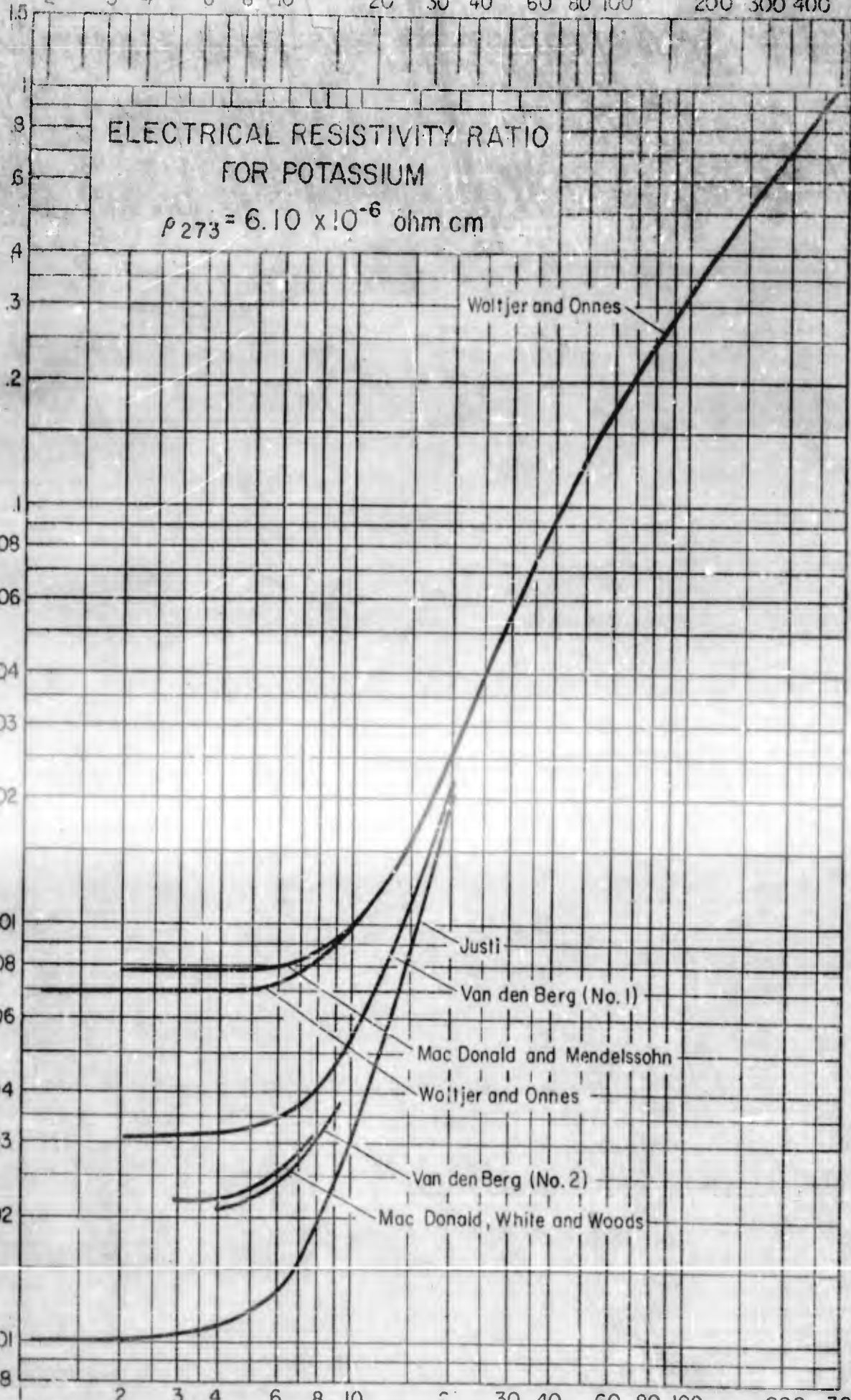
TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

### ELECTRICAL RESISTIVITY RATIO FOR POTASSIUM

$$\rho_{273} = 6.10 \times 10^{-6} \text{ ohm cm}$$

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$



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 ( $\rho_{273}$ ) for rubidium to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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-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 ratios listed with a datum value other than at 273°K, ratios were calculated for  $\rho/\rho_{273}$ .) The value of  $\rho_{273}$  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  $\rho_{273}$  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 composition. 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

 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm) $\rho_{290}$  = Resistivity at 290°K, (ohm-cm)

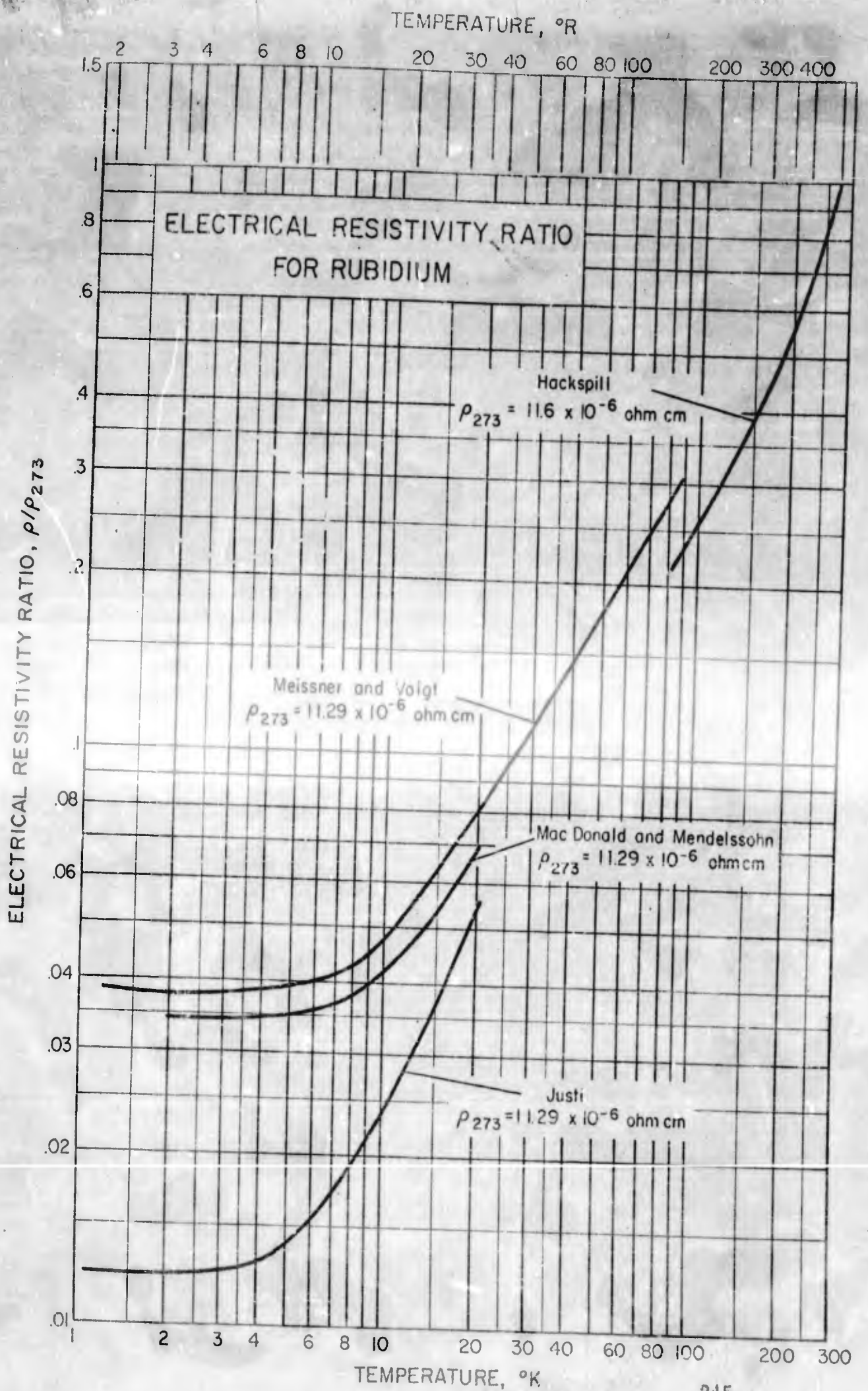
Meissner and Voigt		Justi		MacDonald and Mendelssohn	
Temp.* °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{290}^{**}$
1.25	0.0380	0.88	0.0124	2	0.0311
4.20	0.0391	4.22	0.0133	5	0.0325
20.4	0.0817	14.0	0.0339	10	0.0387
77.6	0.2701	20.4	0.0554	15	0.0487
87.8	0.3043			20	0.0628

\* 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.



## 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 ( $\rho_{273}$ ) for cesium to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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  $\rho/\rho_{273}$ .) The actual values of  $\rho_{273}$  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  $\rho_{273}$  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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

$\rho_{290}$  = Resistivity at 290°K, (ohm-cm)

McLennan, Niven and Wilhelm		Meissner and Voigt		Justi		MacDonald and Mendelssohn	
Temp. °K	$\rho/\rho_{273}^*$	Temp.** °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{290}$
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*

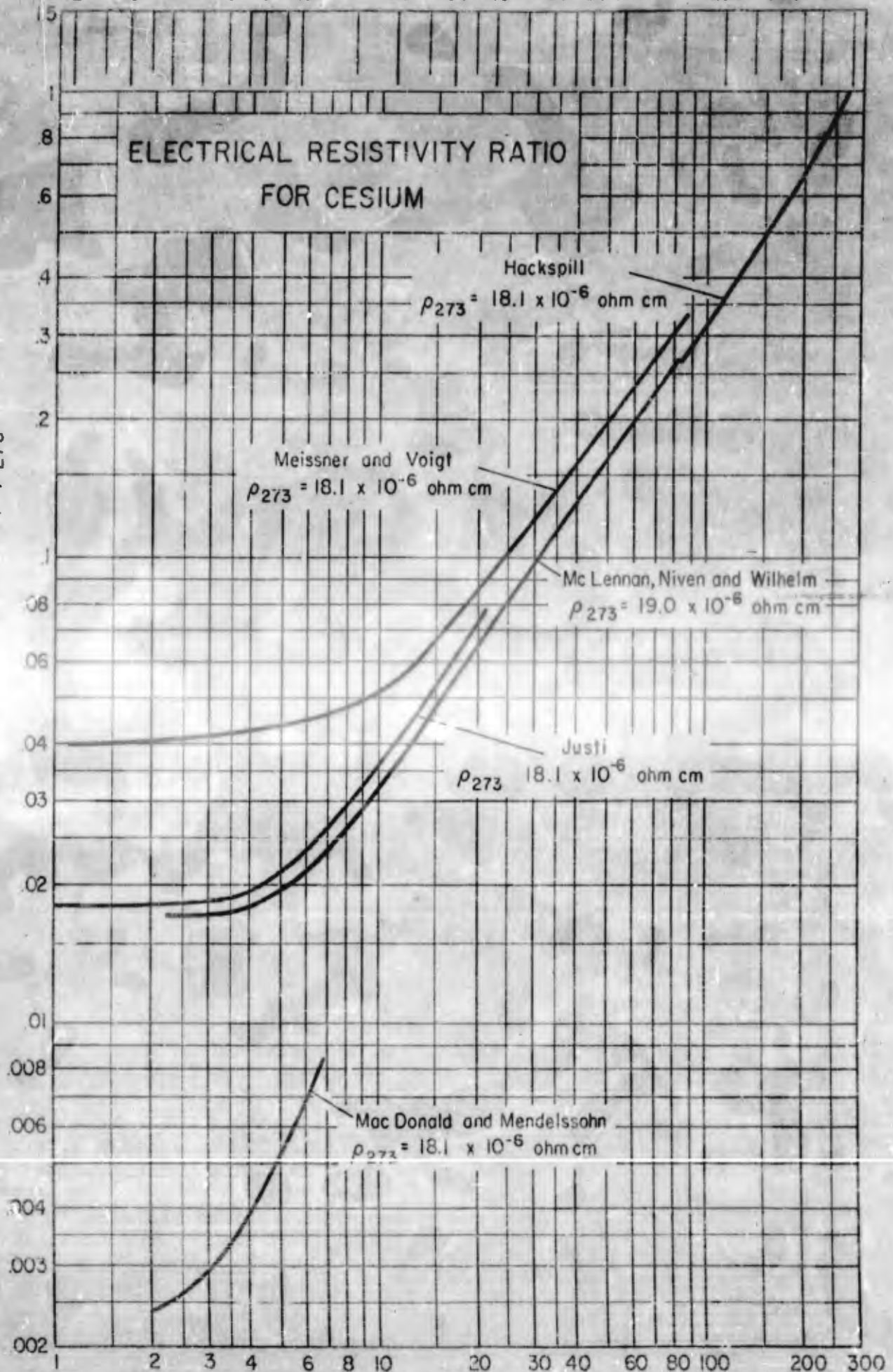
\*Observed values. Values without asterisks have been interpolated.

TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

### ELECTRICAL RESISTIVITY RATIO FOR CESIUM

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$



Hackspill  
 $\rho_{273} = 18.1 \times 10^{-6}$  ohm cm

Meissner and Voigt  
 $\rho_{273} = 18.1 \times 10^{-6}$  ohm cm

McLennan, Niven and Wilhelm  
 $\rho_{273} = 19.0 \times 10^{-6}$  ohm cm

Justi  
 $\rho_{273} = 18.1 \times 10^{-6}$  ohm cm

Mac Donald and Mendelssohn  
 $\rho_{273} = 18.1 \times 10^{-6}$  ohm cm

TEMPERATURE, °K

ELECTRICAL RESISTIVITY of COPPER, Cu  
(Atomic Number 29)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI. 2nd 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 ( $\rho_{273}$ ) for copper to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $1.55 \times 10^{-6}$  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  $\rho_{273}$  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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

de Haas, de Boer and Van den Berg		Henning	
Temp. °K	$\rho/\rho_{273}$	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	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}^{**}$
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.

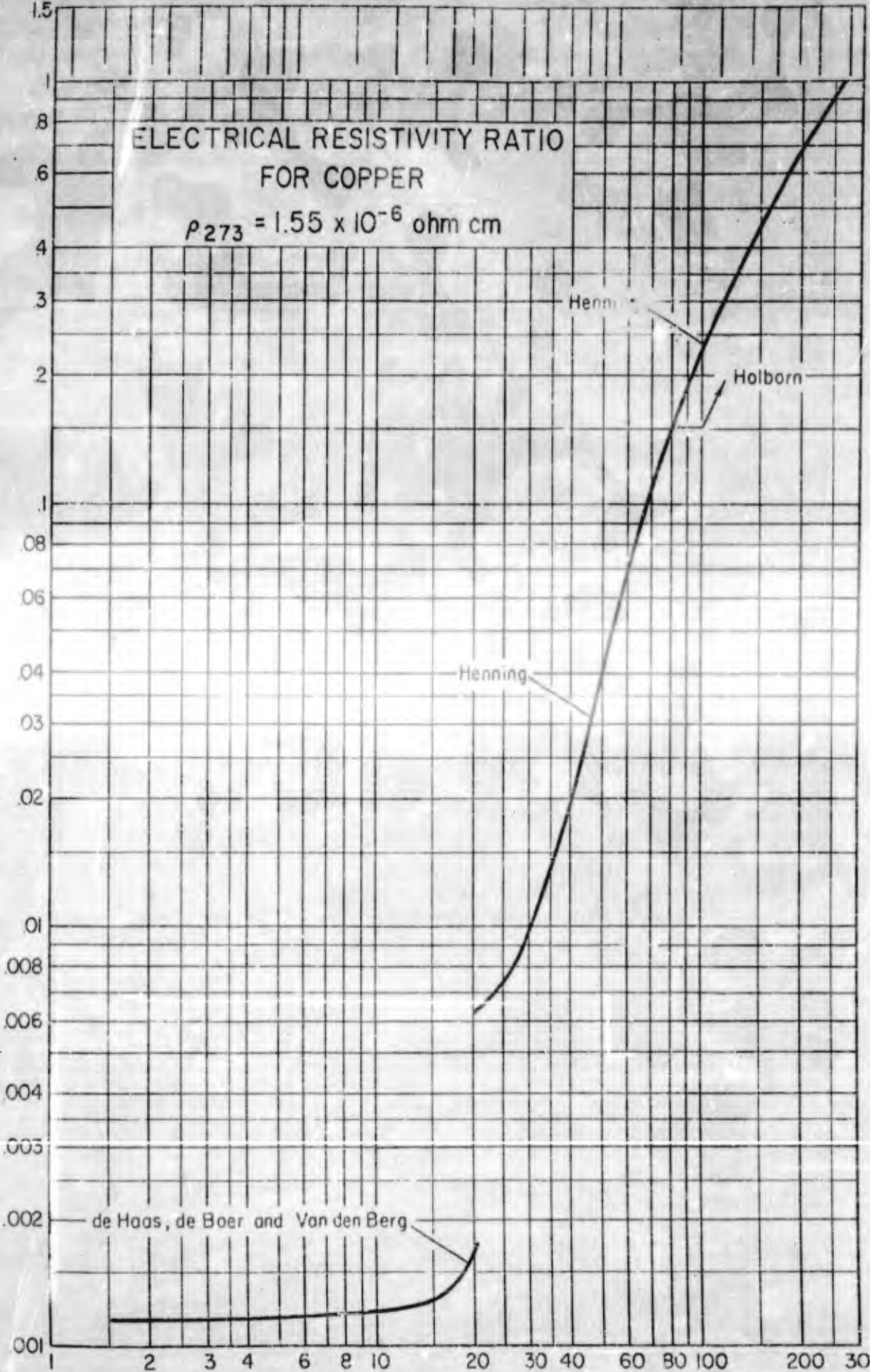
TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$

ELECTRICAL RESISTIVITY RATIO FOR COPPER

$\rho_{273} = 1.55 \times 10^{-6}$  ohm cm



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 ( $\rho_{273}$ ) for silver to be used in calculating values of electrical resistivity is  $1.47 \times 10^{-6}$  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  $\rho_{273}$  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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

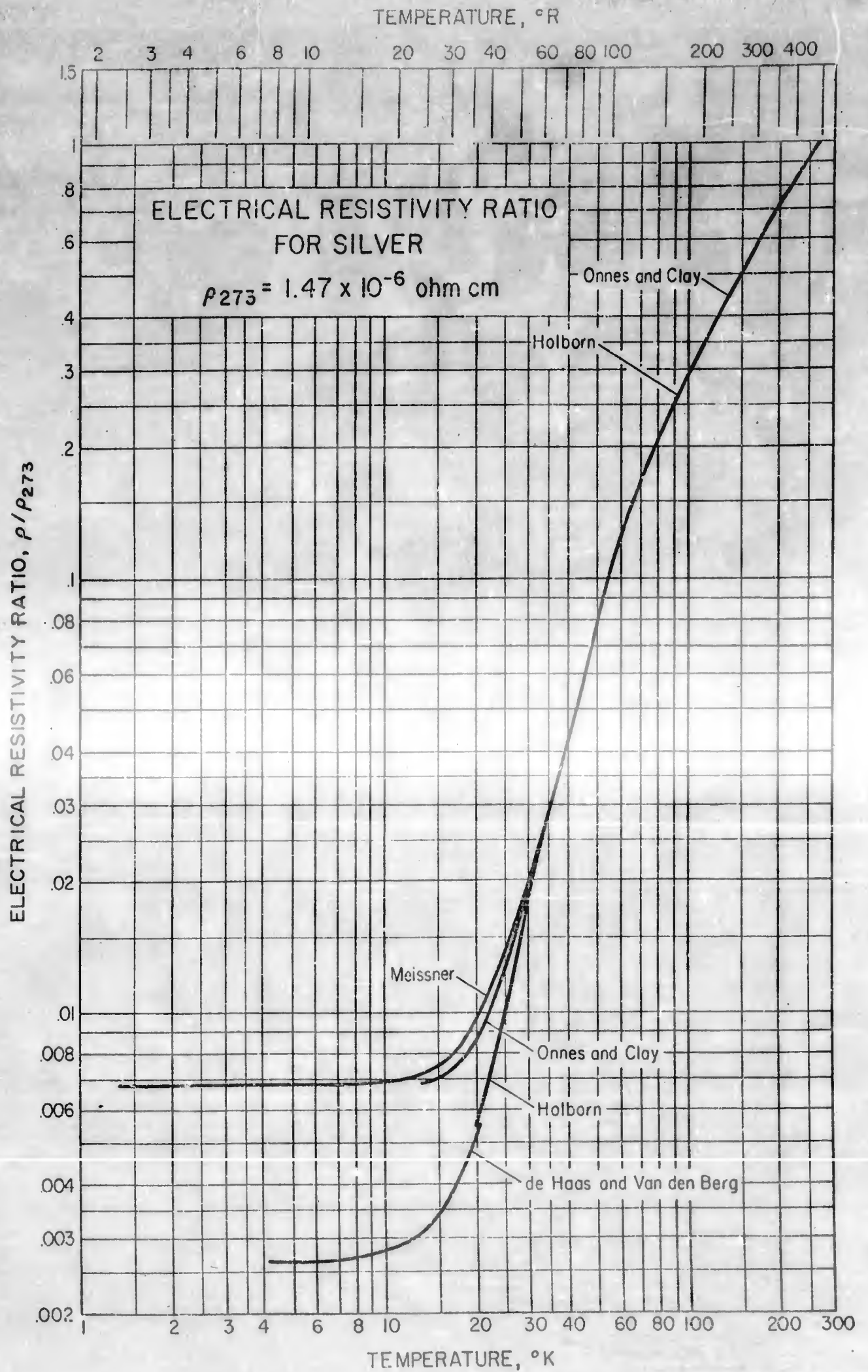
Onnes and Clay					
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 80 +	67.8	-140 +	43.2	-204.67	15.528
-100 +	59.6	-160 +	34.8	-220 +	9.2
-103.81	58.087	-180 +	26.3	-240 +	2.6
-120 +	51.4	-183.57	24.679	-252.92	0.8913
-139.87	43.282	-195.17	19.703	-259.22	0.6942
		-200 +	17.6		

Holborn		Meissner		de Haas and Van den Berg	
Temp. °K	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}$ **	Temp. °K	$\rho/\rho_{273}$
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.



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 ( $\rho_{273}$ ) for gold to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $2.06 \times 10^{-6}$  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  $\rho_{273}$  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.

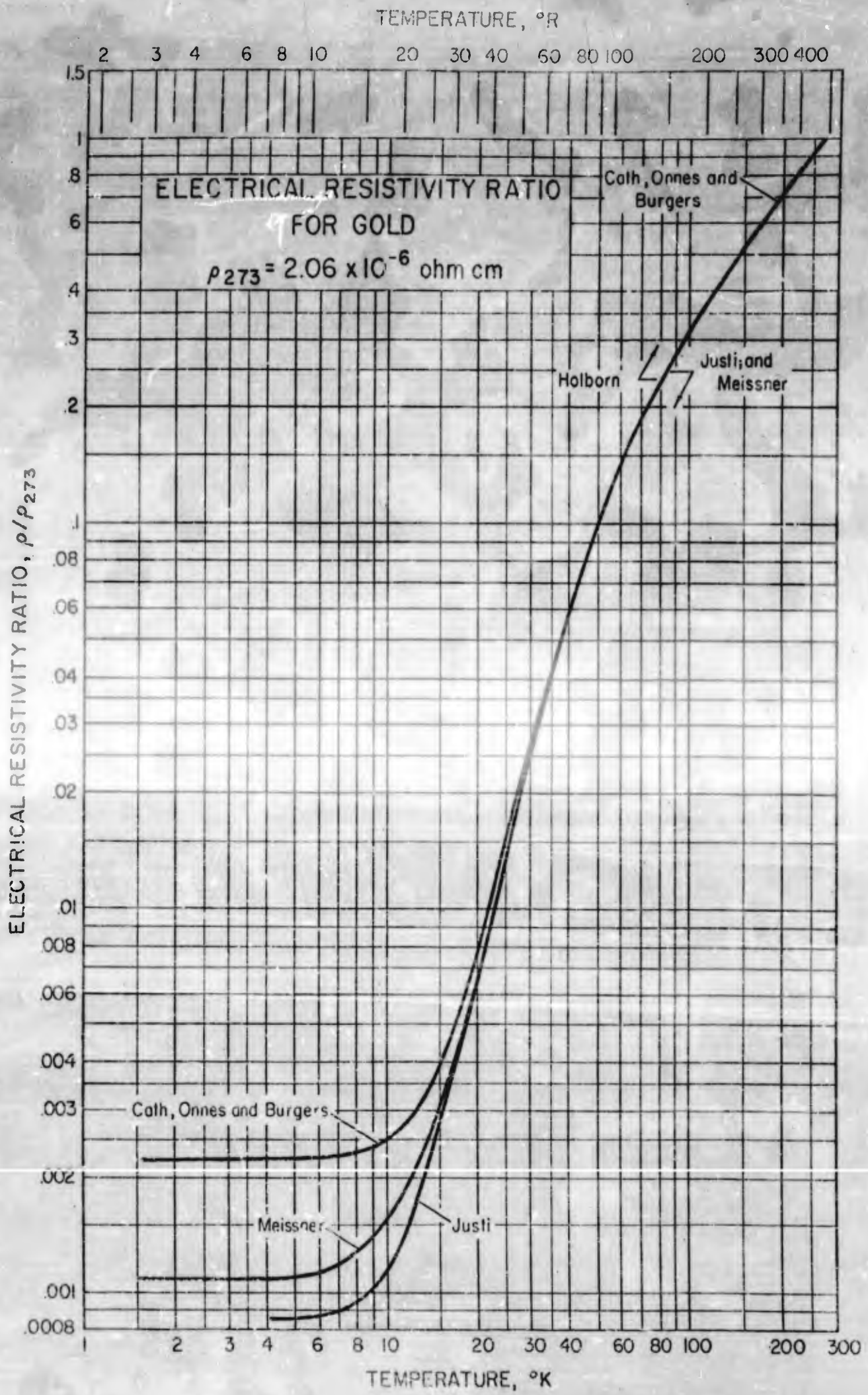
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## ELECTRICAL RESISTIVITY of GOLD (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = 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	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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		



ELECTRICAL RESISTIVITY 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 ( $\rho_{273}$ ) for beryllium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $3.2 \times 10^{-6}$  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  $\rho_{273}$  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  $\rho_{273}$ .

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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K; (ohm-cm)

Lewis	
Temp. °K	$\rho/\rho_{273}$
84.2	0.273
196.2	0.586
294.2	1.174

MacDonald and Mendelssohn	
Temp. °K	$\rho/\rho_{290}^*$
4.2	0.276
20.4	0.276
90.0	0.322

Meissner and Voigt	
Temp.** °K	$\rho/\rho_{273}$
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.

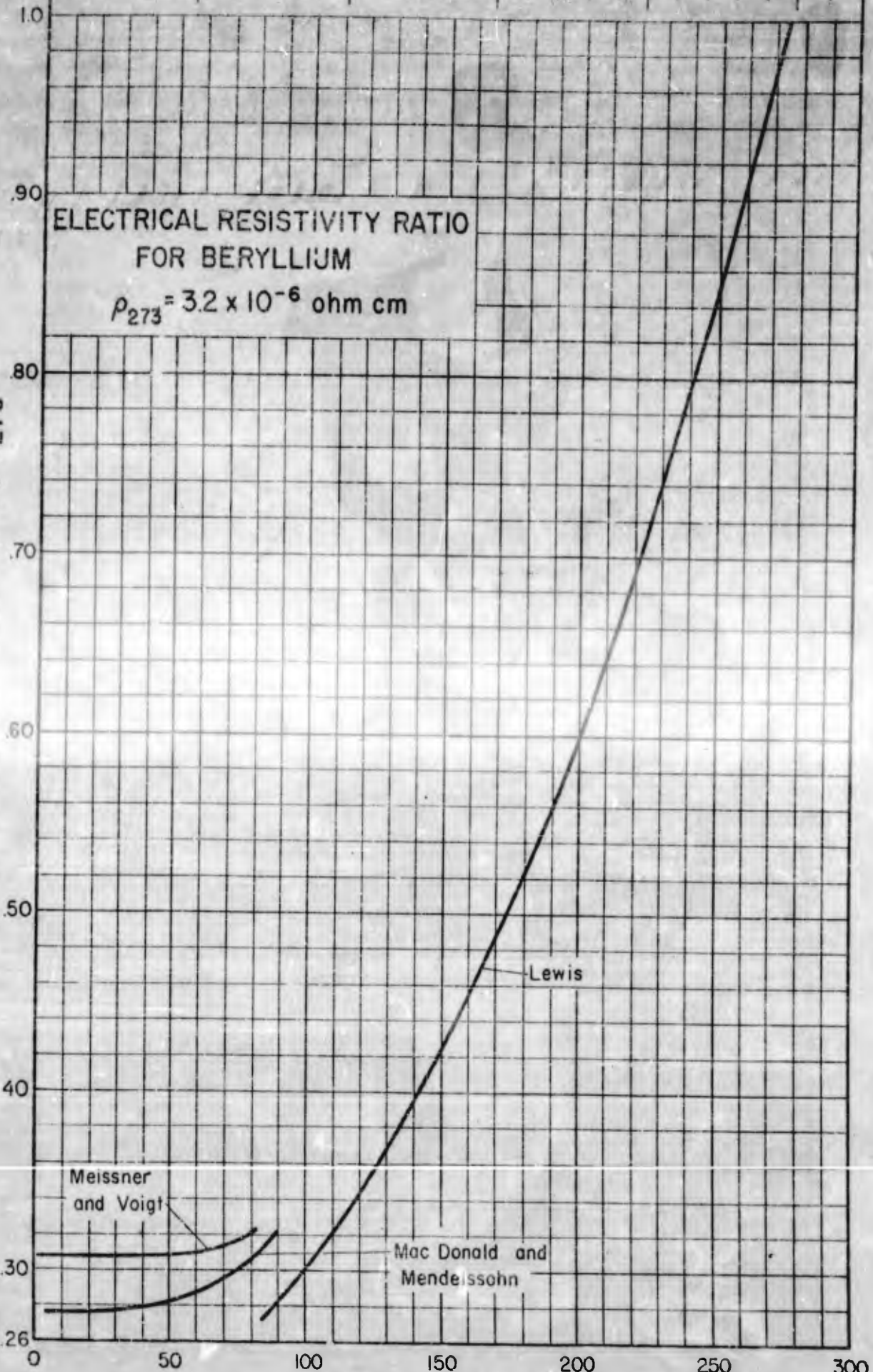
TEMPERATURE, °R

0 100 200 300 400 500

ELECTRICAL RESISTIVITY RATIO  
FOR BERYLLIUM

$\rho_{273} = 3.2 \times 10^{-6}$  ohm cm

ELECTRICAL RESISTIVITY RATIO,  $\rho / \rho_{273}$



Lewis

Meissner  
and Voigt

Mac Donald and  
Mendelsohn

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 ( $\rho_{273}$ ) for magnesium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $4.31 \times 10^{-6}$  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  $\rho_{273}$  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

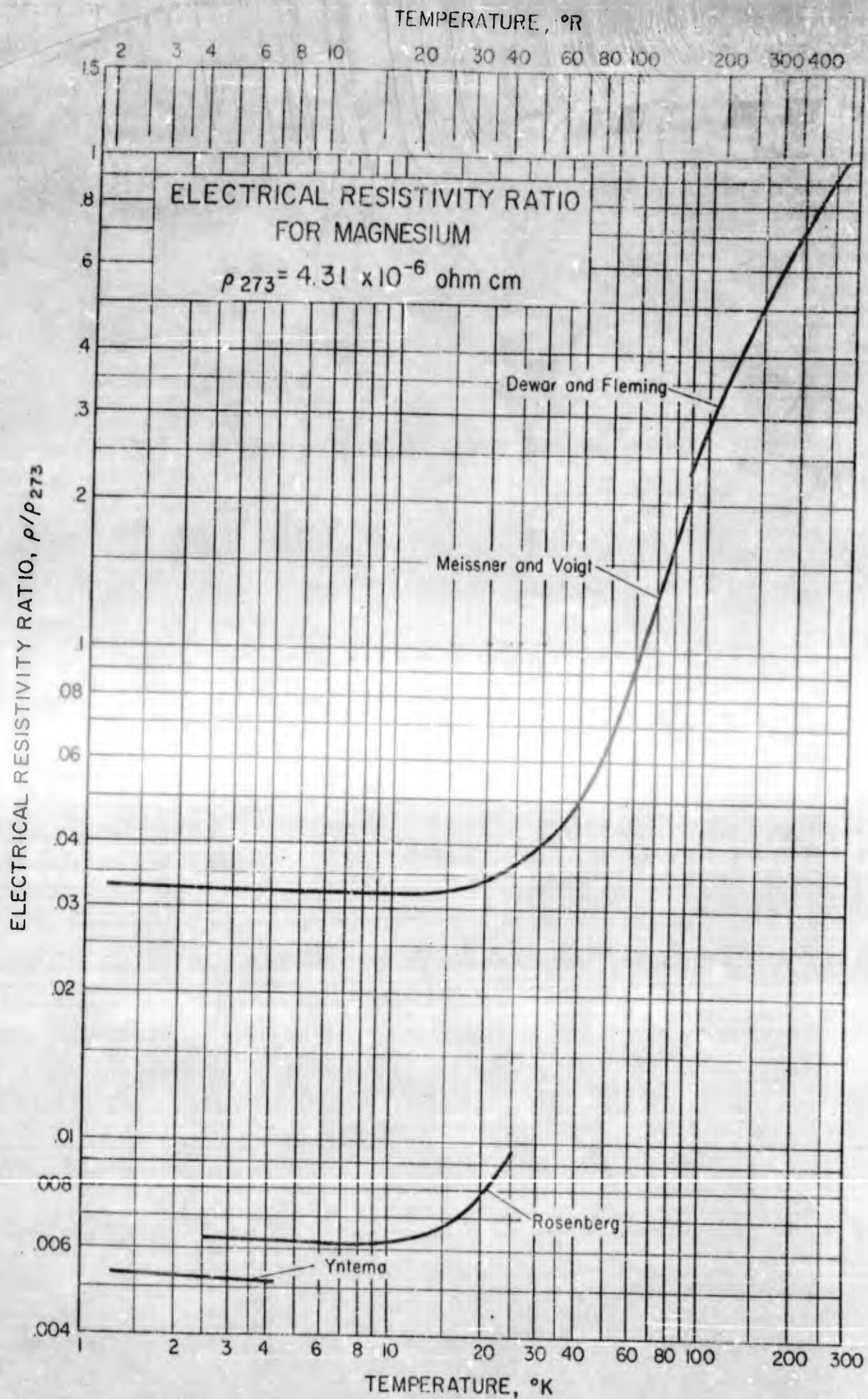
 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K (ohm-cm)

Meissner and Voigt		Rosenberg	
Temp.* °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$ **
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	$\rho/\rho_{273}$	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.



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 ( $\rho_{273}$ ) for calcium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $4.06 \times 10^{-6}$  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  $\rho/\rho_{273}$ .) The actual values of  $\rho_{273}$  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  $\rho_{273}$ .

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.)

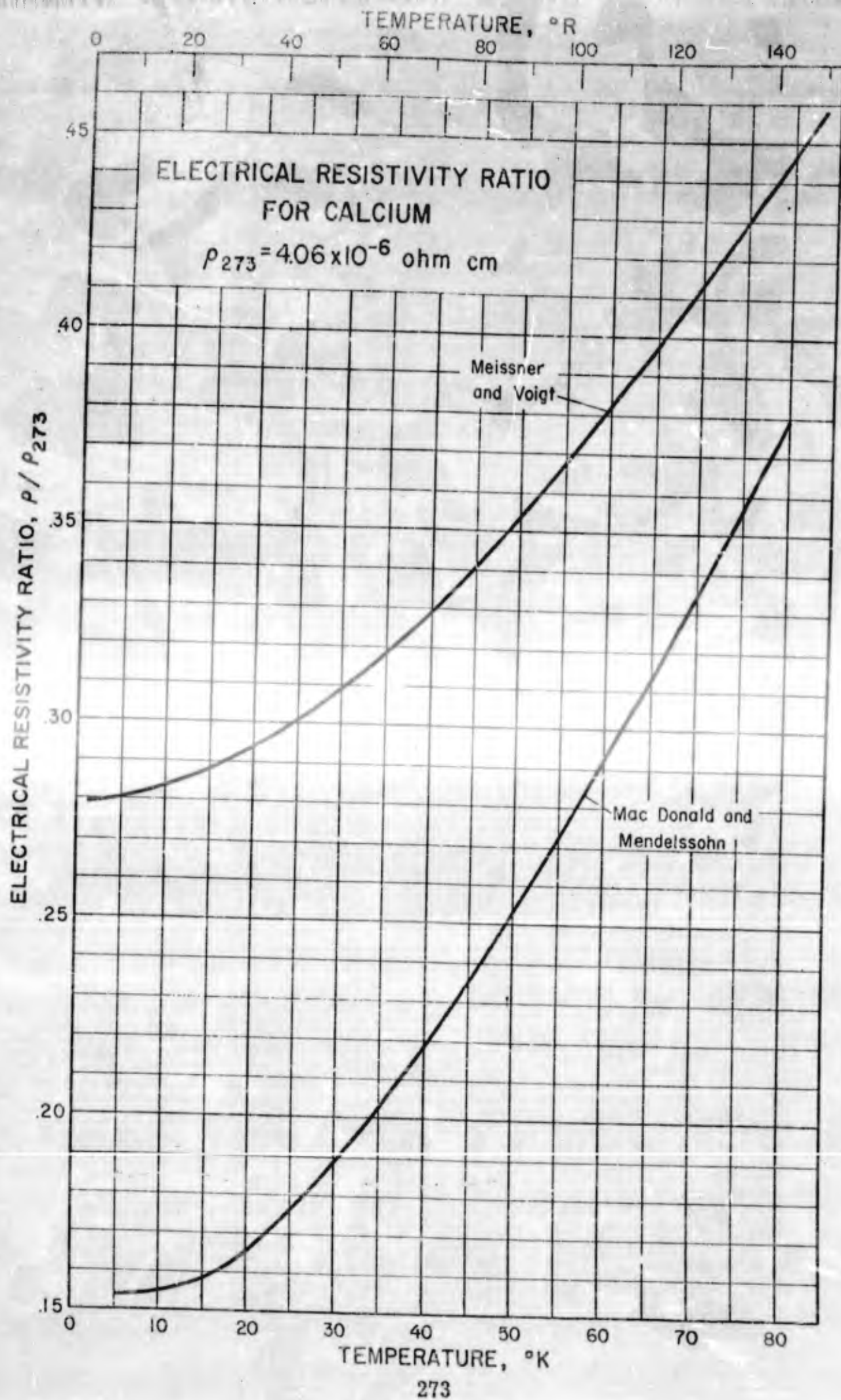
## ELECTRICAL RESISTIVITY of CALCIUM (Cont.)

Tables of Values of Electrical Resistivity

- $\rho$  = Resistivity, (ohm-cm)  
 $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)  
 $\rho_{290}$  = Resistivity at 290°K, (ohm-cm)

MacDonald and Mendelssohn	
Temp. °K	$\rho/\rho_{290}$
5	0.143
10	0.144
20	0.155
40	0.205
60	0.275
80	0.355

Meissner and Voigt	
Temp. °K	$\rho/\rho_{273}$
1.3	0.2792
4.2	0.2807
20.4	0.3536
77.7	0.4398
83.6	0.4582



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 ( $\rho_{273}$ ) for strontium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $30.7 \times 10^{-6}$  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  $\rho/\rho_{273}$ .) The actual values of  $\rho_{273}$  are not available for the samples used by the investigators whose data appear on the graph so a datum value reported by Bridgman ( $\rho_{273} = 30.7 \times 10^{-6}$  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  $\rho_{273}$ .

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.)

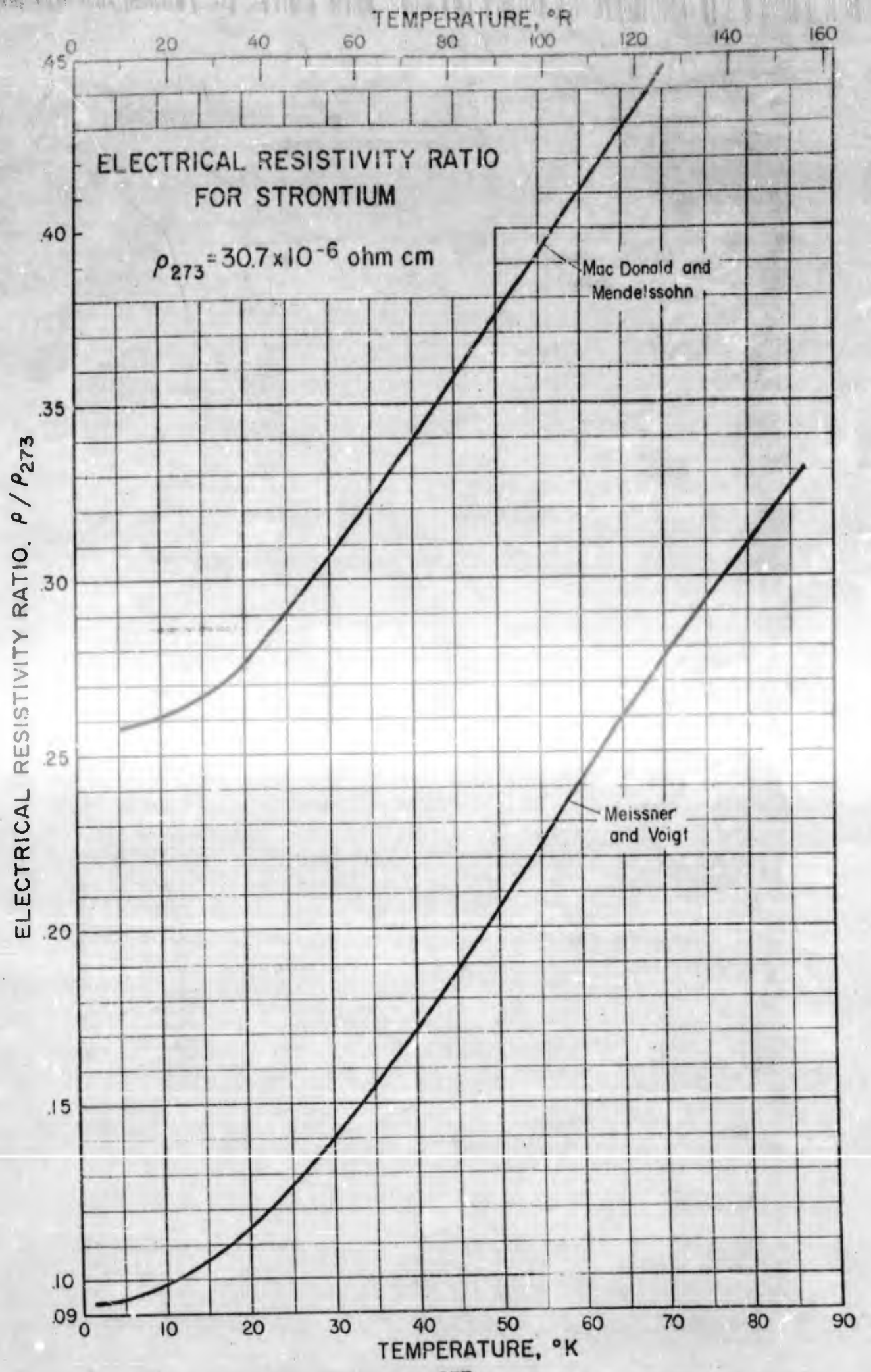
## ELECTRICAL RESISTIVITY of STRONTIUM (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm) $\rho_{290}$  = Resistivity at 290°K, (ohm-cm)

Meissner and Voigt	
Temp. °K	$\rho/\rho_{273}$
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	$\rho/\rho_{290}^*$
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.



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 ( $\rho_{273}$ ) for barium to be used in calculating electrical resistivity ( $\rho_T$ ) 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  $\rho_{273}$  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  $\rho_{273}$ .

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.)

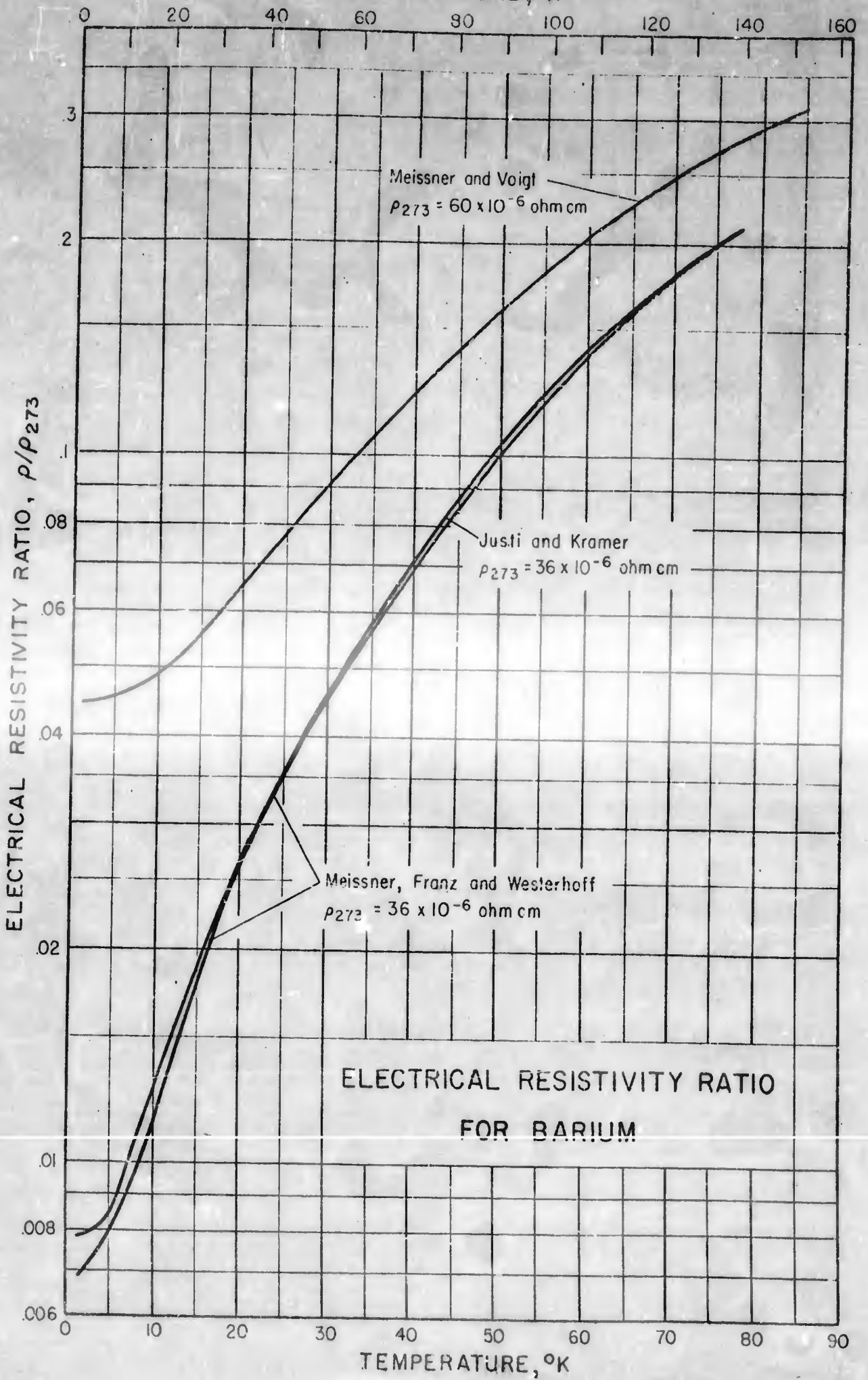
Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Justi and Kramer		Meissner, Franz and Westerhoff	
Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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	$\rho/\rho_{273}$
1.26	0.0446
4.21	0.0450
20.4	0.0670
78.0	0.2843
85.7	0.3149

17.121e

TEMPERATURE, °R



ELECTRICAL RESISTIVITY RATIO  
FOR BARIUM

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 ( $\rho_{273}$ ) for zinc to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $5.65 \times 10^{-6}$  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  $\rho_{273}$  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.)

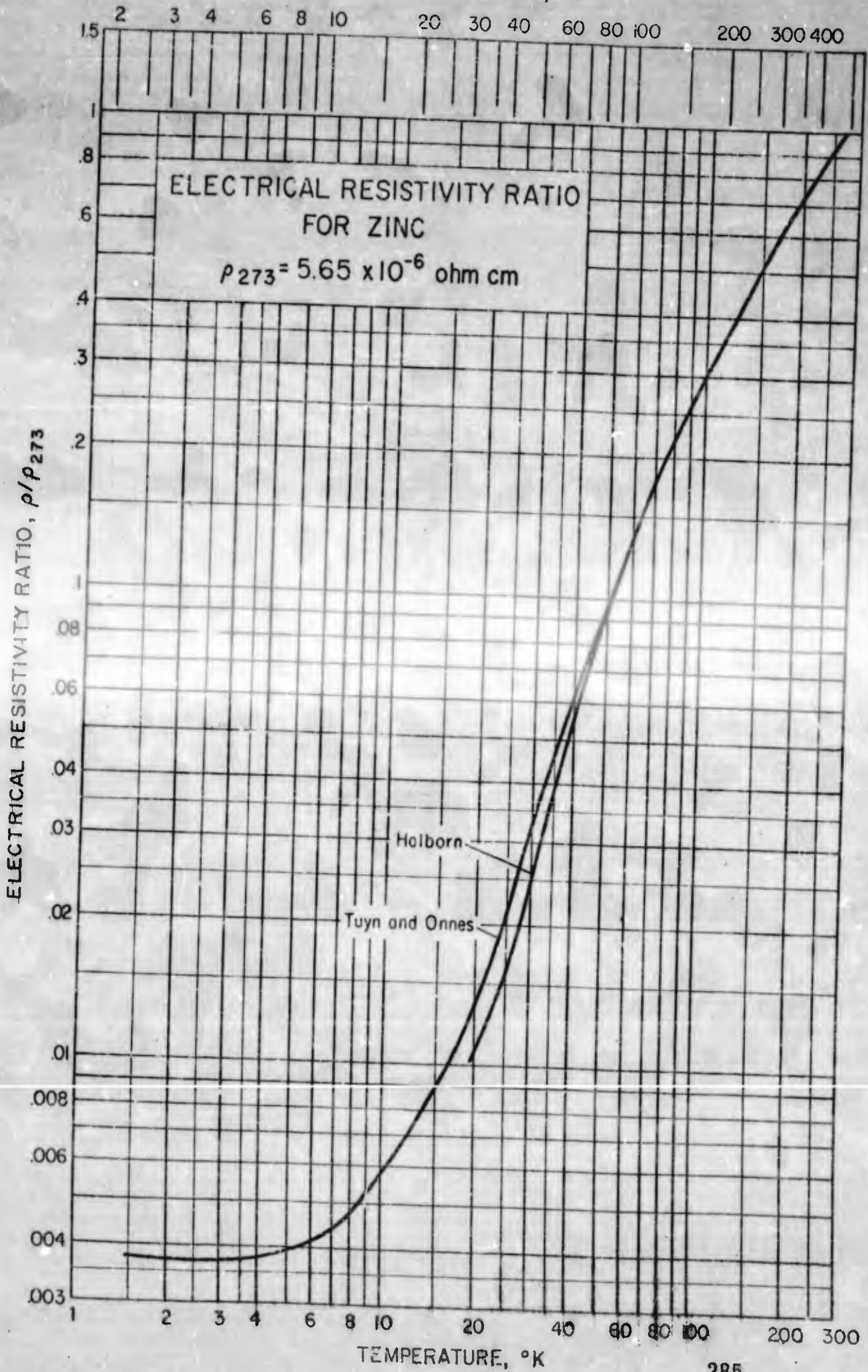
Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273° K, (ohm-cm)

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	25.507	-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	$\rho/\rho_{273}$
20	0.0104
81	0.2200
195	0.6862

17.122 a

TEMPERATURE, °R



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, I.; 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 ( $\rho_{273}$ ) for cadmium to be used in calculating electrical resistivity is  $7.07 \times 10^{-6}$  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  $\rho_{273}$  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.

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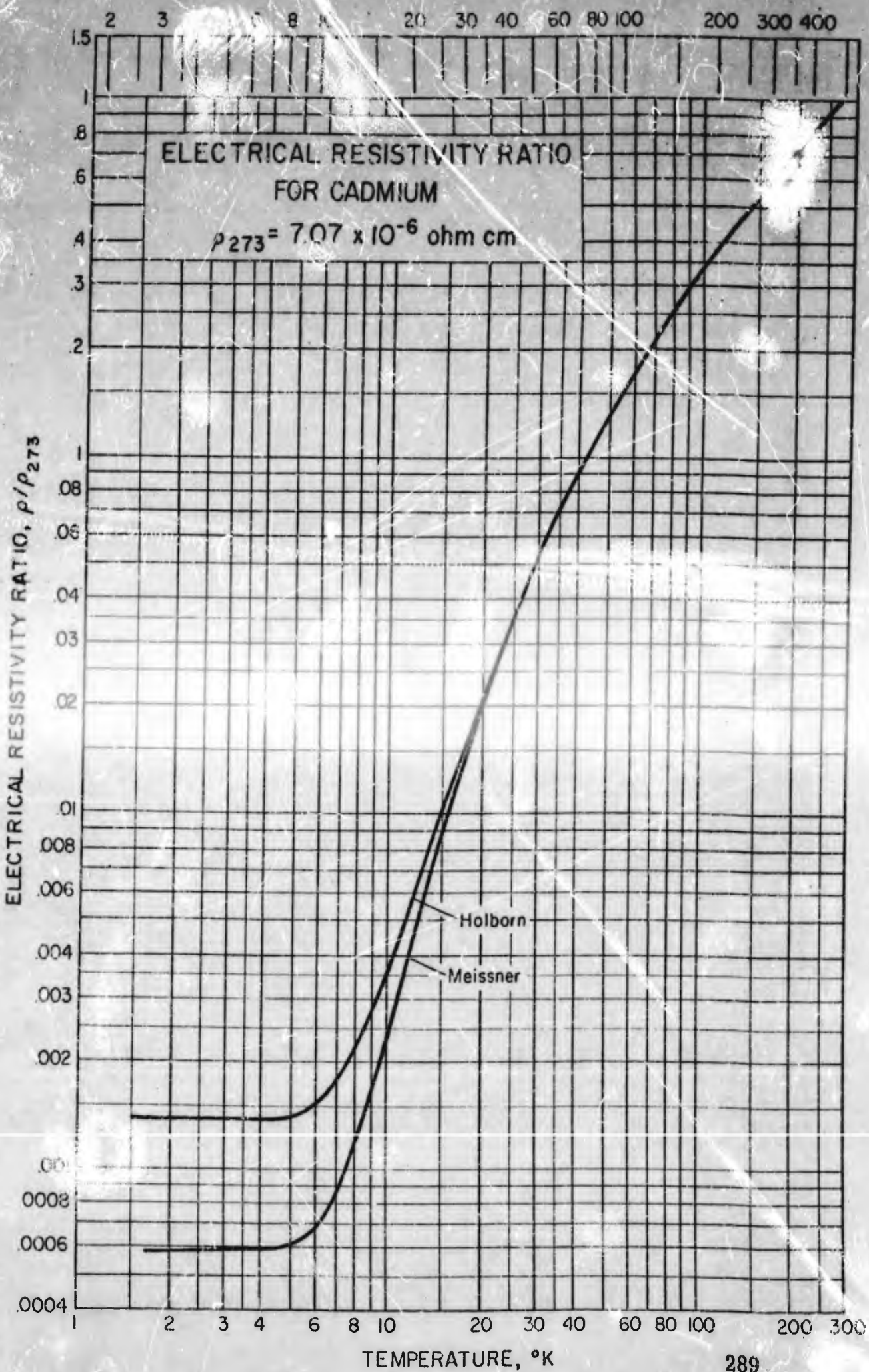
## ELECTRICAL RESISTIVITY of CADMIUM (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  - 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	$\rho/\rho_{273}$
1.68	0.000594
4.2	0.000614
20.4	0.0209
82.5	0.2579

TEMPERATURE, °R



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 ( $\rho_{273}$ ) for mercury to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $26.6 \times 10^{-6}$  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  $\rho_{273}$  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  $\rho_{273}$ . 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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt	
Temp.* °K	$\rho/\rho_{273}$
4.20	0.0020
20.46	0.0642
77.8	0.2820
88.9	0.3259

Onnes and Holst	
Temp.* °K	$\rho/\rho_{273}$
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.

TEMPERATURE, °R

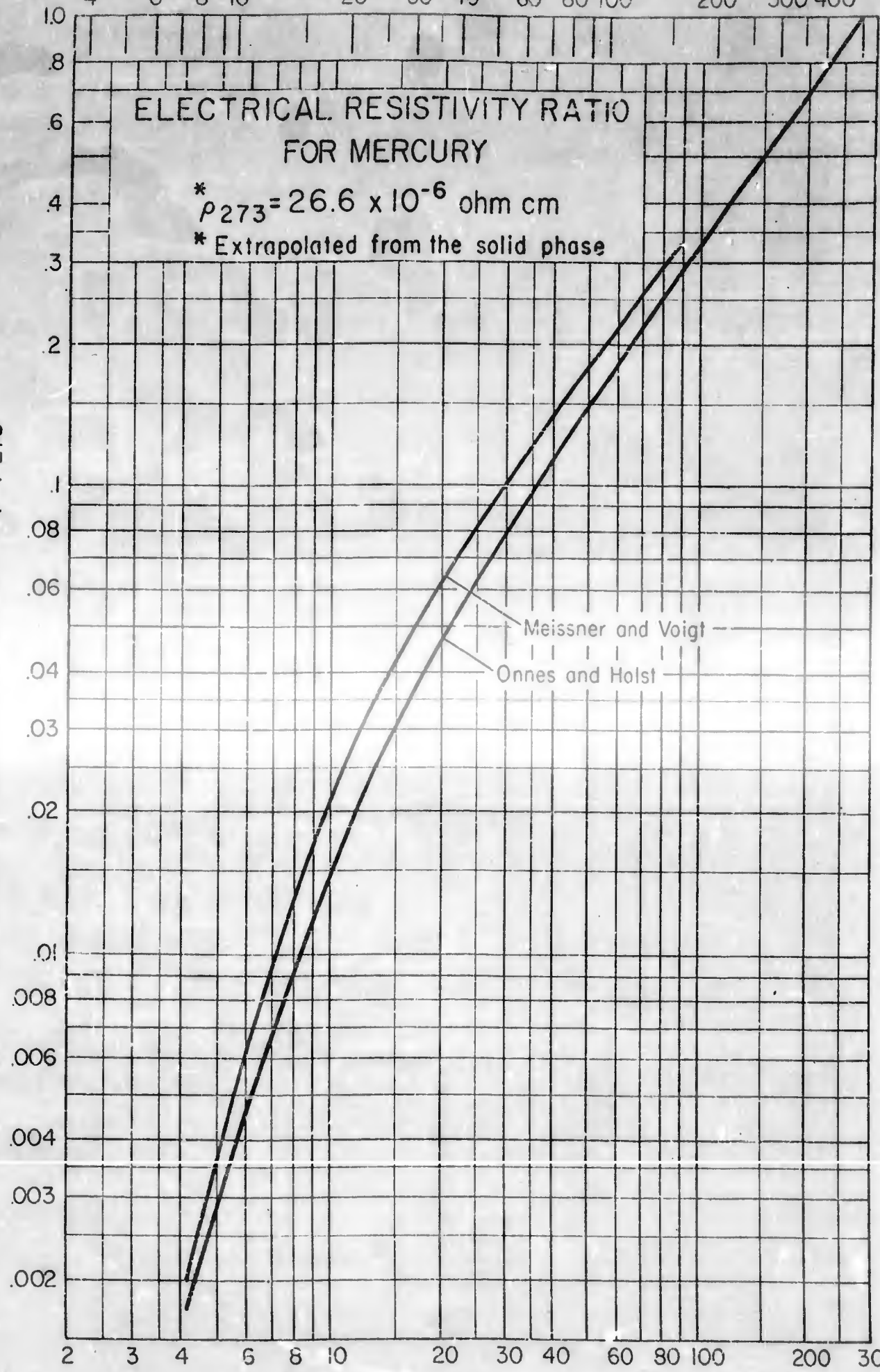
4 6 8 10 20 30 40 60 80 100 200 300 400

### ELECTRICAL RESISTIVITY RATIO FOR MERCURY

\*  $\rho_{273} = 26.6 \times 10^{-6}$  ohm cm

\* Extrapolated from the solid phase

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$



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 ( $\rho_{273}$ ) for lanthanum to be used in calculating electrical resistivity is  $63.0 \times 10^{-6}$  ohm-cm. The curve should not be extrapolated to lower temperatures since lanthanum becomes a superconductor between 4.8°K and 5.8°K.

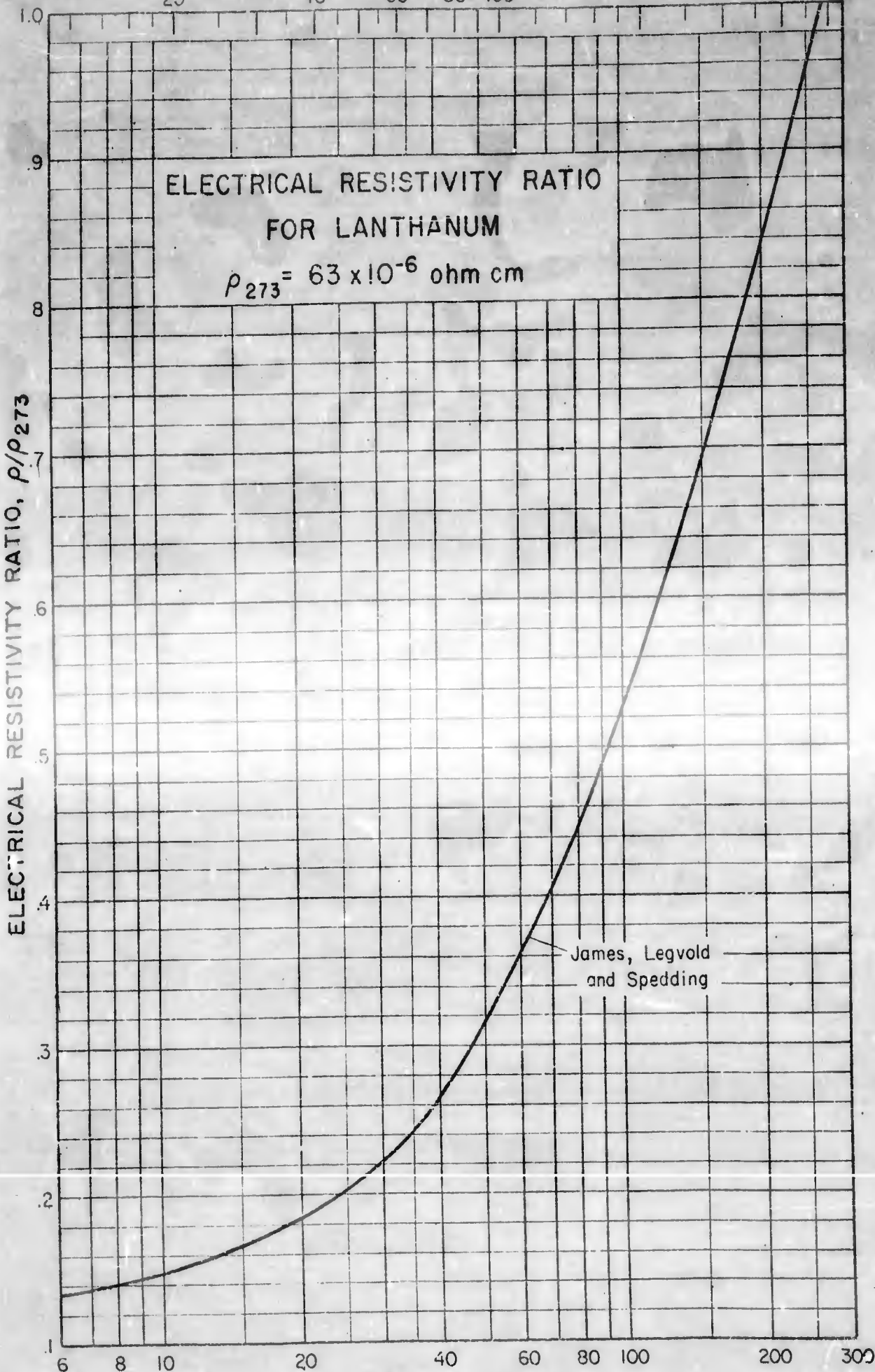
The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of  $\rho_{273}$  determined by James, et al., and suggested as a datum value here is  $\rho_{273} = 63.0 \times 10^{-6}$  ohm-cm.

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	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K (ohm-cm)	
James, et al.	
Temp. °K	$\rho/\rho_{273}^*$
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.	

TEMPERATURE, °R

20 40 60 80 100 200 400



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 ( $\rho_{273}$ ) for cerium to be used in calculating electrical resistivity is  $81.0 \times 10^{-6}$  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".

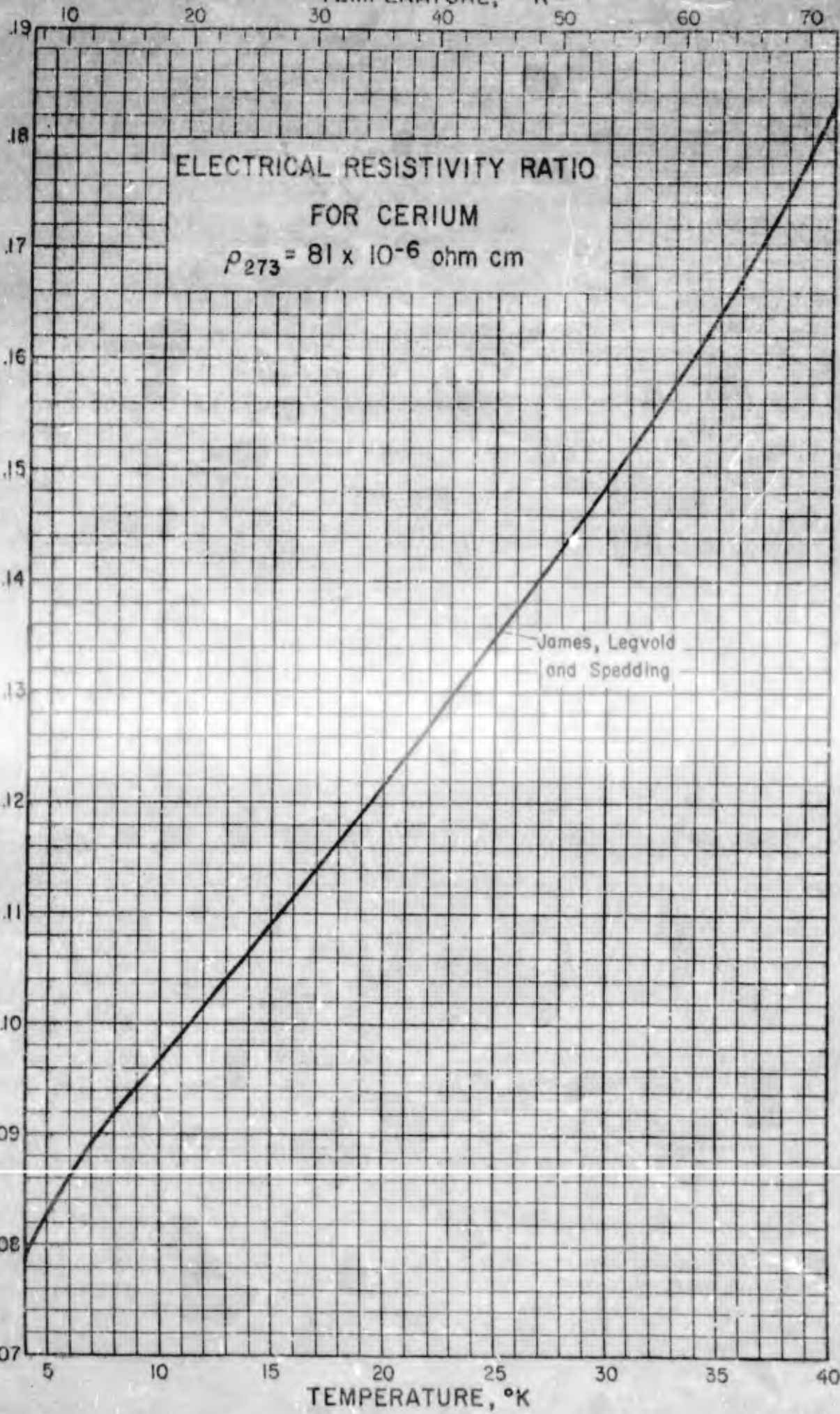
The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of  $\rho_{273}$  determined by James, et al., and suggested as a datum value here is  $\rho_{273} = 81.0 \times 10^{-6}$  ohm-cm.

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	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K (ohm-cm)	
James, et al.	
Temp. °K	$\rho/\rho_{273}$ *
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.	

17.131b

TEMPERATURE, °R



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 ( $\rho_{273}$ ) for praseodymium to be used in calculating electrical resistivity ( $\rho_T$ ) is  $76.0 \times 10^{-6}$  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  $\rho_{273}$  determined by James, et al., and suggested as a datum value here is  $\rho_{273} = 76.0 \times 10^{-6}$  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 0.0315% 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	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)	
James, et al.	
Temp. °K	$\rho/\rho_{273}$ *
4	0.112
20	0.209
80	0.550
160	0.768
* The third decimal place of the electrical resistivity is somewhat in doubt.	

17.131c

TEMPERATURE, °R

10 20 40 60 80 100 200 400

ELECTRICAL RESISTIVITY RATIO  
FOR PRASEODYMIUM  
 $\rho_{273} = 76 \times 10^{-6}$  ohm cm

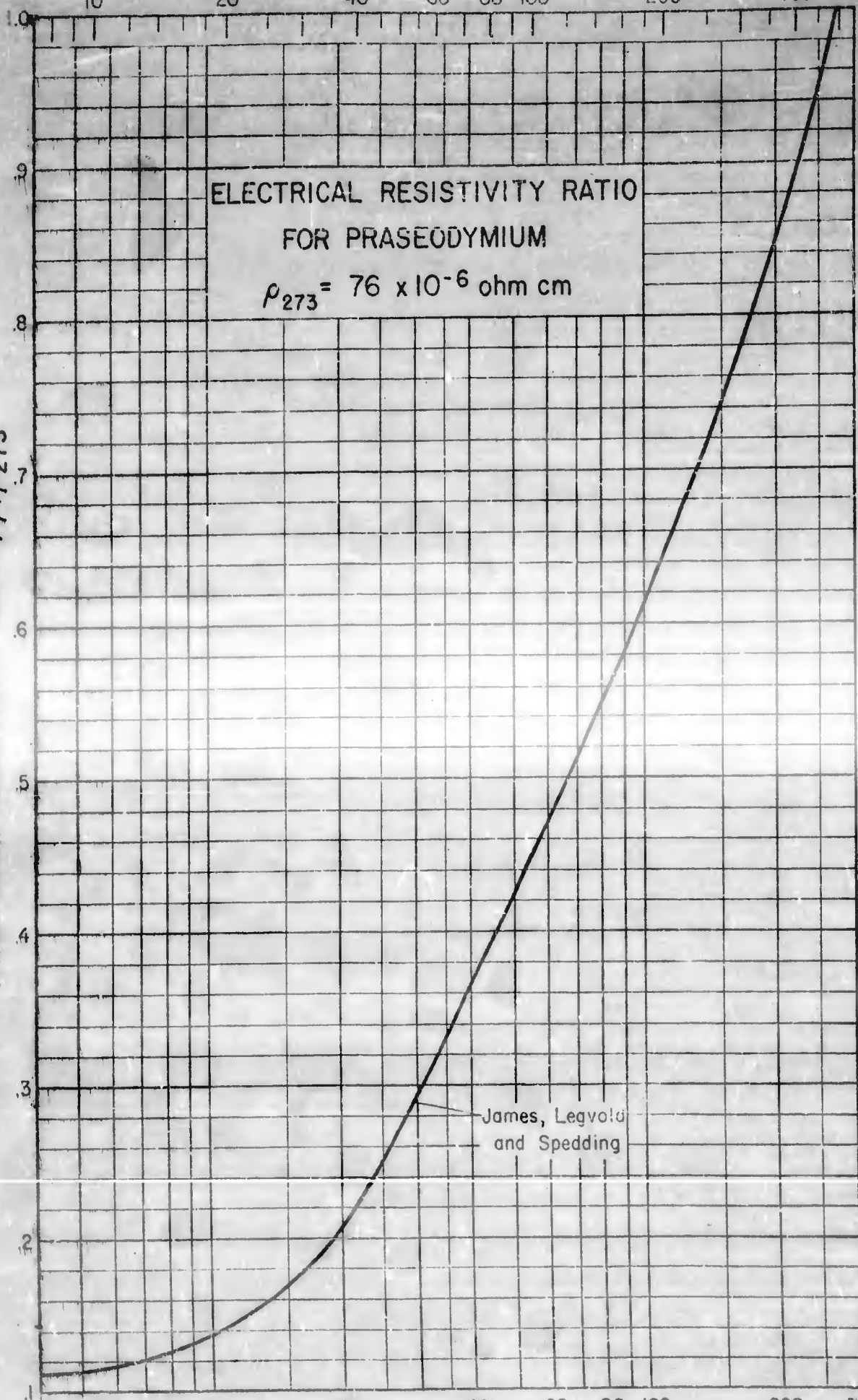
ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$

James, Legvold  
and Spedding

TEMPERATURE, °K

4 6 8 10 20 40 60 80 100 200 300

300



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 ( $\rho_{273}$ ) for neodymium to be used in calculating electrical resistivity is  $71.0 \times 10^{-6}$  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  $\rho_{273}$  determined by James, et al., and suggested as a datum value here is  $\rho_{273} = 71.0 \times 10^{-6}$  ohm-cm.

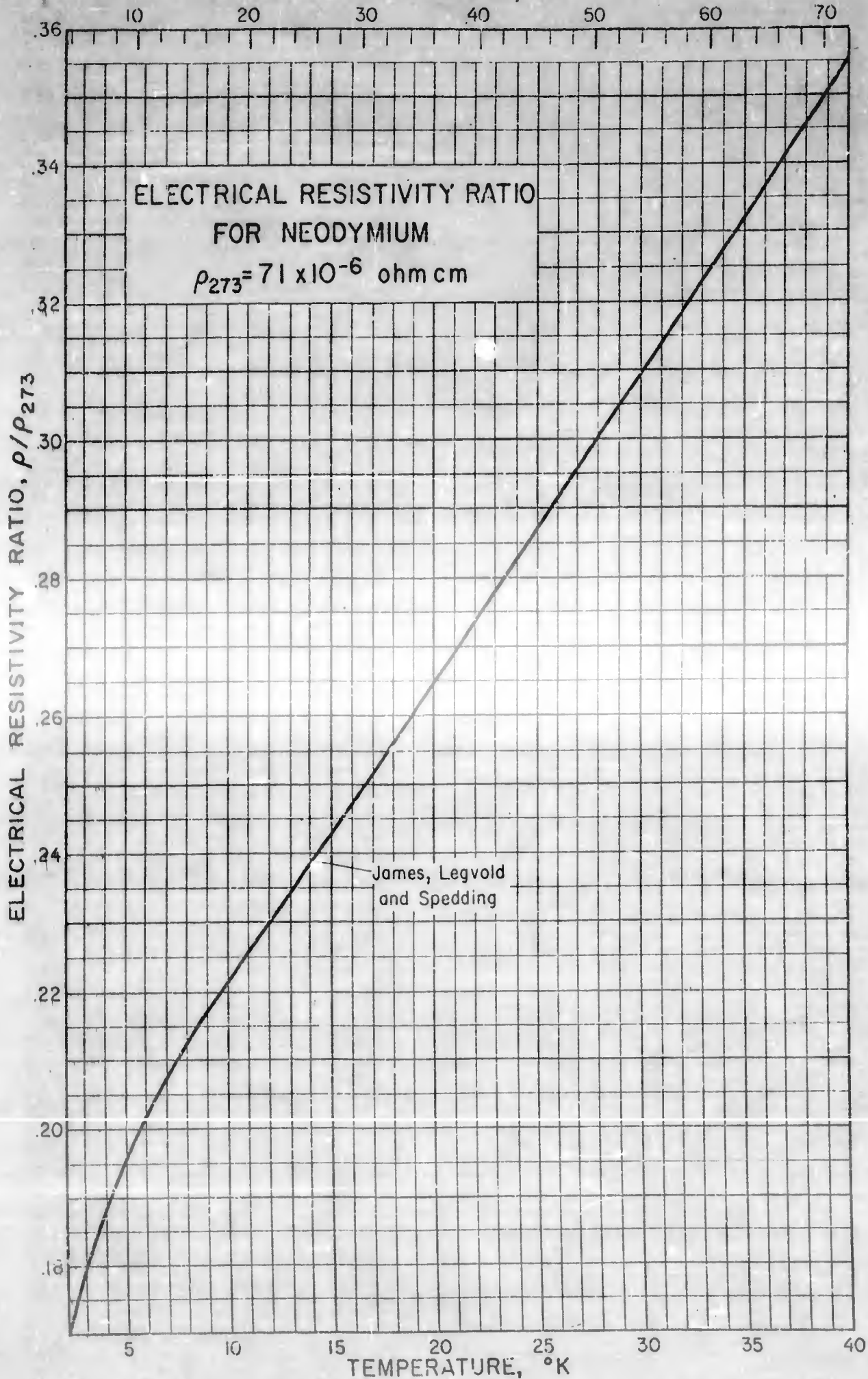
The samples used by James, et al., were of the cast polycrystalline type with less than 1.1% impurities. The impurities are further listed as being < 1% Mg; < 0.025% Ca; < 0.01% other rare earths, and 0.0178% Fe. No information was listed in Landolt-Börnstein on mechanical strain or heat treatment for any of the samples.

Table of Values of Electrical Resistivity	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K (ohm-cm)	
James, et al.	
Temp. °K	$\rho/\rho_{273}$ *
2	0.170
8	0.213
24	0.283
40	0.356

\* The third decimal place of the electrical resistivity values is somewhat in doubt.

17.131d

TEMPERATURE, °R



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 ( $\rho_{273}$ ) for gadolinium to be used in calculating electrical resistivity ( $\rho_T$ ) is  $140 \times 10^{-6}$  ohm-cm.

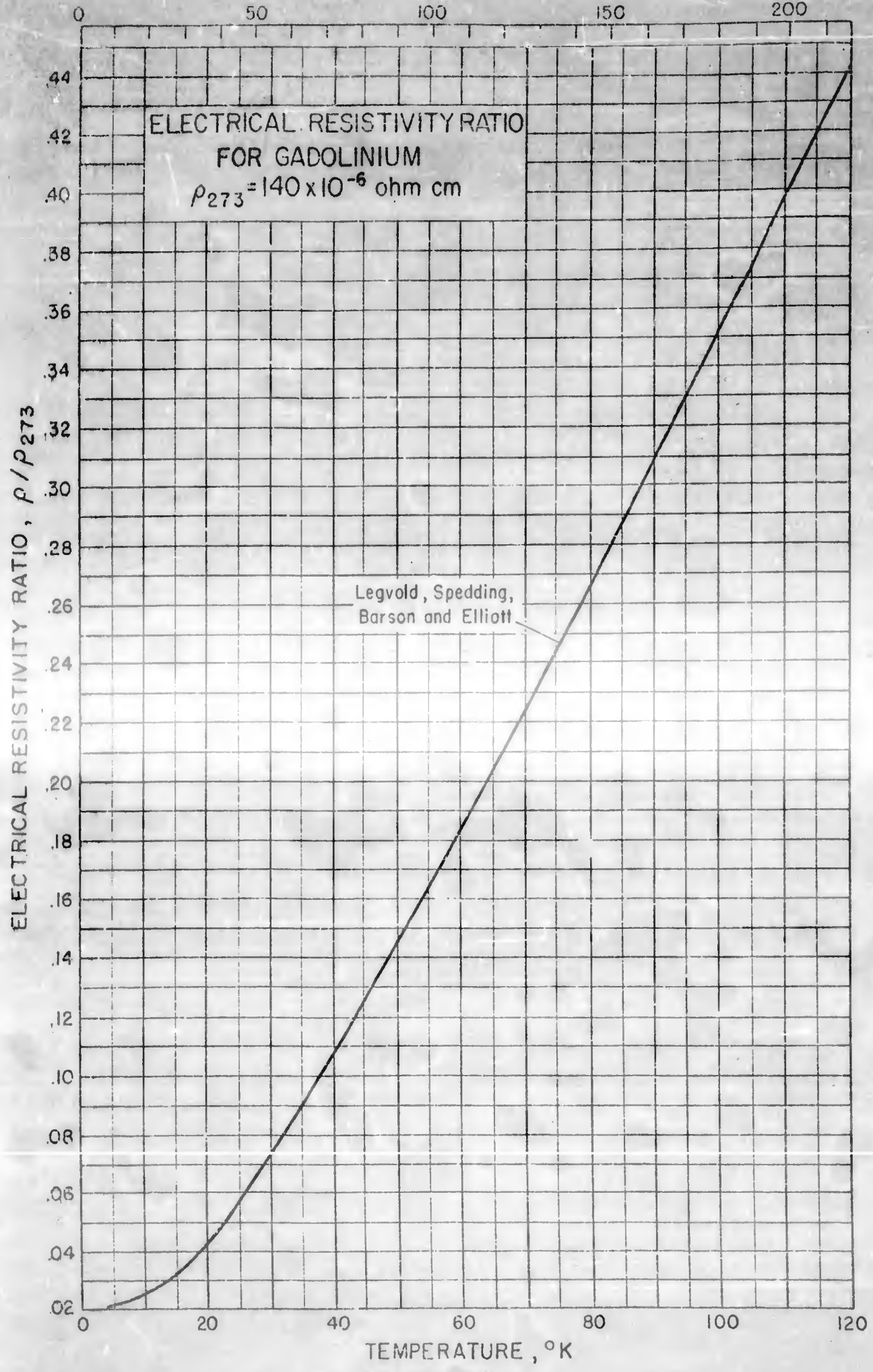
The data for this graph were taken from the reference cited above under "Source of Data". The values listed in the Landolt-Börnstein tables are those reported by Legvold, et al., cited under "Other Reference".

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 ( $\rho_{273}$ ) determined by Legvold, et al., is  $140 \times 10^{-6}$  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	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)	
Legvold, Spedding, Borson and Elliott	
Temp. °K	$\rho/\rho_{273}$ *
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.	

17.10.71  
TEMPERATURE, °R



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 ( $\rho_{273}$ ) for dysprosium to be used in calculating electrical resistivity ( $\rho_T$ ) is  $135 \times 10^{-6}$  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 ( $\rho_{273}$ ) determined by Legvold, et al. is  $135 \times 10^{-6}$  ohm-cm. This value is suggested for calculating the resistivity from the ratios given here.

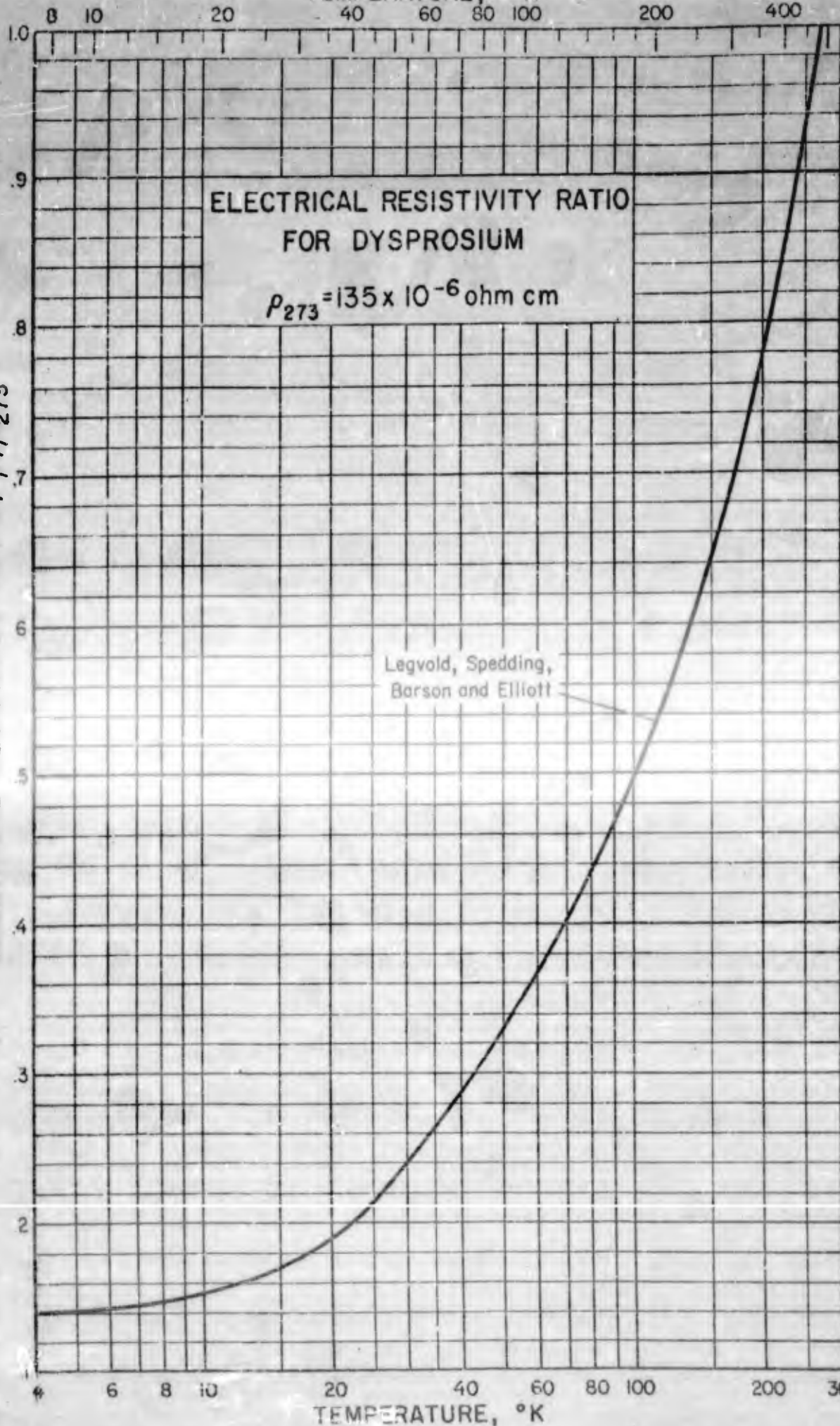
The Landolt-Börnstein tables list the samples used by the authors as polycrystalline. The samples were cast and later annealed at 500°C. The impurities in the samples are approximately 0.1% Ho and 0.07% Y.

Table of Values of Electrical Resistivity	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)	
Legvold, Spedding, Borson and Elliott	
Temp. °K	$\rho/\rho_{273}$
4	0.14
20	0.19
40	0.29
100	0.67

RDM/RS Issued: 12/23/60

17.131g

TEMPERATURE, °R



41.1311

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 ( $\rho_{273}$ ) for erbium to be used in calculating electrical resistivity ( $\rho_T$ ) is  $176.0 \times 10^{-6}$  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 ( $\rho_{273}$ ) determined by Legvold, et al., is  $176.0 \times 10^{-6}$  ohm-cm. This value is suggested for calculating the resistivity from the ratios given here.

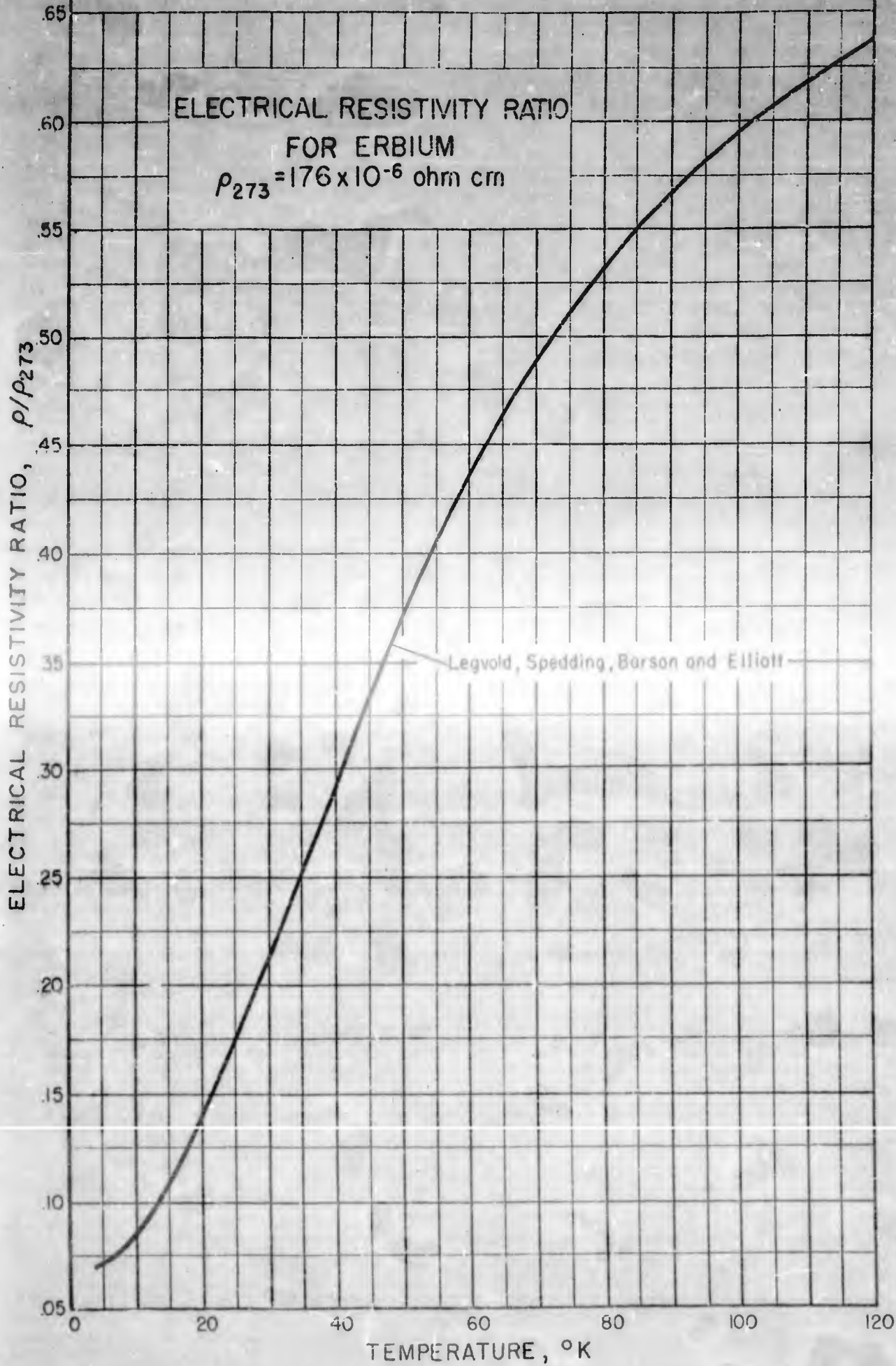
The Landolt-Börnstein tables list the samples used as being cast in a vacuum and of the polycrystalline type. Impurities in the sample are reported as being of less than 0.1% in total composed of Ca and Fe. No information is listed on the mechanical and heat treatment of the samples.

Table of Values of Electrical Resistivity	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)	
Legvold, Spedding, Borson and Elliott	
Temp. °K	$\rho/\rho_{273}$ *
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.	

17.1311

TEMPERATURE, °R

0 20 40 60 80 100 120 140 160 180 200



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) 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 ( $\rho_{273}$ ) for thorium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $13 \times 10^{-6}$  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 ( $\rho_{273}$ ) determined by Meissner and Voigt and suggested for calculating values of electrical resistivity here is  $\rho_{273} = 13 \times 10^{-6}$  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.

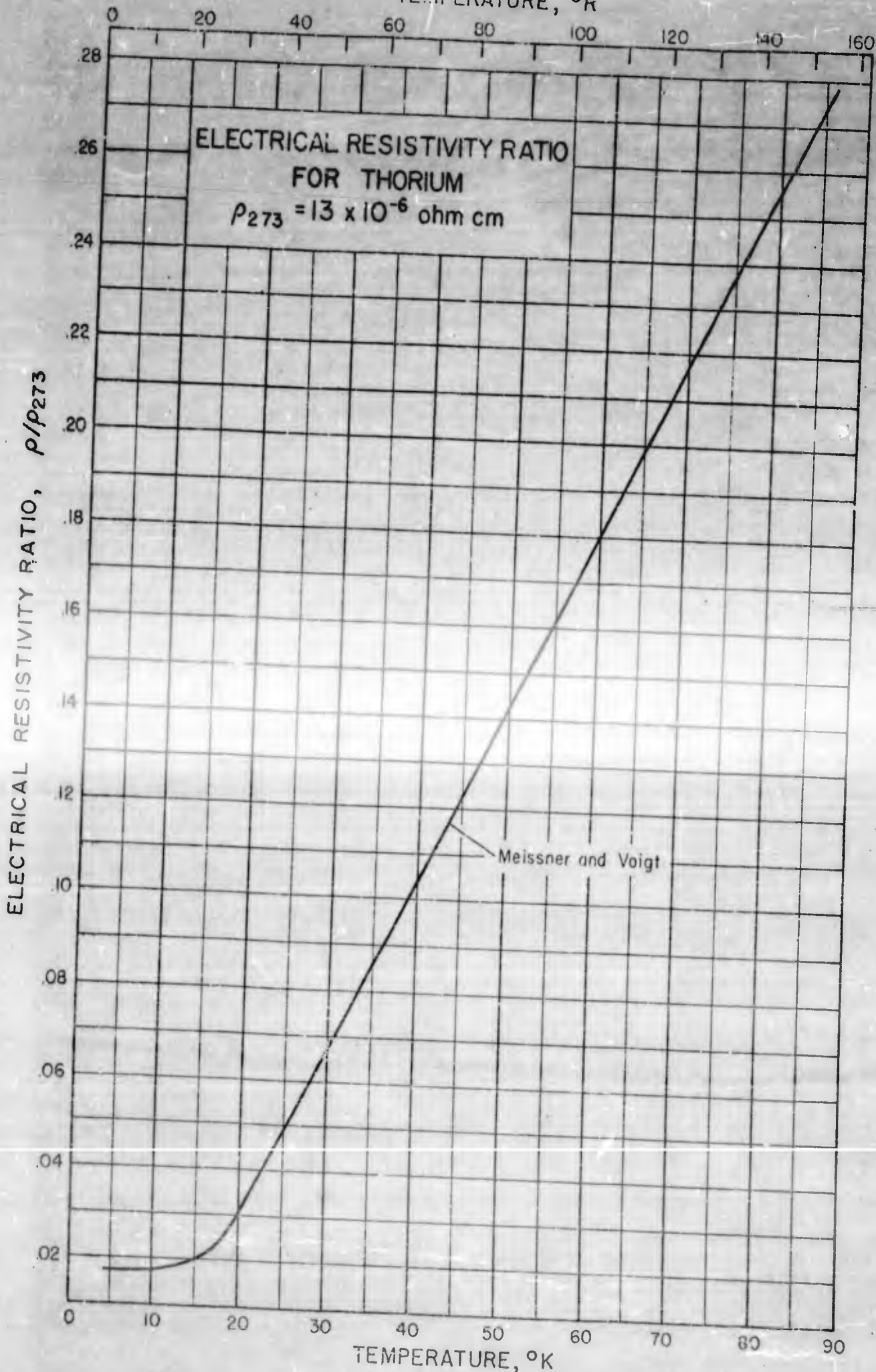
Table of Values of Electrical Resistivity	
$\rho$ = Resistivity, (ohm-cm)	
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)	
Meissner and Voigt	
Temp., °K*	$\rho/\rho_{273}$ **
1.49	0.0136
4.21	0.0171
20.4	0.0308
77.9	0.2454
86.1	0.2785

\*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



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 ( $\rho_{273}$ ) for uranium to be used in calculating electrical resistivity ( $\rho_T$ ) is  $21.0 \times 10^{-6}$  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".

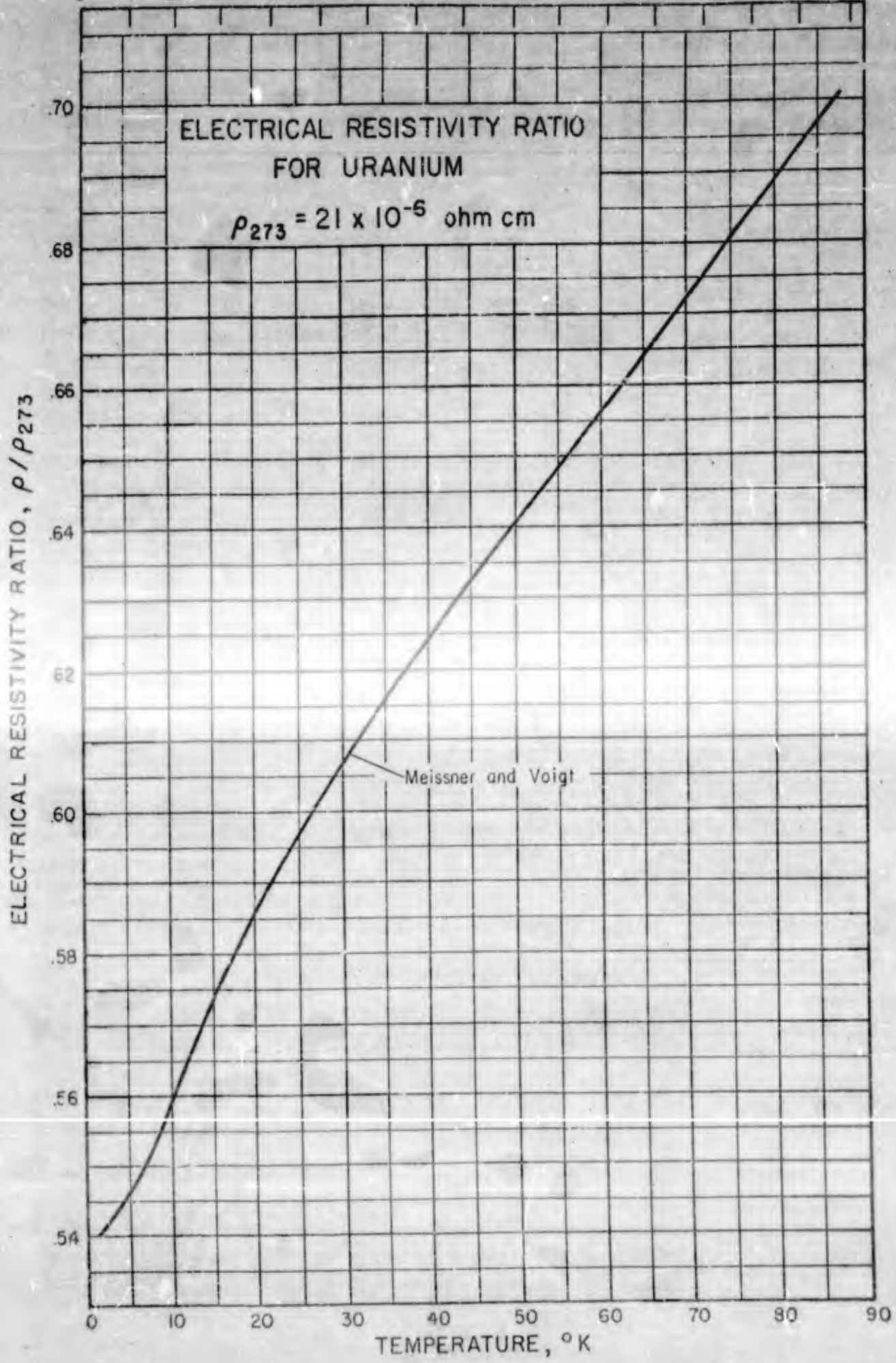
The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual value of  $\rho_{273}$  is not available for the samples used by Meissner and Voigt, so a datum value reported by Dahl and Van Dusen ( $\rho_{273} = 21.0 \times 10^{-6}$  ohm-cm) is suggested for calculating values of resistivity from these ratios.

The Landolt-Börnstein tables list the samples used by Meissner 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	
$\rho$	= Resistivity, (ohm-cm)
$\rho_{273}$	= Resistivity at 273°K, (ohm-cm)
Meissner and Voigt	
Temp. °K*	$\rho/\rho_{273}$
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



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. (London) 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 ( $\rho_{273}$ ) for aluminum to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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  $\rho_{273}$  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  $\rho_{273}$  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

$\rho$  = Resistivity, (ohm-cm)

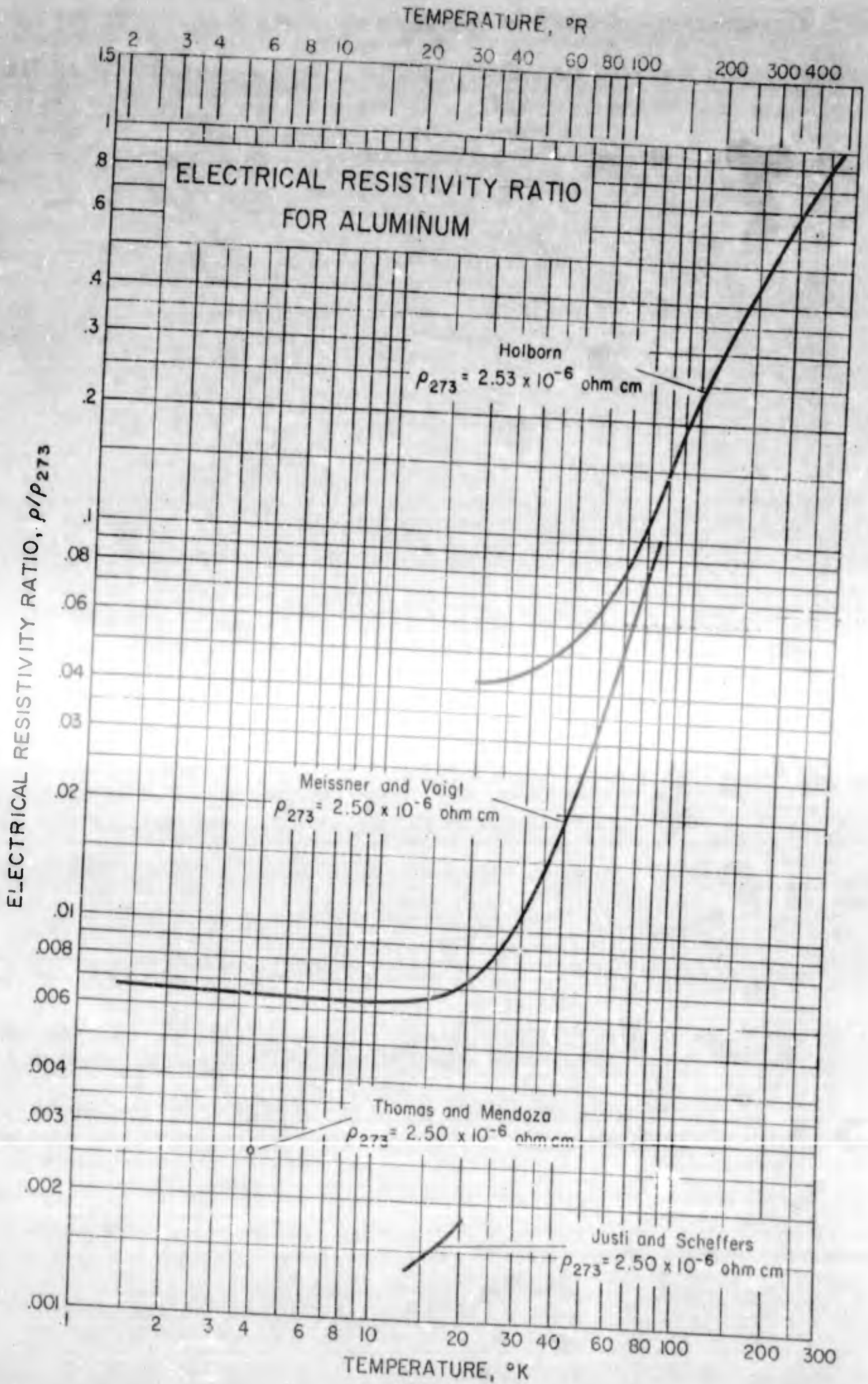
$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

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	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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.



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.; Commun. 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 ( $\rho_{273}$ ) for Gallium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $40 \times 10^{-6}$  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  $\rho_{273}$  is not available for the sample used by de Haas and Voogd so a datum value reported by Bridgman ( $\rho_{273} = 40 \times 10^{-6}$  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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

de Haas and Voogd	
Temp. °K	$\rho/\rho_{273}$ *
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 ( $\rho_{273}$ ) for indium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $8.19 \times 10^{-6}$  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  $\rho_{273}$  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

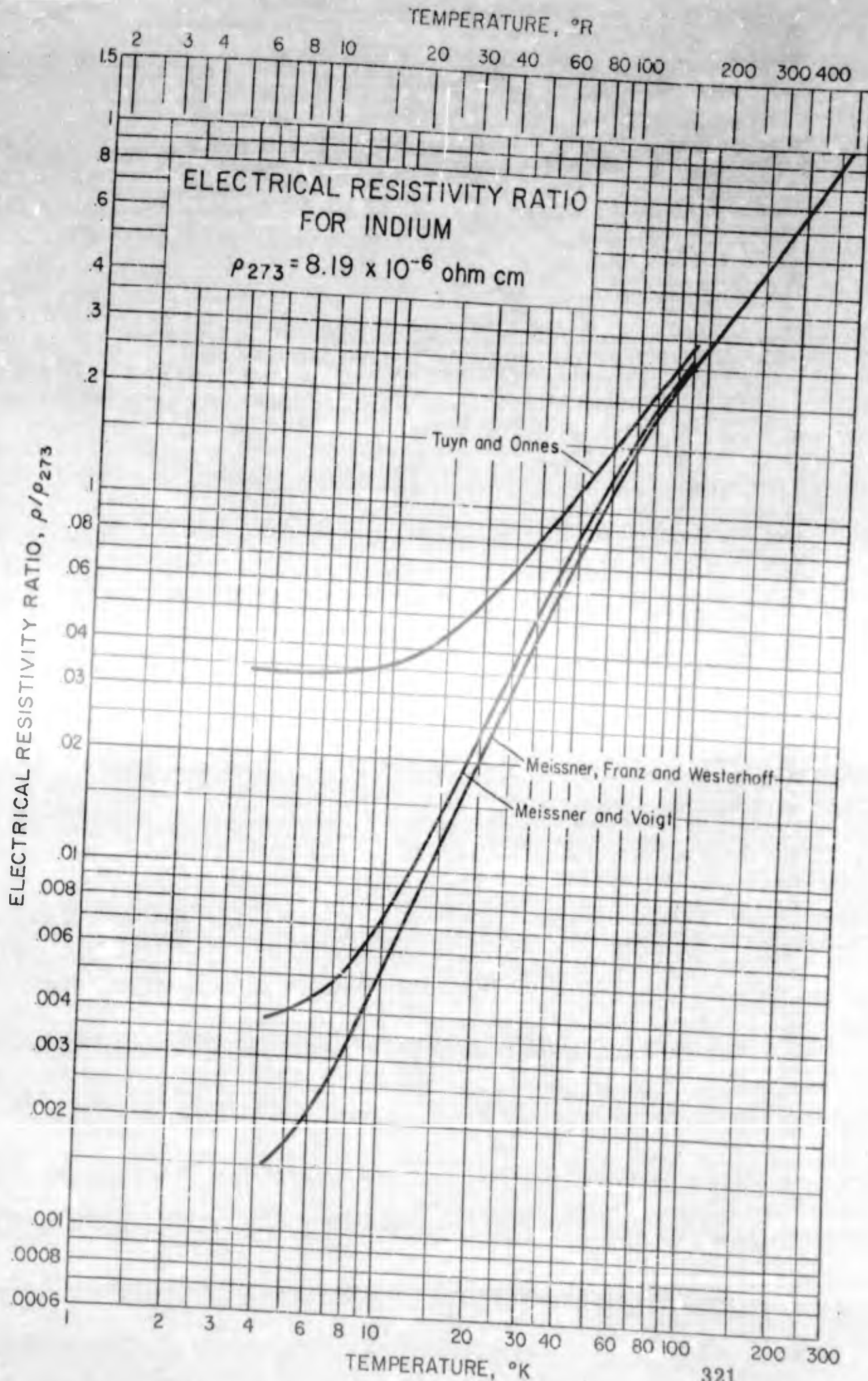
$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt		Meissner, Franz and Westerhoff	
Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
4.21	0.0038	4.23	0.0015
20.5	0.0256	20.4	0.0216
77.8	0.2177	77.8	0.212
88.9	0.2567		

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

17.132 f



## 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 ( $\rho_{273}$ ) for thallium to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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  $\rho_{273}$  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  $\rho_{273}$  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  $\rho_{273}$ .

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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

de Haas, de Boer and Van den Berg		Meissner, Franz and Westerhoff	
Temp.* °K	$\rho/\rho_{273}$ *	Temp. °K	$\rho/\rho_{273}$
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		

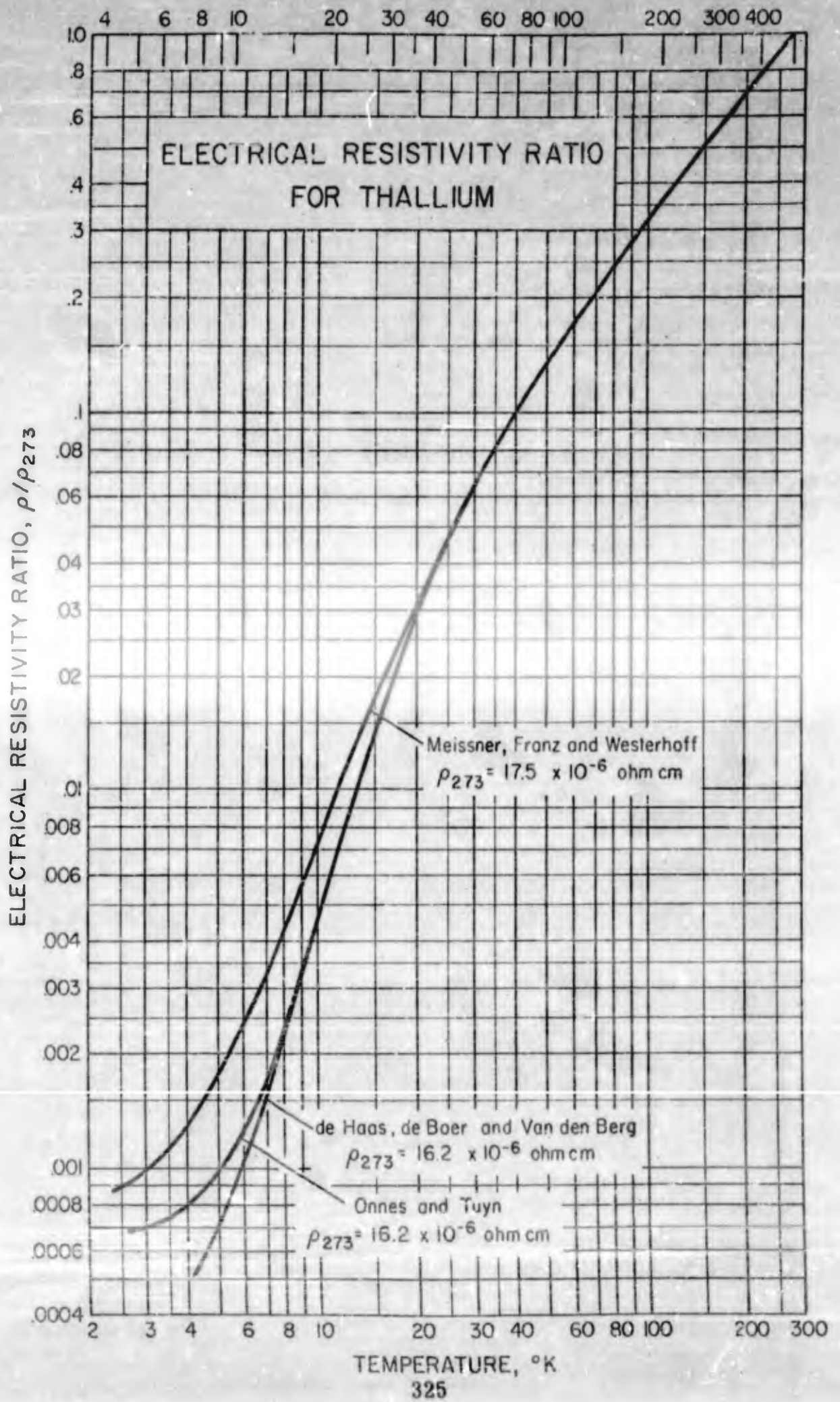
Onnes and Tuyn					
International Critical Tables				Landolt-Börnstein	
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$	Temp.	$\rho/\rho_{273}$
-78.3	67.10	-252.62	3.023	4.2	0.0008
-184.52	27.20	-255.05	2.286	14.2	0.0126
-192.04	24.52	-256.62	1.841	20.5	0.0302
-200.03	21.69	-258.93	1.259	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



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 ( $\rho_{273}$ ) 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  $\rho_{273}$  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  $\rho_{273}$ .

The Landolt-Börnstein tables list the sample used by Clausing and Moubis 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.)

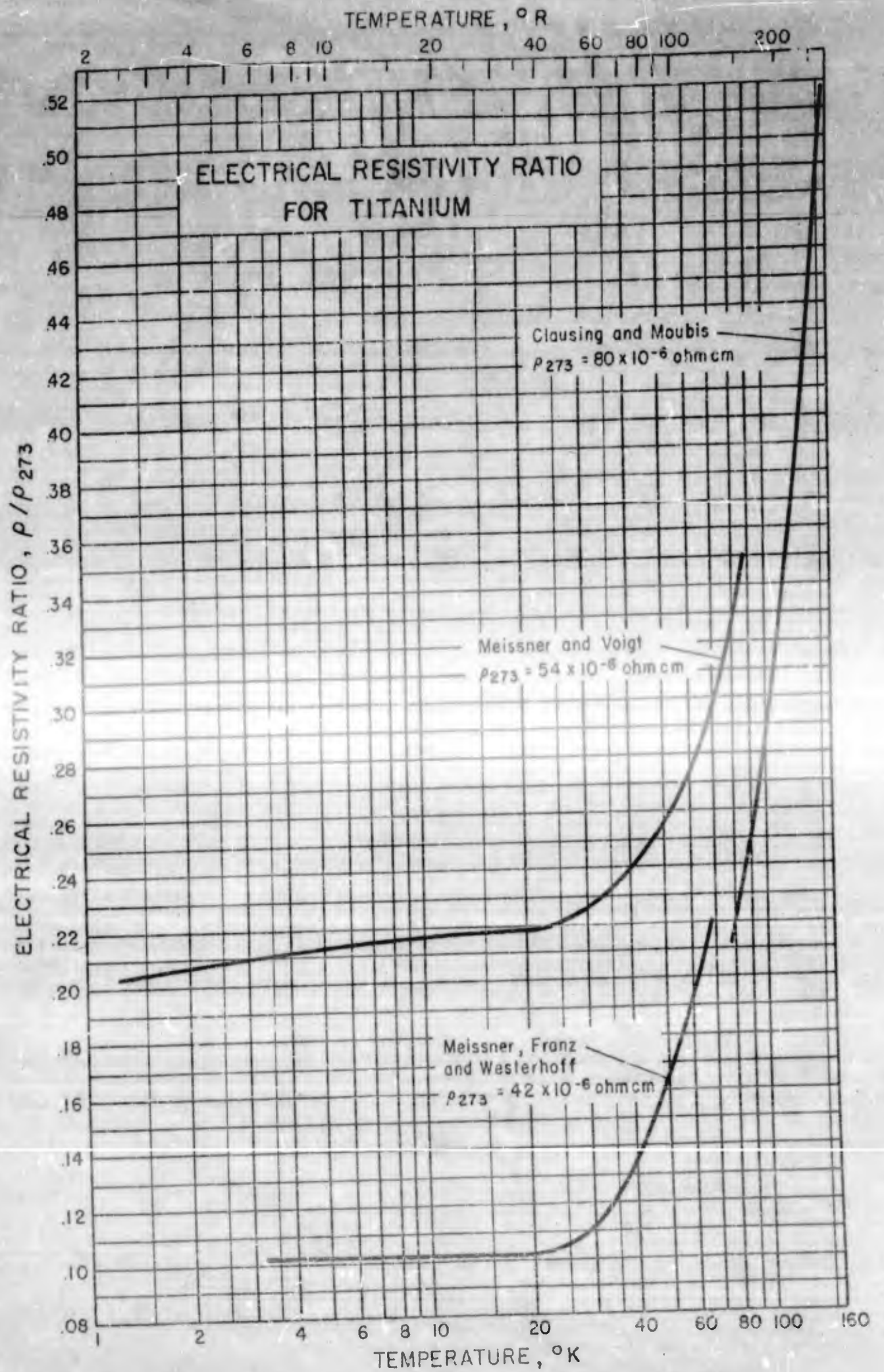
## ELECTRICAL RESISTIVITY OF TITANIUM (cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Clausing & Moubis		Meissner, Franz & Westerhoff	
Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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	$\rho/\rho_{273}$
1.26	0.203
4.21	0.215
20.5	0.2180
88.2	0.3505

RDM/RS Issued: 1/18/61



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.; Commun. 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 ( $\rho_{273}$ ) for zirconium to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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  $\rho_{273}$  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  $\rho_{273}$  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  $\rho_{273}$ .

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

 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt		de Haas and Voogd	
Temp.* °K	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}$
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*

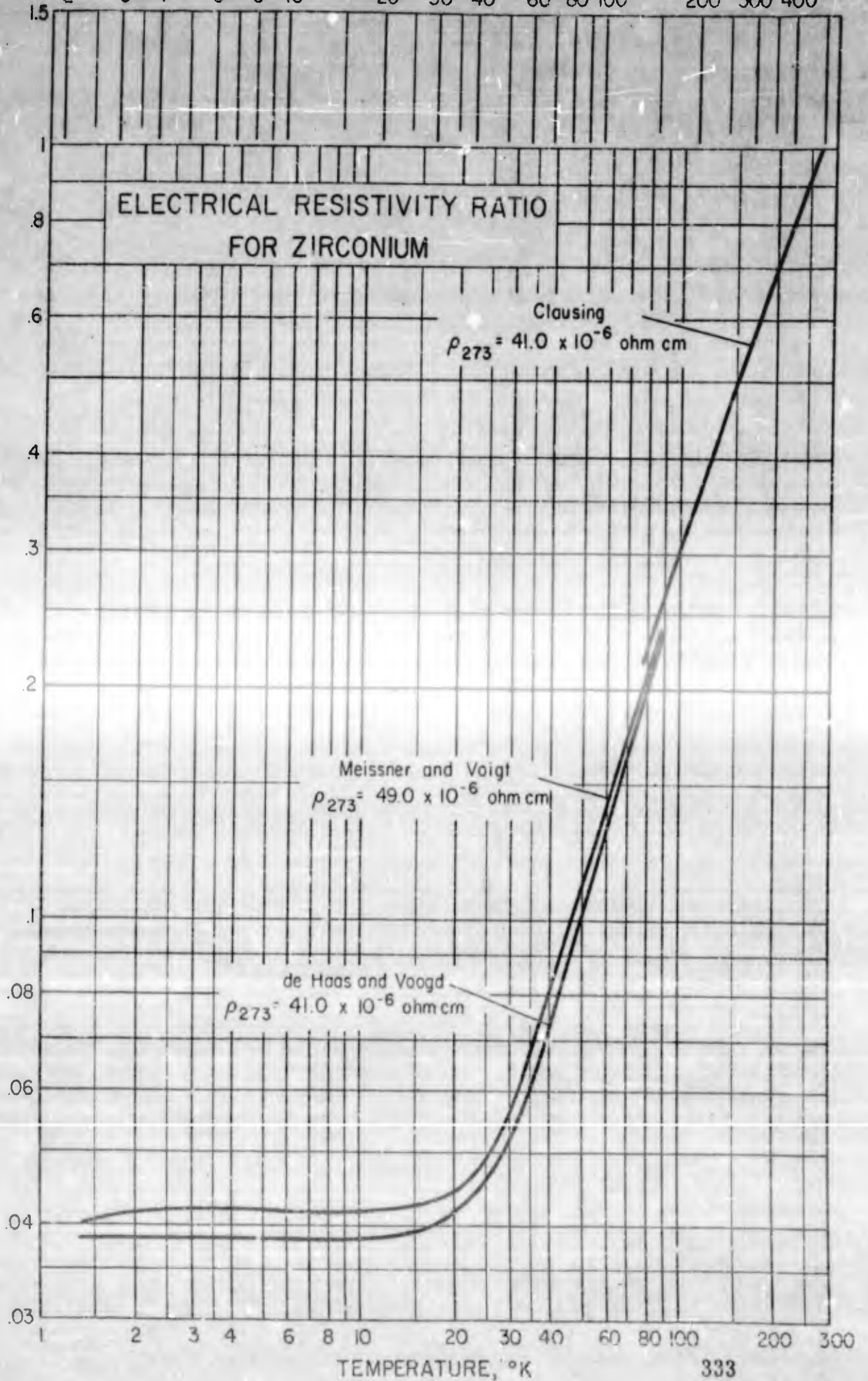
\* Results of actual observations. All other values from interpolations.

TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

ELECTRICAL RESISTIVITY RATIO  
FOR ZIRCONIUM

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$



Clausing  
 $\rho_{273} = 41.0 \times 10^{-6}$  ohm cm

Meissner and Voigt  
 $\rho_{273} = 49.0 \times 10^{-6}$  ohm cm

de Haas and Voogd  
 $\rho_{273} = 41.0 \times 10^{-6}$  ohm cm

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.; Commun. 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 ( $\rho_{273}$ ) for hafnium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $30 \times 10^{-6}$  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  $\rho_{273}$  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  $\rho_{273}$ .

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.

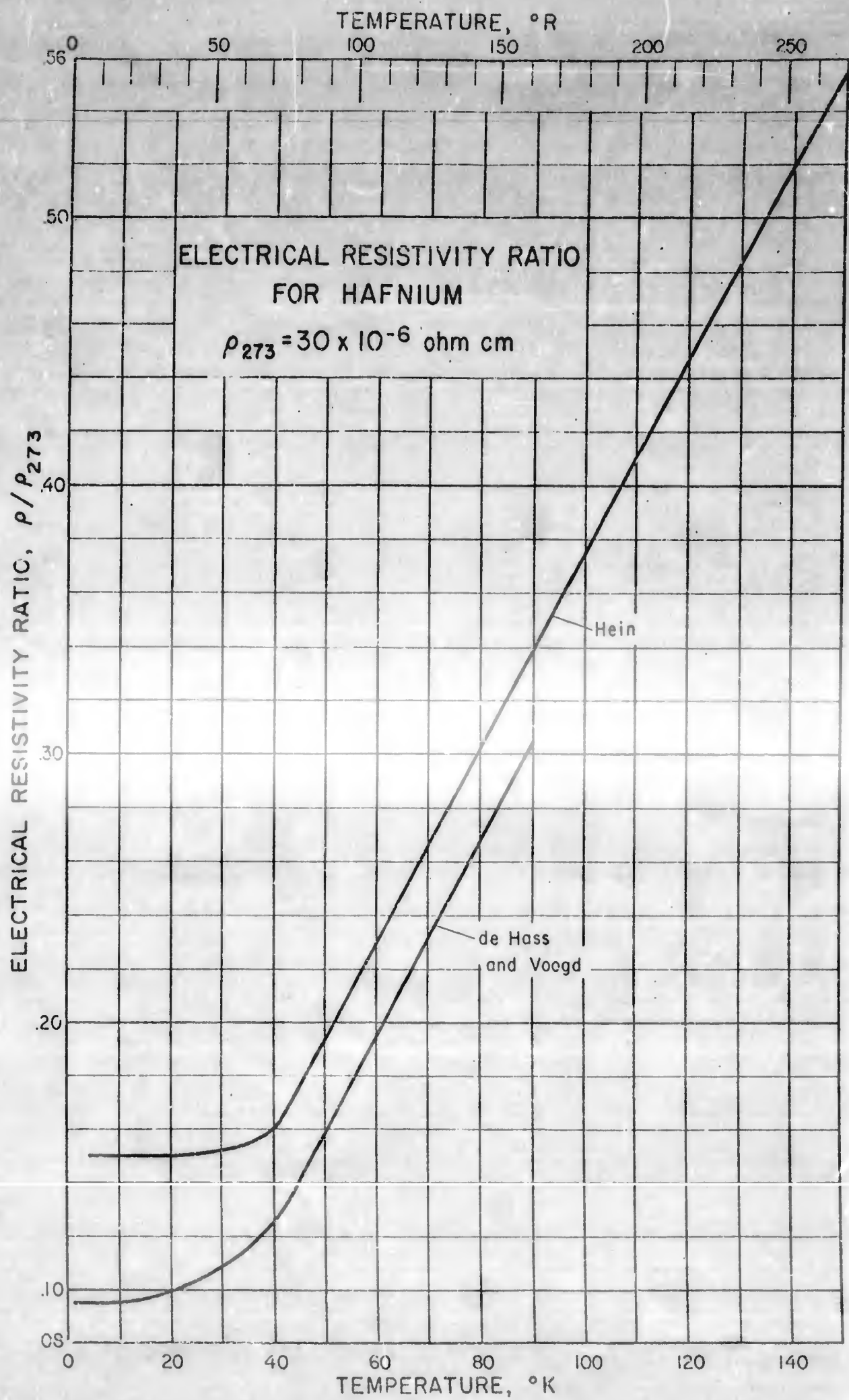
(Continued on following page.)

## ELECTRICAL RESISTIVITY OF HAFNIUM (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

de Haas and Voogd	
Temp. °K	$\rho/\rho_{273}$
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	$\rho/\rho_{273}$
4.2	0.15
20.0	0.15
40.0	0.16
50.0	0.19
150.0	0.55



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 ( $\rho_{273}$ ) for tin to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $11.15 \times 10^{-6}$  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  $\rho_{273}$  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  $\rho_{273}$ .

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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = 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	$\rho/\rho_{273}$
4.2	0.00078
20.4	0.0120
88.2	0.2457

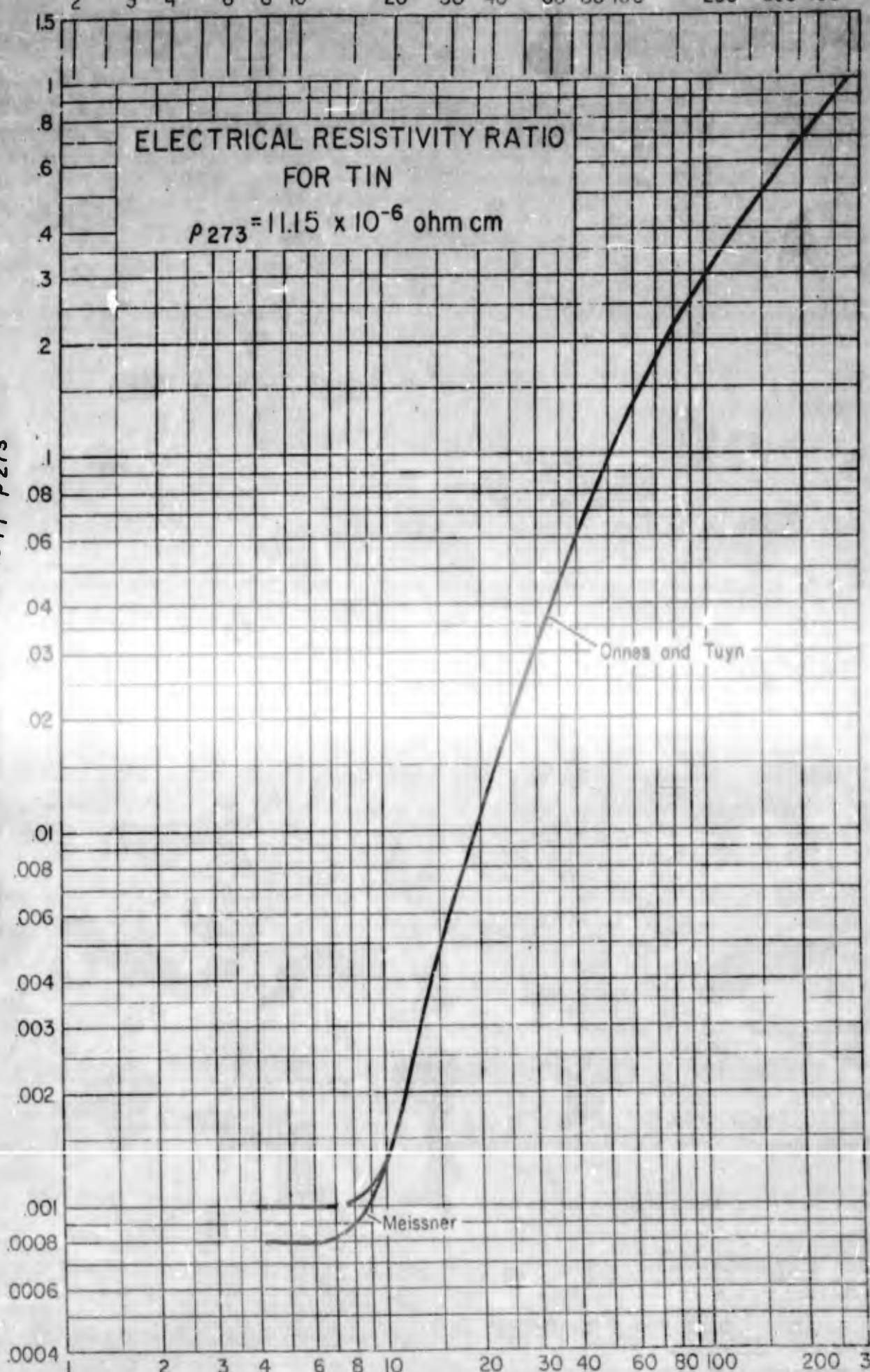
TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$

ELECTRICAL RESISTIVITY RATIO FOR TIN

$\rho_{273} = 11.15 \times 10^{-6}$  ohm cm



TEMPERATURE, °K

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.; Commun. 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 ( $\rho_{273}$ ) for lead to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $19.2 \times 10^{-6}$  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  $\rho_{273}$  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  $\rho_{273}$  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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Franz		Meissner	
Temp.* °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
7.26	0.0007	1.3	$1.55 \times 10^{-4}+$
14.02	0.0104	4.2	$1.75 \times 10^{-4}+$
20.32	0.0292		

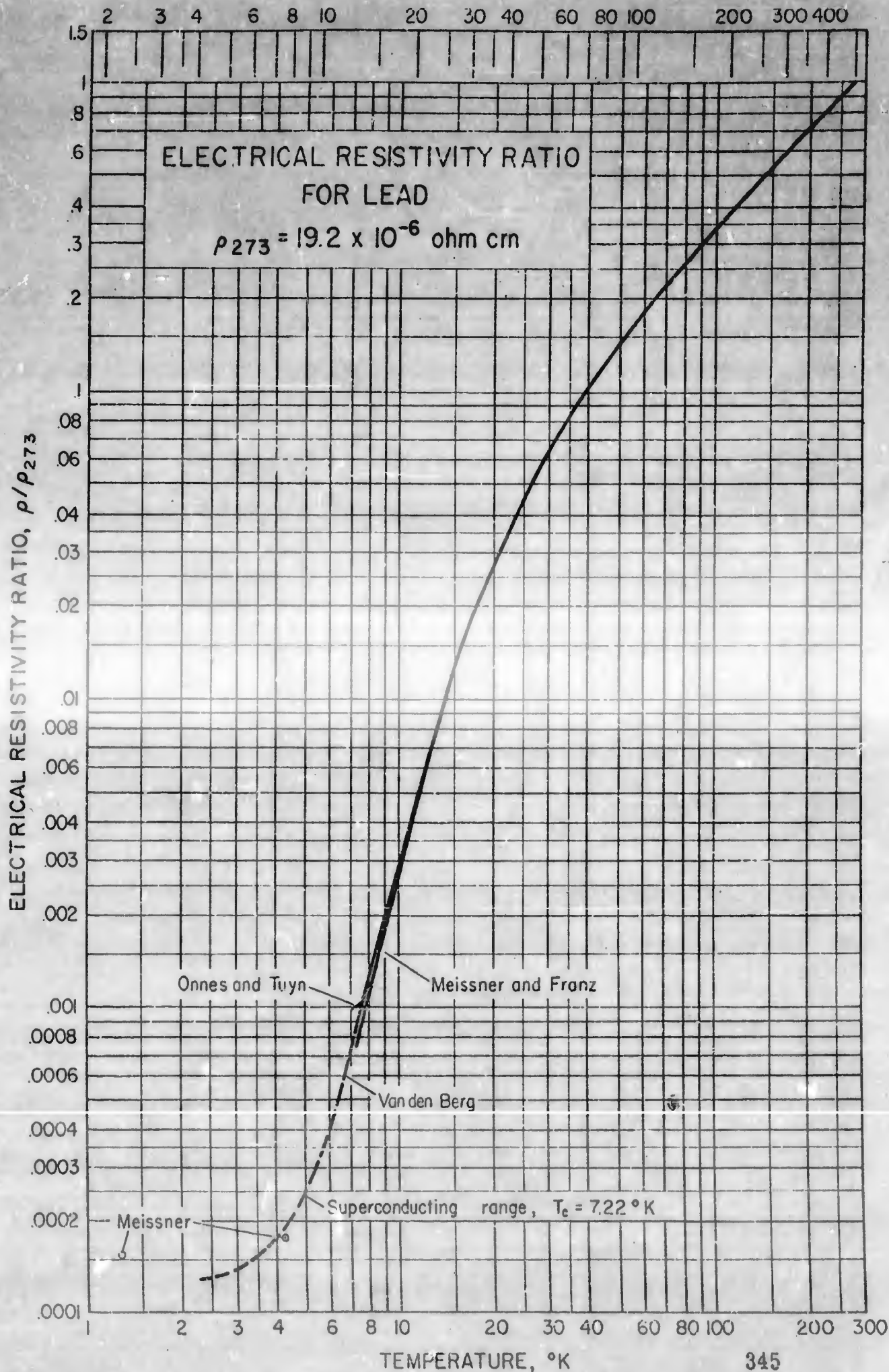
Onnes and Tuyn		Van den Berg	
Temp.* °K	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}^{***}$
7.26	0.0010	2.30	0.00013+
14.32	0.0113	3.22	0.00015+
20.52	0.0301	4.24	0.00019+
73.11	0.2321	7.22	0.00083
88.56	0.2895	9.38	0.0025
		20.32	0.0301

\* 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 super-critical 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



ELECTRICAL RESISTIVITY of NIOBIUM, Ni  
(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 ( $\rho_{273}$ ) for Niobium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $16.1 \times 10^{-6}$  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  $\rho_{273}$  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<sub>2</sub> and 0.02% Ta impurities present. No other pertinent information is given about either of the samples.

Table of Values of Electrical Resistivity

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner, Franz and Westerhoff	
Temp. °K	$\rho/\rho_{273}$
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 ( $\rho_{273}$ ) for tantalum to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $12.4 \times 10^{-6}$  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  $\rho_{273}$  are not available for the samples used by the several investigators so a datum value reported by Burgers and Basart ( $\rho_{273} = 12.4 \times 10^{-6}$  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 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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = 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	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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.

17.151 D

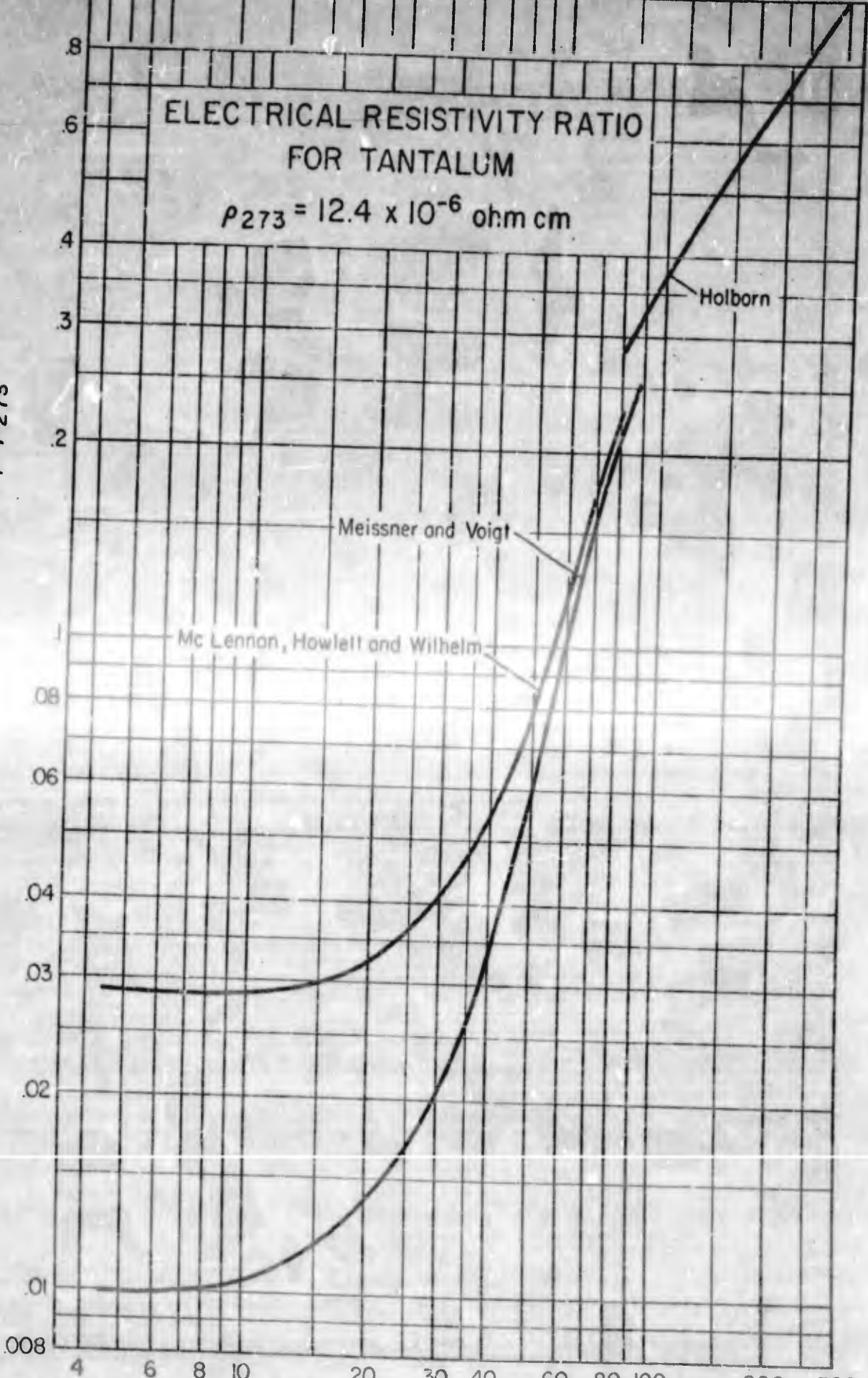
TEMPERATURE, °R

8 10 20 30 40 60 80 100 200 300 400

### ELECTRICAL RESISTIVITY RATIO FOR TANTALUM

$$\rho_{273} = 12.4 \times 10^{-6} \text{ ohm cm}$$

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$



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 ( $\rho_{273}$ ) for vanadium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $18.2 \times 10^{-6}$  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  $\rho_{273}$  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

$\rho$  = Resistivity (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Westerhoff	
Temp. °K	$\rho/\rho_{273}$
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 ( $\rho_{273}$ ) for arsenic to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $26 \times 10^{-6}$  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".

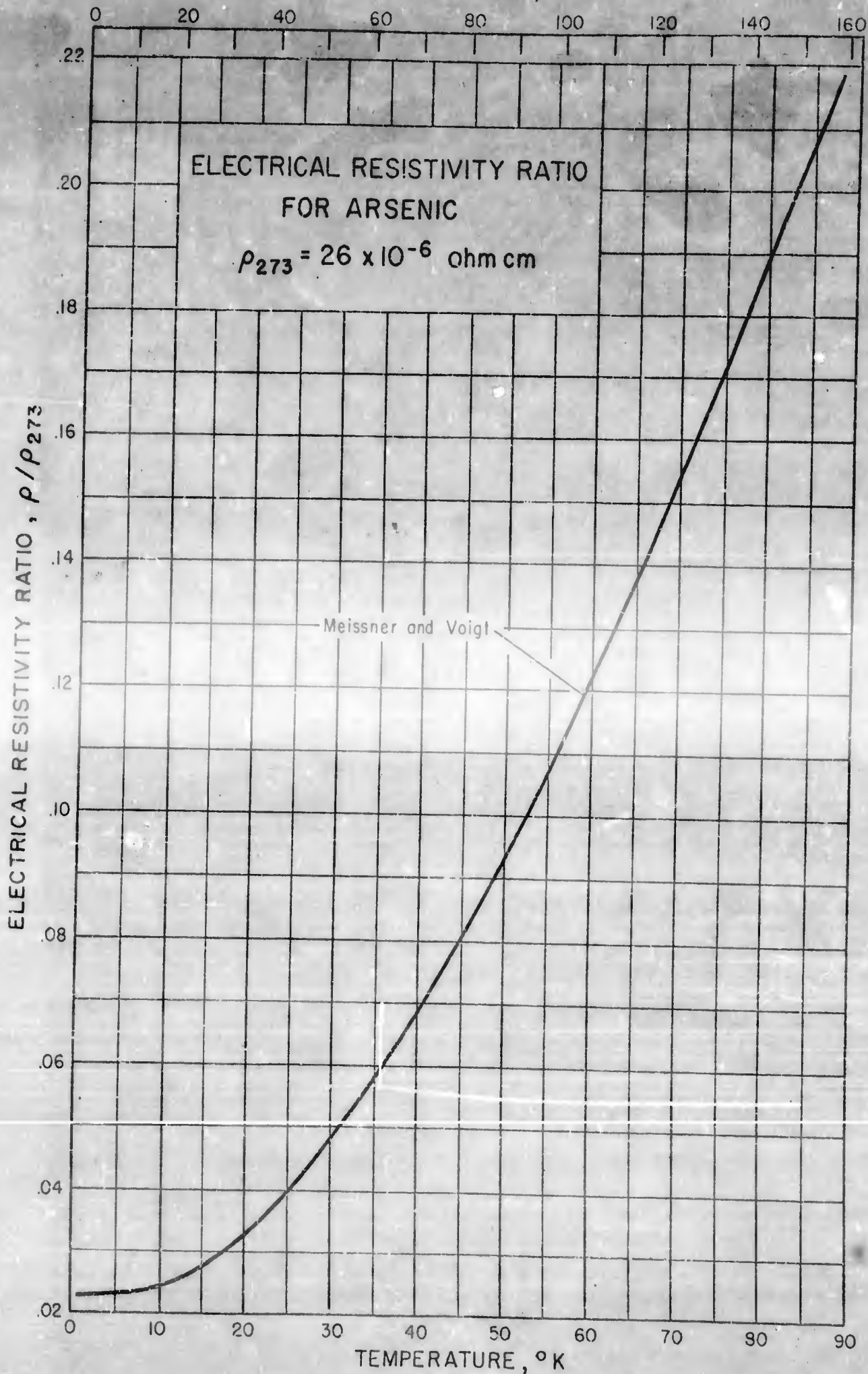
The data reported in the Landolt-Börnstein tables and tabulated here are listed as ratios of electrical resistivity at a datum temperature of 273°K. The value of  $\rho_{273}$  determined by Meissner and Voigt and suggested as a datum value here is  $\rho_{273} = 26 \times 10^{-6}$  ohm-cm.

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	
$\rho$	= Resistivity, (ohm-cm)
$\rho_{273}$	= Resistivity at 273°K, (ohm-cm)
Meissner and Voigt	
Temp.* °K	$\rho/\rho_{273}$
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

17.152  $\alpha$   
TEMPERATURE,  $^{\circ}\text{R}$



## 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 ( $\rho_{273}$ ) for antimony to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $39 \times 10^{-6}$  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  $\rho_{273}$  are not available for the samples used by the several investigators so that a datum value reported by Eucken and Gehlhoff ( $\rho_{273} = 39 \times 10^{-6}$  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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

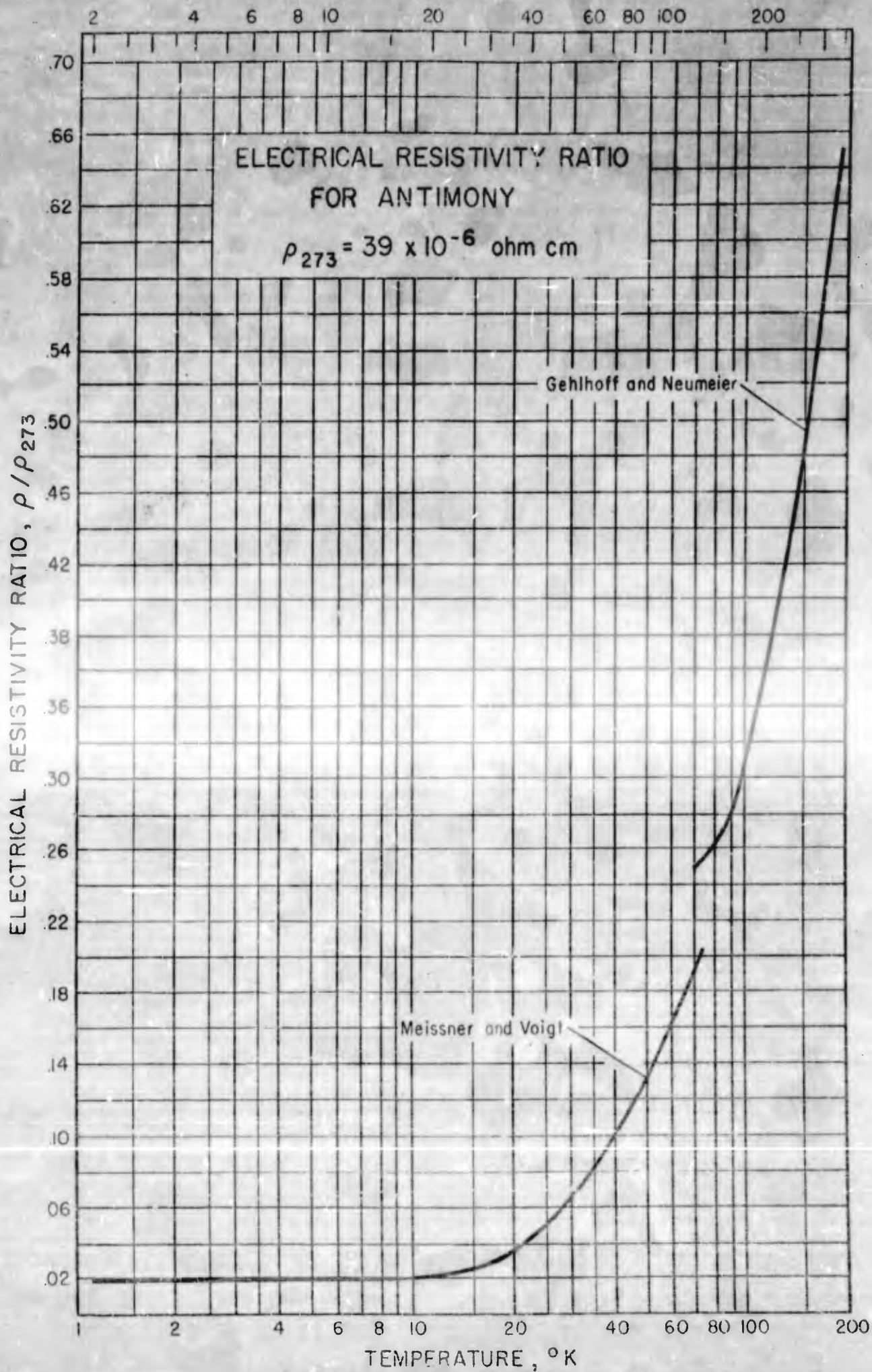
Meissner and Voigt	
Temp.* °K	$\rho/\rho_{273}$
1.16	0.0180
1.30	0.0192
4.20	0.0195
20.42	0.0319
77.7	0.2041
88.4	0.2441

\*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.

17.152 b  
TEMPERATURE °R



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 ( $\rho_{273}$ ) for bismuth to be used in calculating electrical resistivity is  $110.0 \times 10^{-6}$  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 Cláý. 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  $\rho_{273}$  are not available for the samples used by the several investigators so a datum value reported by Jaeger and Diesselhorst ( $\rho_{273} = 110.0 \times 10^{-6}$  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)

17.152c

ELECTRICAL RESISTIVITY of BISMUTH (Cont.)

Tables of Values of Electrical Resistivity

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = 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	$\rho/\rho_{273}$
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.

TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

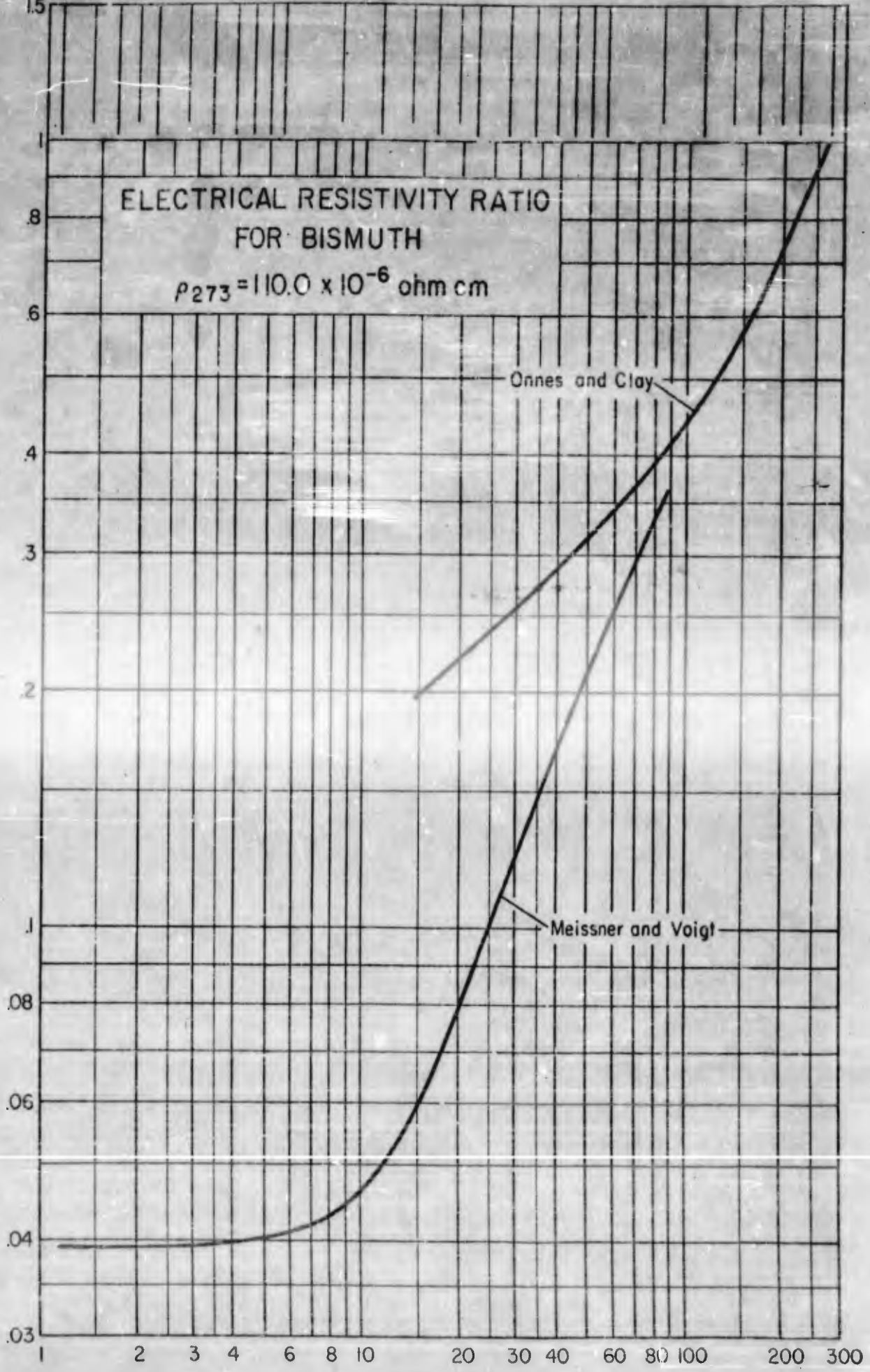
ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$

ELECTRICAL RESISTIVITY RATIO  
FOR BISMUTH

$\rho_{273} = 110.0 \times 10^{-6} \text{ ohm cm}$

Onnes and Clay

Meissner and Voigt



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 ( $\rho_{273}$ ) for chromium to be used in calculating the electrical resistivity ( $\rho_T$ ) is  $18.2 \times 10^{-6}$  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  $\rho_{273}$  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.)

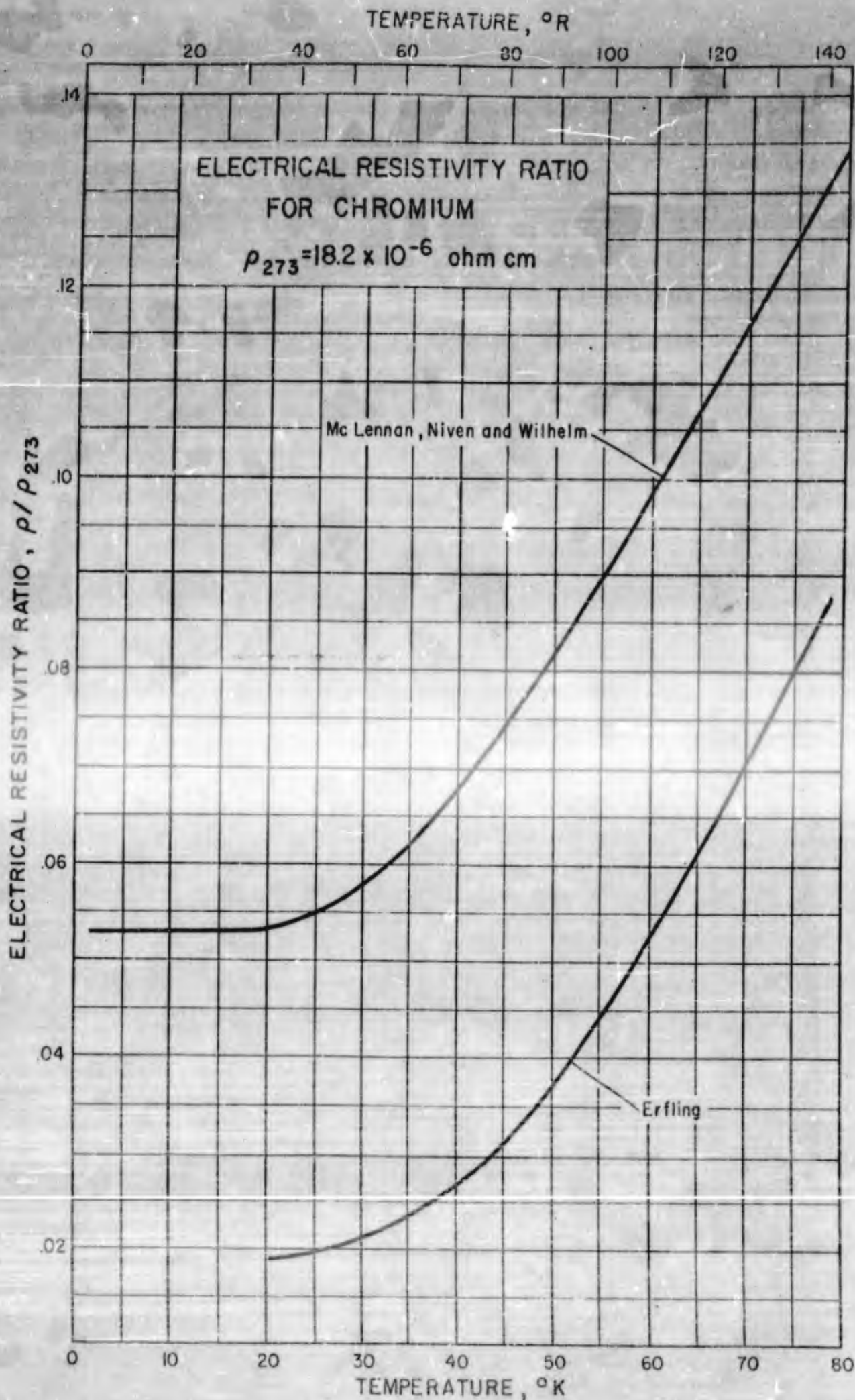
## ELECTRICAL RESISTIVITY of CHROMIUM, Cr (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

McLennan, Niven and Wilhelm	
Temp. °K	$\rho/\rho_{273}$ *
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	$\rho/\rho_{273}$
20.4	0.0188
79.0	0.0874



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 ( $\rho_{273}$ ) for molybdenum to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $4.4 \times 10^{-6}$  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  $\rho_{273}$  for the samples used by the several investigators are not available so a datum value reported by Blom ( $\rho_{273} = 4.4 \times 10^{-6}$  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.)

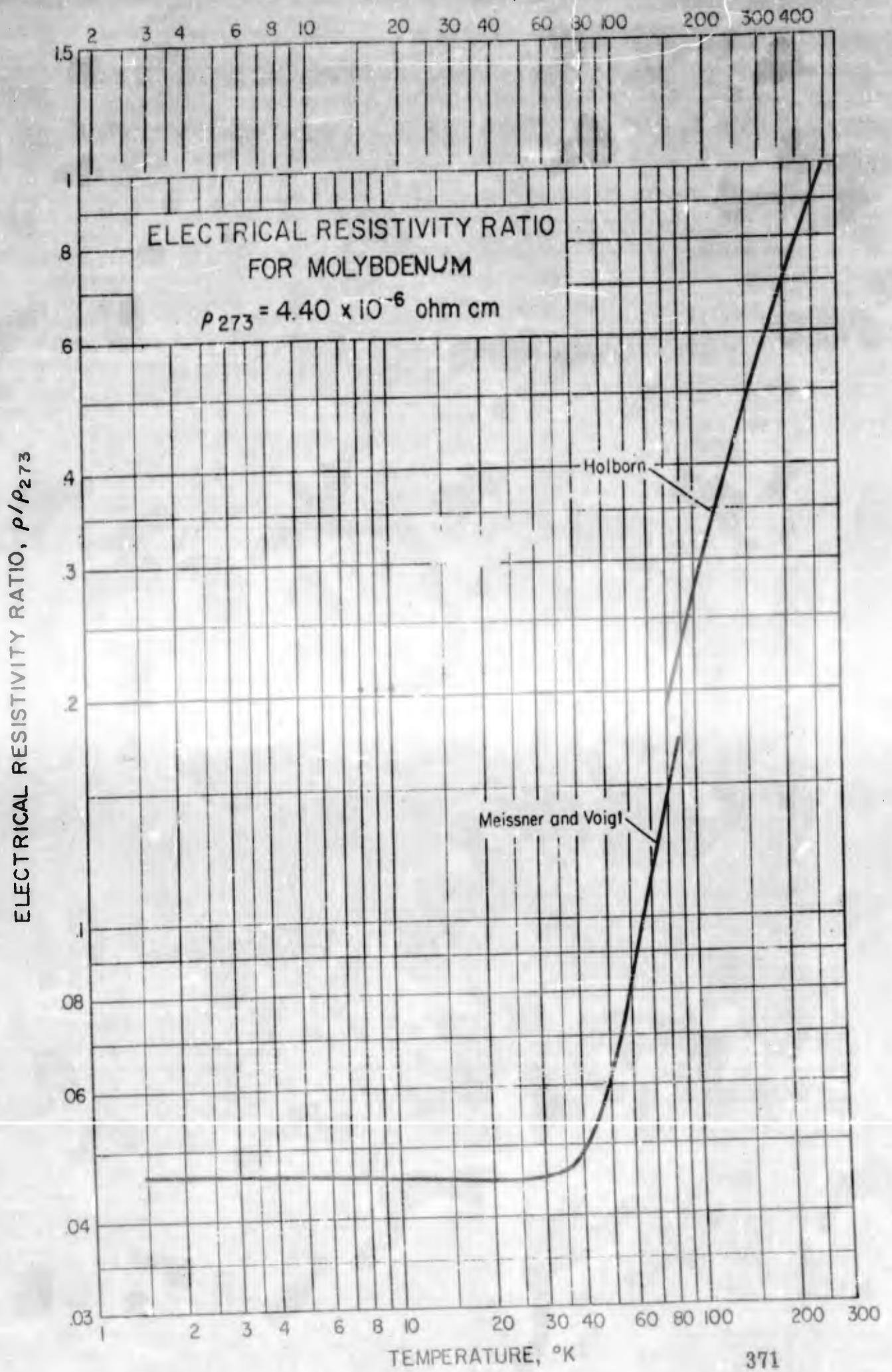
Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

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	$\rho/\rho_{273}$
1.5	0.0462
4.2	0.0455
20.4	0.0448
77.8	0.1370
86.9	0.1701

TEMPERATURE, °R



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 ( $\rho_{273}$ ) for tungsten to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $4.86 \times 10^{-6}$  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  $\rho_{273}$  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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

de Haas and de Nobel		Holborn	
Temp. °K	$\rho/\rho_{273}^*$	Temp. °C	$100\rho/\rho_{273}$
1.57	0.00033	- 78.3+	65.09+
4.21	0.00035	- 80	64.4
14.14	0.00048	-100	55.7
20.42	0.00086	-120	46.9
50.55	0.0291	-140	38.2
90.15	0.1650	-160	29.5
		-180	20.8
		192.8+	15.29+

Meissner and Voigt		Van den Berg	
Temp.** °K	$\rho/\rho_{273}^*$	Temp. °K	$\rho/\rho_{273}$
1.31	0.00053	2.01	0.00044
4.21	0.00054	4.40	0.00046
20.4	0.0011	20.41	0.00097
77.6	0.1156		
87.4	0.1565		

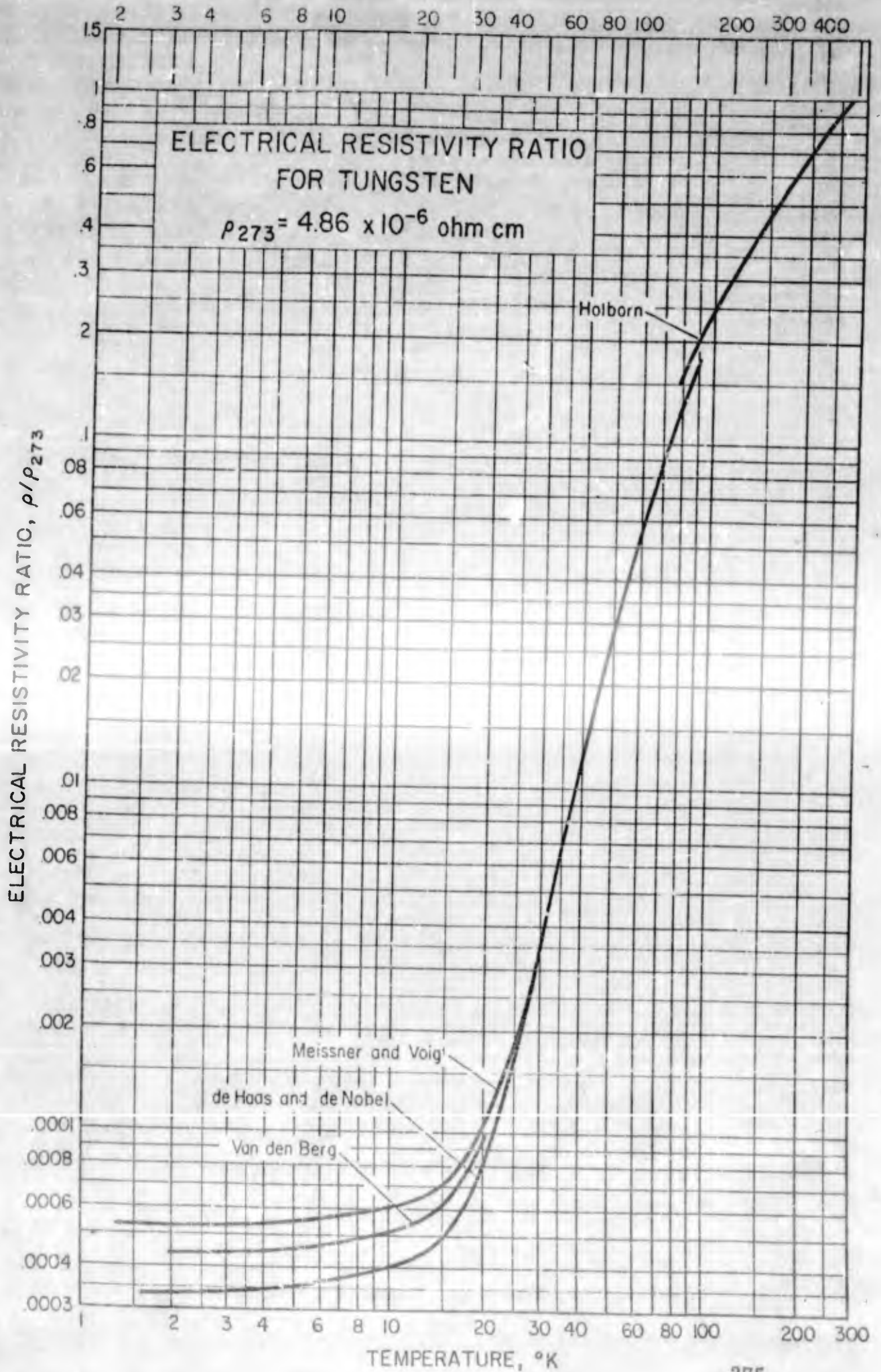
\* The fifth decimal place of the electrical resistivity ratio values is somewhat in doubt.

\*\* The second decimal place of the temperature values is somewhat in doubt.

+ Observed values. Other values have been interpolated.

17.161 c

TEMPERATURE, °R



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 ( $\rho_{273}$ ) for manganese to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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  $\rho_{273}$  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  $\rho_{273}$  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  $\alpha$ ,  $\beta$ ,  $\gamma$ . The Meissner and Voigt data are reported as determined from a sample composed of a combination of the  $\alpha$  and  $\beta$  phase. The Brunke sample is reported as being in the  $\alpha$  phase. The Reddemann sample is reported as being in the  $\beta$  phase and the Erfling sample is reported as being in the  $\gamma$  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 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt ( $\alpha + \beta$ )-Manganese $\rho_{273} = 150 \times 10^{-6}$ ohm-cm		Reddemann $\beta$ -Manganese $\rho_{273} = 91 \times 10^{-6}$ ohm-cm	
Temp.* °K	$\rho/\rho_{273}$ **	Temp. °K	$\rho/\rho_{273}$
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 $\alpha$ -Manganese $\rho_{273} = 715 \times 10^{-6}$ ohm-cm		Erfiling $\gamma$ -Manganese $\rho_{273} = 39.2 \times 10^{-6}$ ohm-cm	
Temp. °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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 ( $\rho_{273}$ ) for rhenium to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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".

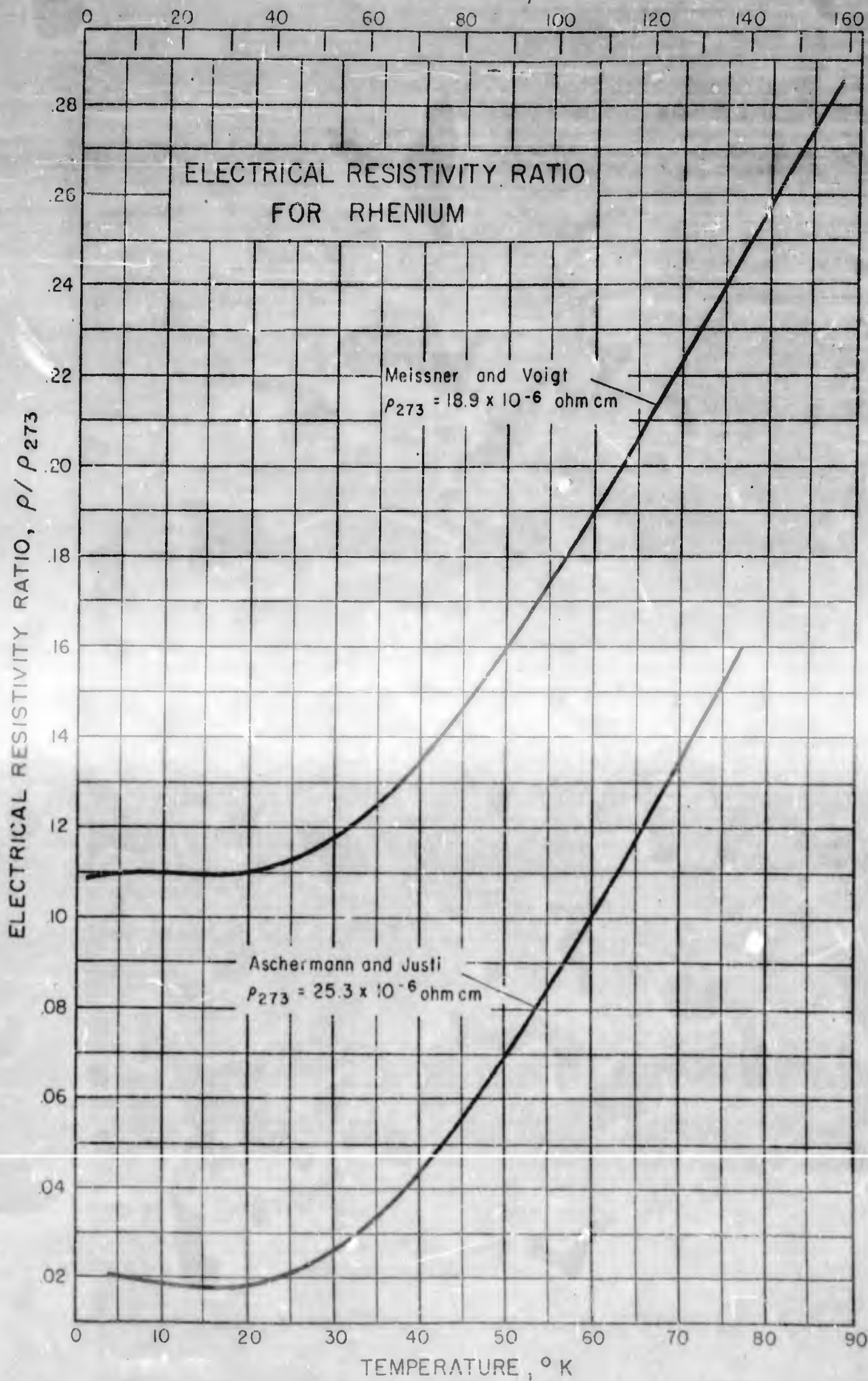
The data reported in the Landolt-Börnstein tables are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The values of  $\rho_{273}$  which appear on the graph below the authors' names are the values determined by those authors.

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			
$\rho$ = Resistivity, (ohm-cm)			
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)			
Aschermann and Justi		Meissner and Voigt	
Temp. °K	$\rho/\rho_{273}$ *	Temp.** °K	$\rho/\rho_{273}$
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



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 ( $\rho_{273}$ ) for iron to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $8.6 \times 10^{-6}$  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  $\rho_{273}$  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)

17.181H

ELECTRICAL RESISTIVITY of IRON (Cont.)

Tables of Values of Electrical Resistivity

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

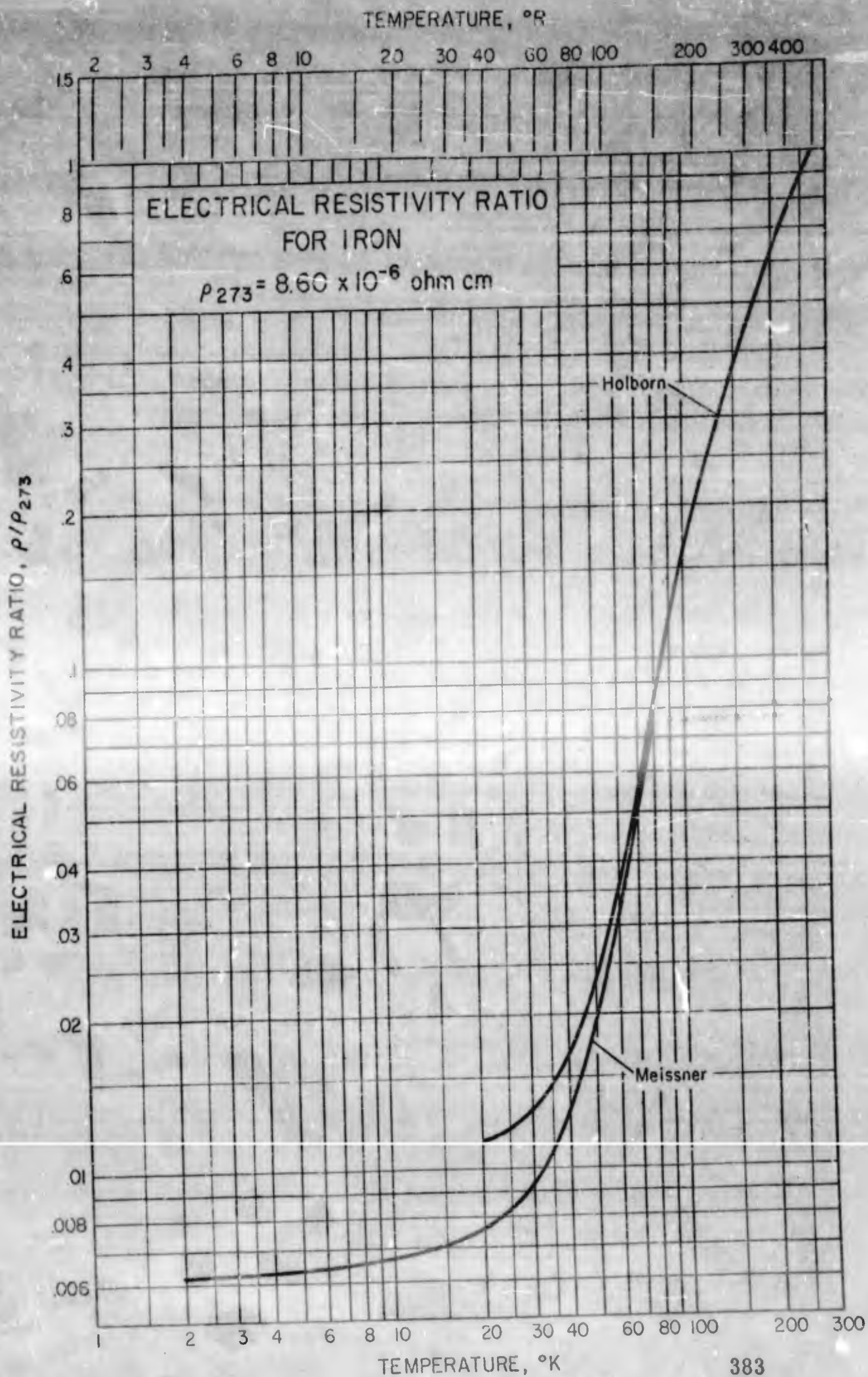
Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
- 78.1	57.86	-192.7	8.48
- 80 *	55.9	-200 *	6.2
-100 *	47.3	-220 *	2.7
-120 *	38.1	-240 *	1.4
-140 *	29.2	-253	1.13
-160 *	20.7		

\* Values from interpolation

Meissner	
Temp.* °K	$\rho/\rho_{273}^{**}$
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



17-1010

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 ( $\rho_{273}$ ) for nickel to be used in calculating electrical resistivity is  $6.14 \times 10^{-6}$  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  $\rho_{273}$  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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = 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	- 20 +	11.2
-140 +	36.1	-240 +	8.9
-160 +	28.7	-252.7	8.5

+ Values are from interpolation

Meissner	
Temp.** °K	$\rho/\rho_{273}$ *
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.

TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$

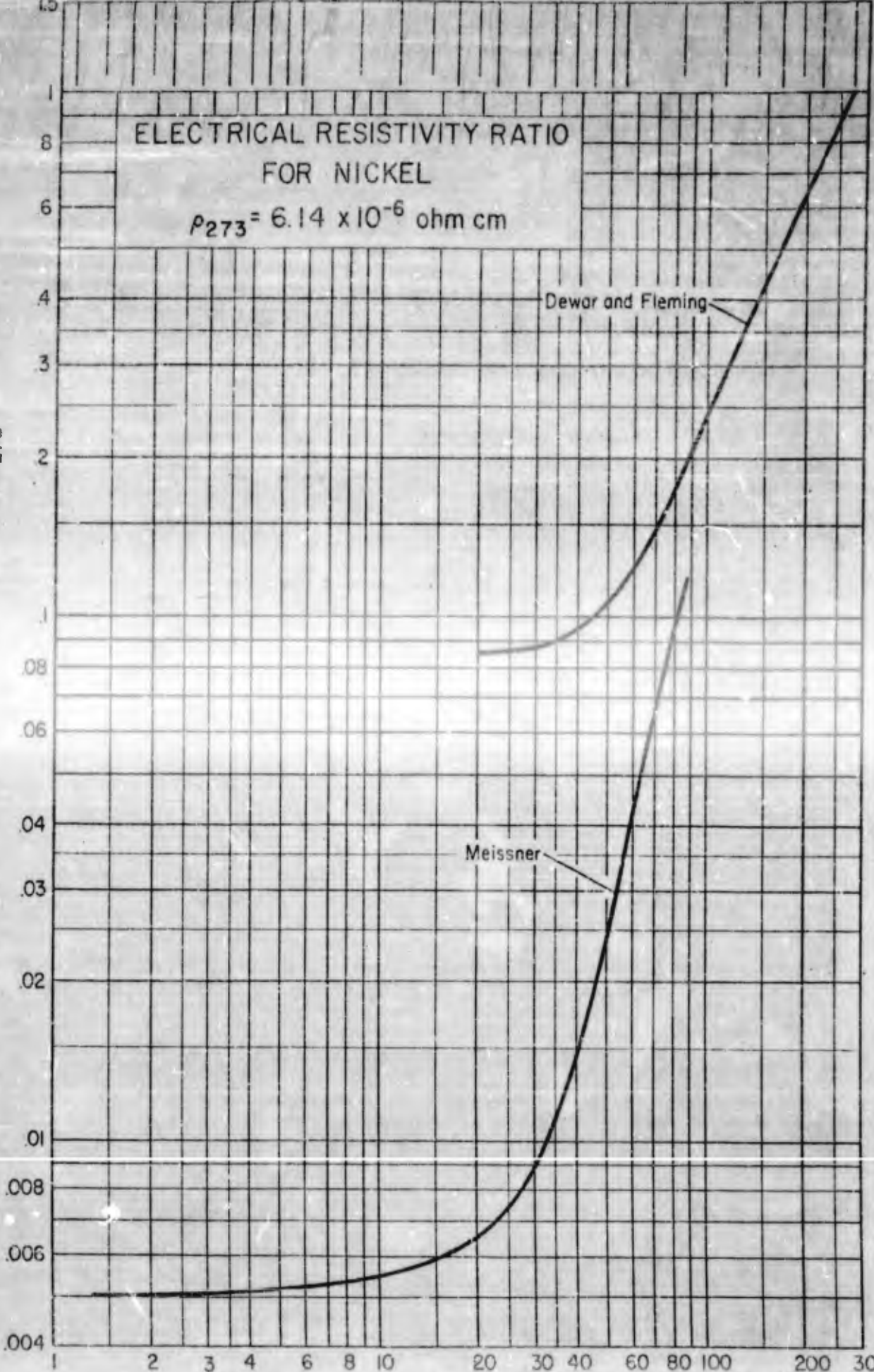
ELECTRICAL RESISTIVITY RATIO

FOR NICKEL

$$\rho_{273} = 6.14 \times 10^{-6} \text{ ohm cm}$$

Dewar and Fleming

Meissner



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 ( $\rho_{273}$ ) for cobalt to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $5.57 \times 10^{-6}$  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  $\rho_{273}$  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.

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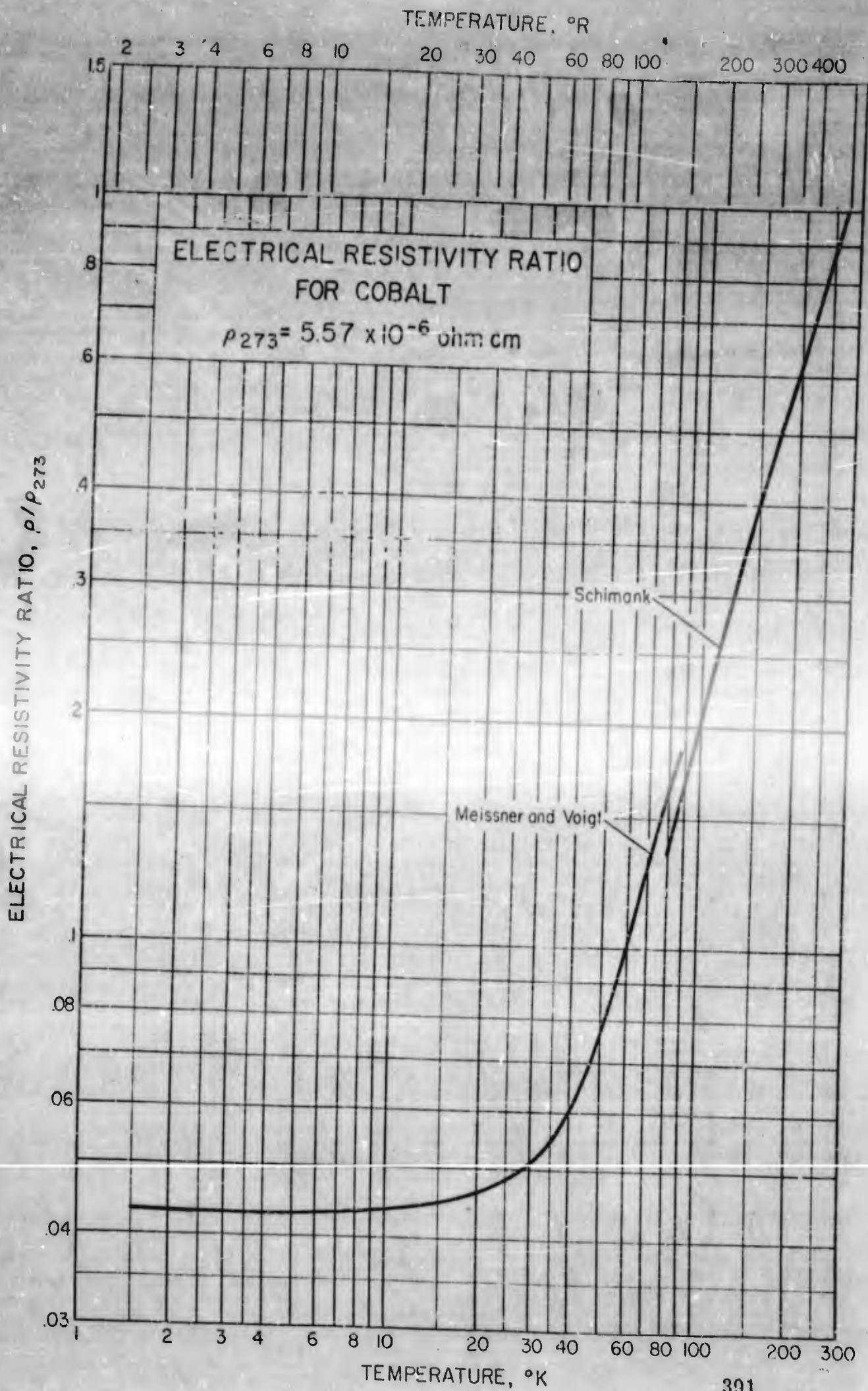
## ELECTRICAL RESISTIVITY of COBALT (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt	
Temp. °K	$\rho/\rho_{273}$
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



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 ( $\rho_{273}$ ) for ruthenium to be used in calculating values of electrical resistivity ( $\rho_T$ ) 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".

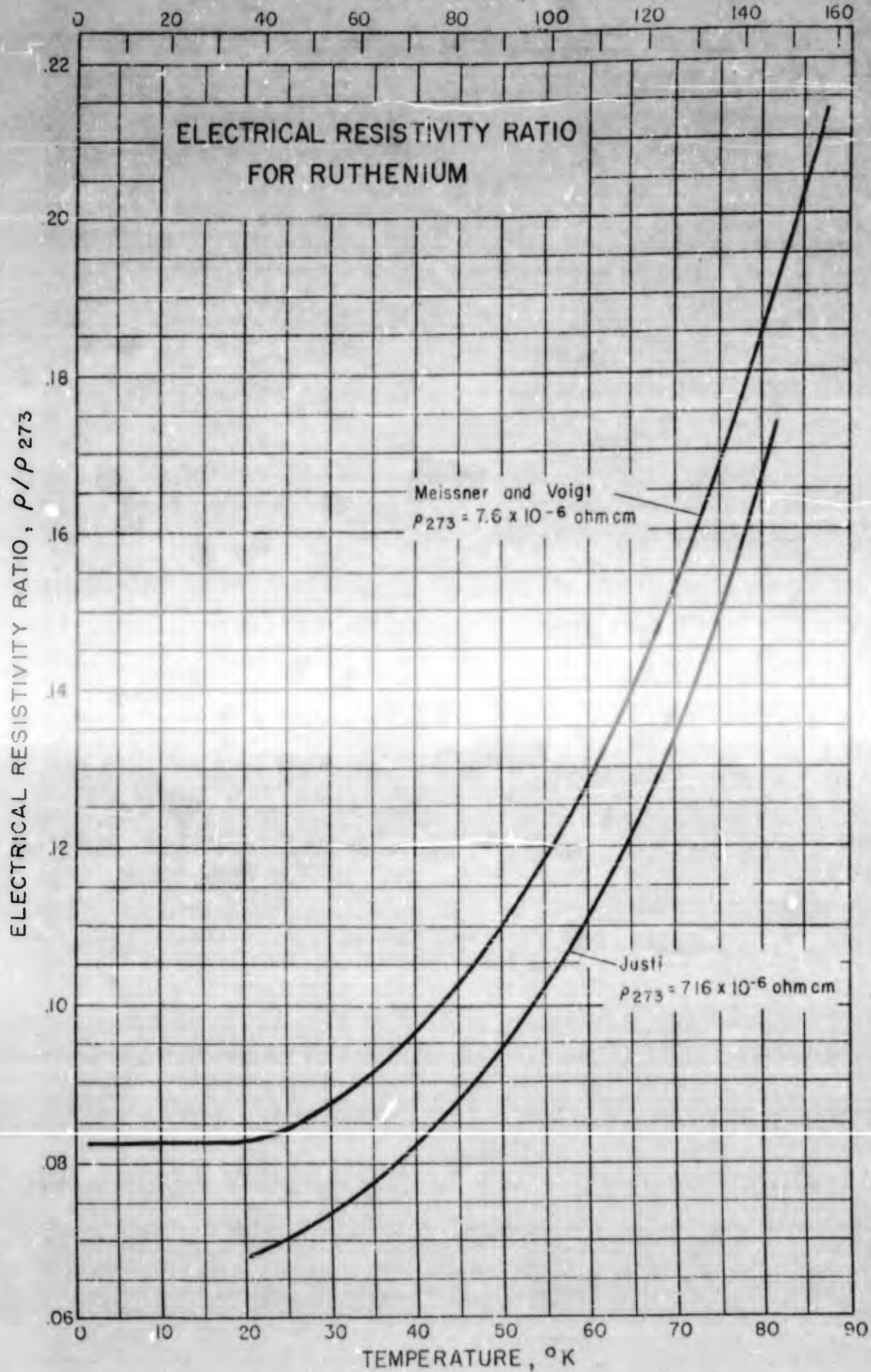
The data reported in Landolt-Börnstein tables and tabulated here are listed as ratios of the electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The values of  $\rho_{273}$  which appear on the graph below the authors' names are the values determined by those authors.

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			
$\rho$ = Resistivity, (ohm-cm)			
$\rho_{273}$ = Resistivity at 273°K, (ohm-cm)			
Justi		Meissner and Voigt	
Temp.* °K	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}$
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.

17.182 $\alpha$   
TEMPERATURE,  $^{\circ}$ R



TEMPERATURE,  $^{\circ}$ K

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 ( $\rho_{273}$ ) for rhodium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $4.35 \times 10^{-6}$  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  $\rho_{273}$  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.)

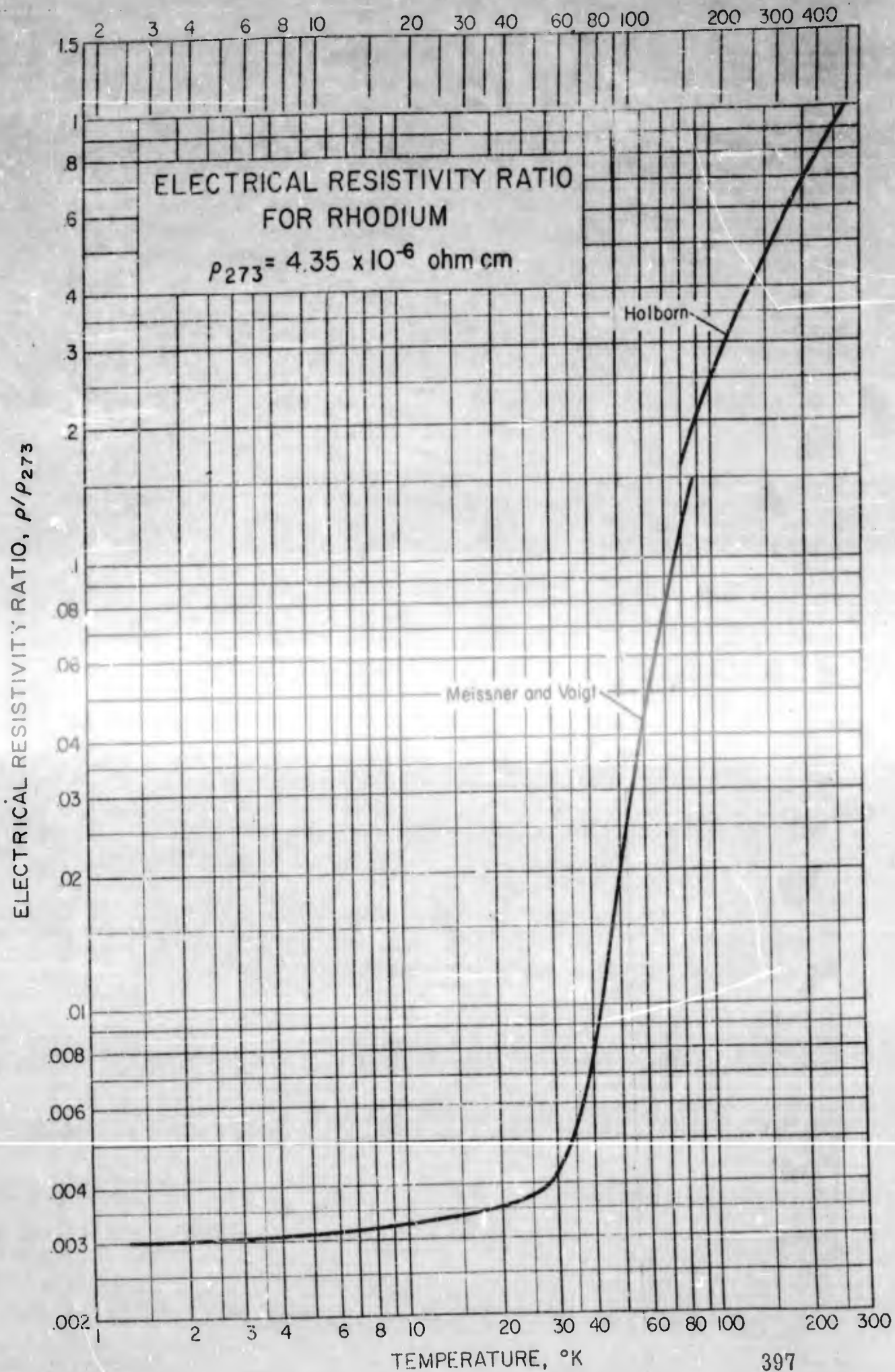
## ELECTRICAL RESISTIVITY of RHODIUM (Cont.)

Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = 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	$\rho/\rho_{273}$ **
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.	

TEMPERATURE, °R



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 ( $\rho_{273}$ ) for palladium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $9.77 \times 10^{-6}$  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  $\rho_{273}$  are not available for the samples used by the several investigators so a datum value reported by Grüneisen and Reddemann ( $\rho_{273} = 9.77 \times 10^{-6}$  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.

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## ELECTRICAL RESISTIVITY of PALLADIUM (Cont.)

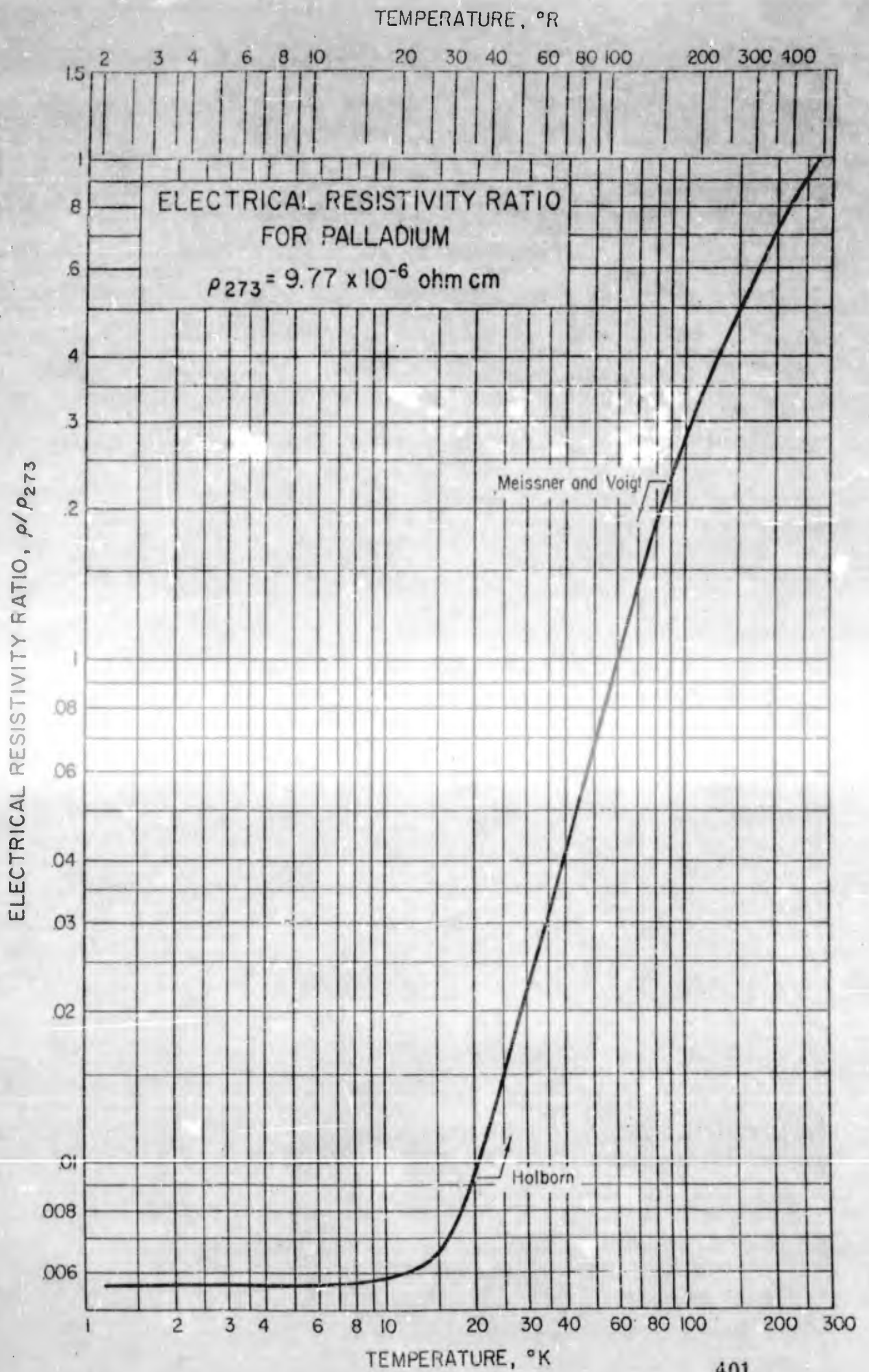
Tables of Values of Electrical Resistivity $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Meissner and Voigt.			
Temp.* °K	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}$ **
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	$\rho/\rho_{273}$
20	0.0093
81	0.1874
195	0.6855



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 ( $\rho_{273}$ ) for iridium to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $4.93 \times 10^{-6}$  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  $\rho_{273}$  for the samples used by the several investigators are not available so a datum value reported by Jaeger and Diesselhorst ( $\rho_{273} = 4.93 \times 10^{-6}$  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 IRIIDIUM, (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

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

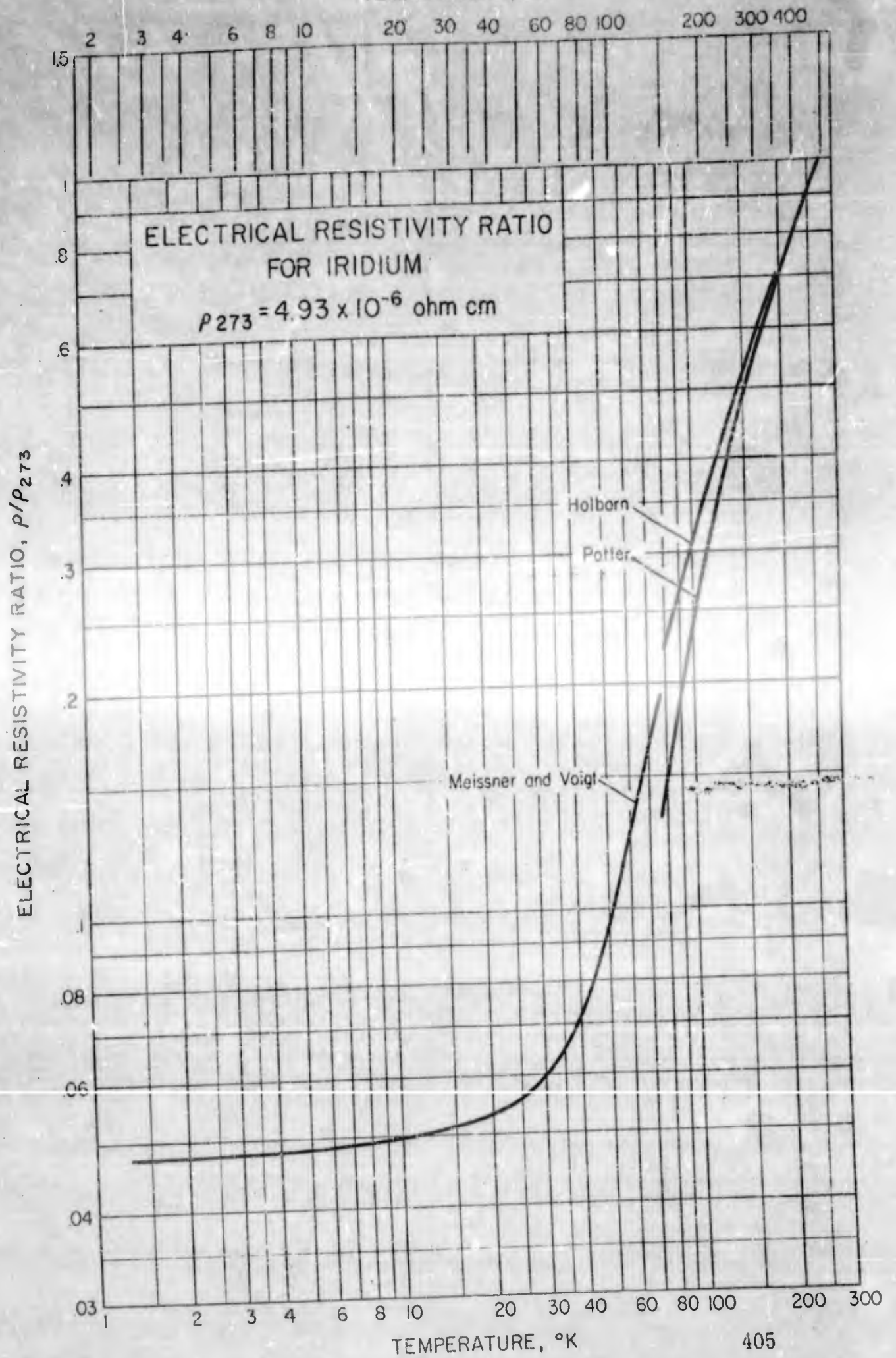
Holborn			
Temp. °C	$100\rho/\rho_{273}$	Temp. °C	$100\rho/\rho_{273}$
-78.4	69.22	-140 *	44.4
-80 *	68.6	-160 *	36.0
-100 *	60.6	-180 *	27.5
-120 *	52.5	-191.9	22.57

\* Values from interpolation.

Meissner and Voigt		Potter	
Temp.* °K	$\rho/\rho_{273}$	Temp. °K	$\rho/\rho_{273}$
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.

17.182 e  
TEMPERATURE, °R



ELECTRICAL RESISTIVITY of PLATINUM, Pt  
(Atomic Number 78)

Sources of Data:

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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 ( $\rho_{273}$ ) for platinum to be used in calculating values of electrical resistivity ( $\rho_T$ ) is  $9.81 \times 10^{-6}$  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  $\rho_{273}$  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 from any of the sources of data.

Tables of Values of Electrical Resistivity

$\rho$  = Resistivity, (ohm-cm)

$\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Holborn		Meissner		Meissner and Grassmann	
Temp. °K	$\rho/\rho_{273}$	Temp.* °K	$\rho/\rho_{273}$ **	Temp.* °K	$\rho/\rho_{273}$ **
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

 $\rho$  = Resistivity, (ohm-cm) $\rho_{273}$  = Resistivity at 273°K, (ohm-cm)

Temp. °C	Tyu and Onnes	Van der Horst et al.	Henning
	$100\rho/\rho_{273}$	$100\rho/\rho_{273}$	$100\rho/\rho_{273}$
- 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	--

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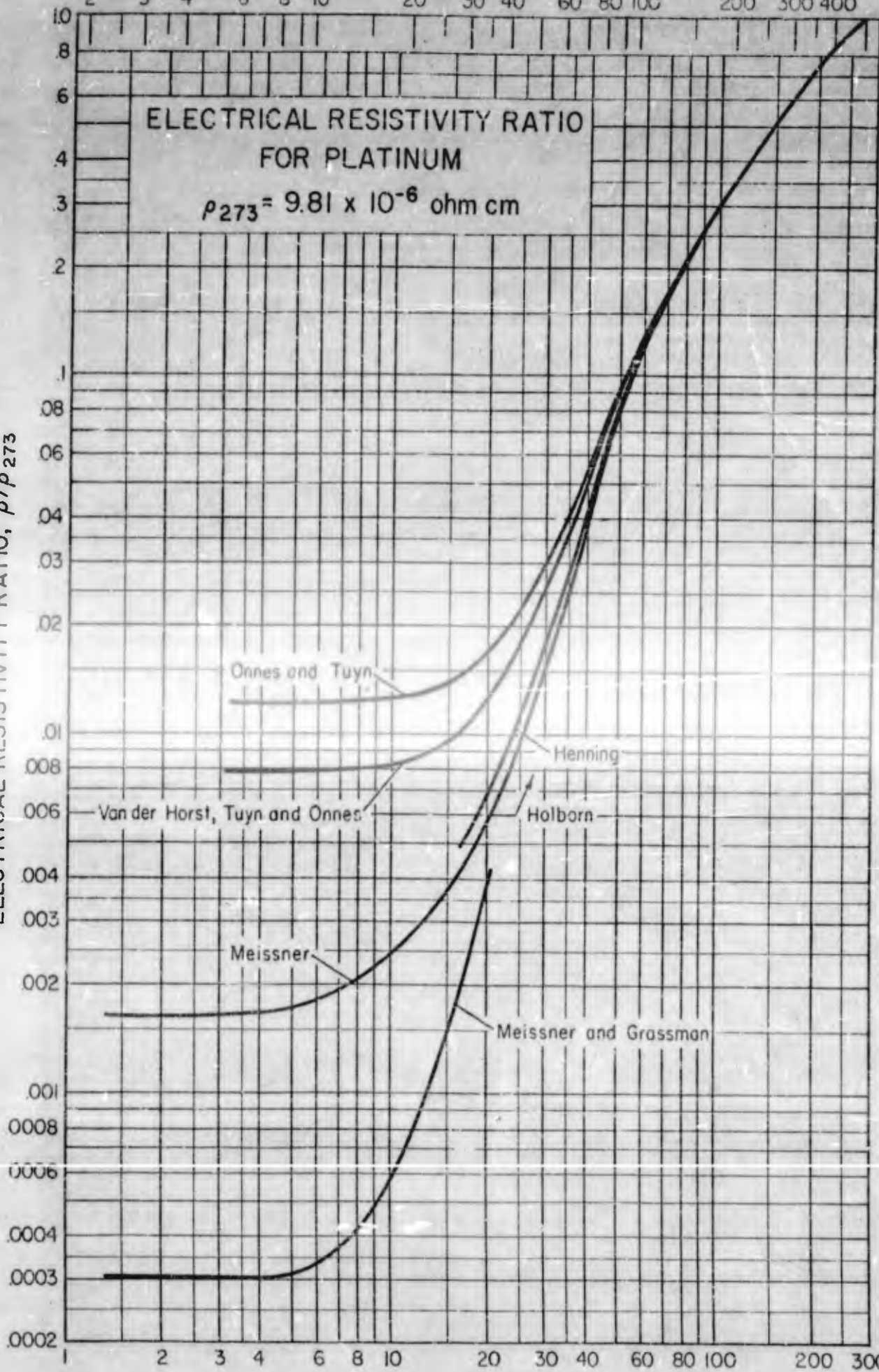
TEMPERATURE, °R

2 3 4 6 8 10 20 30 40 60 80 100 200 300 400

### ELECTRICAL RESISTIVITY RATIO FOR PLATINUM

$$\rho_{273} = 9.81 \times 10^{-6} \text{ ohm cm}$$

ELECTRICAL RESISTIVITY RATIO,  $\rho/\rho_{273}$



TEMPERATURE, °K

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PROPERTY AND MATERIAL INDEX OF REFERENCES

(NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

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+	263+
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  
 + REFERENCE LISTED AS OTHER REFERENCE

PROPERTY AND MATERIAL INDEX OF REFERENCES

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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

\* 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)

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	550*	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						

\* REFERENCE USED AS SOURCE OF DATA  
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PROPERTY AND MATERIAL INDEX OF REFERENCES

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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
523	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			

\* REFERENCE USED AS SOURCE OF DATA  
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PROPERTY AND MATERIAL INDEX OF REFERENCES

(NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

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+
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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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PROPERTY AND MATERIAL INDEX OF REFERENCES

(NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

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 76 123 157 158 160 452 488 602  
 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  
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PROPERTY AND MATERIAL INDEX OF REFERENCES  
 (NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

ELECTRICAL RESISTIVITY (17,000)

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  
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PROPERTY AND MATERIAL INDEX OF REFERENCES

(NUMBERS REFER TO ITEM OF PRIMARY OR SUPPLEMENTAL REFERENCE LIST)

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	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  
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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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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

\* 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)

VELOCITY OF SOUND (15.000)

CARBON MONOXIDE.....15.007

27 138+ 232+ 303+ 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+

\* REFERENCE USED AS SOURCE OF DATA  
+ REFERENCE LISTED AS OTHER REFERENCE

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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*	

- \* 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)

LEAD.....									17.142-38	
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	<del>252*</del>	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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PROPERTY AND MATERIAL INDEX OF REFERENCES

(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+								

\* REFERENCE USED AS SOURCE OF DATA  
 + REFERENCE LISTED AS OTHER REFERENCE

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No Space 3/4 in

R-1542 9474

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