NBS TECHNICAL NOTE 365-1

Survey of Electrical Resistivity Measurements on 8 Additional Pure Metals in the Temperature Range 0 to 273 K

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards [1] was established by an act of Congress March 3, 1901. Today, in addition to serving as the Nation's central measurement laboratory, the Bureau is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end the Bureau conducts research and provides central national services in four broad program areas. These are: (1) basic measurements and standards, (2) materials measurements and standards, (3) technological measurements and standards, and (4) transfer of technology.

The Bureau comprises the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Radiation Research, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of an Office of Measurement Services and the following technical divisions:

> Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic and Molecular Physics—Radio Physics [2]—Radio Engineering [2]—Time and Frequency [2]—Astrophysics [2]—Cryogenics.[2]

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; develops, produces, and distributes standard reference materials; relates the physical and chemical properties of materials to their behavior and their interaction with their environments; and provides advisory and research services to other Government agencies. The Institute consists of an Office of Standard Reference Materials and the following divisions:

> Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations in the development of technological standards, and test methodologies; and provides advisory and research services for Federal, state, and local government agencies. The Institute consists of the following technical divisions and offices:

> Engineering Standards—Weights and Measures — Invention and Innovation — Vehicle Systems Research—Product Evaluation—Building Research—Instrument Shops—Measurement Engineering—Electronic Technology—Technical Analysis.

THE CENTER FOR RADIATION RESEARCH engages in research, measurement, and application of radiation to the solution of Bureau mission problems and the problems of other agencies and institutions. The Center consists of the following divisions:

> Reactor Radiation—Linac Radiation—Nuclear Radiation—Applied Radiation.

THE CENTER FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in the selection, acquisition, and effective use of automatic data processing equipment; and serves as the principal focus for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

> Information Processing Standards—Computer Information — Computer Services — Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System, and provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

> Office of Standard Reference Data—Clearinghouse for Federal Scientific and Technical Information [3]—Office of Technical Information and Publications—Library—Office of Public Information—Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Located at Boulder, Colorado 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

UNITED STATES DEPARTMENT OF COMMERCE
Maurice H. Stans, Secretary
NATIONAL BUREAU OF STANDARDS ● Lewis M. Branscomb, Director

NBS TECHNICAL NOTE 365-1

ISSUED AUGUST 1970

Nat. Bur. Stand. (U.S.), Tech. Note 365-1, 85 pages (Aug. 1970)
CODEN: NBTNA

Survey of Electrical Resistivity Measurements on 8 Additional Pure Metals in the Temperature Range 0 to 273 K

L. A. Hall and F. E. E. Germann

Cryogenics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80302

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.46:365-1), Price $1.00

CONTENTS

SURVEY OF ELECTRICAL RESISTIVITY MEASUREMENTS ON 8 ADDITIONAL PURE METALS IN THE TEMPERATURE RANGE 0 TO 273 K

L. A. Hall and F. E. E. Germann

Experimental electrical resistivity data for 8 pure metals have been compiled tabulated, and graphically illustrated for a temperature range of 0 to 273 K. A section has been prepared for each particular metal which includes references, brief comments concerned with preparation of sample, purity, and any other pertinent information, tabulated data, and graph.

Key words: cadmium; chromium; compilation; electrical resistivity; low temperature; manganese; titanium; tungsten; vanadium; zinc; zirconium.

1. INTRODUCTION

This survey is a continuation of the task of collecting experimental electrical resistivity data for pure metals. The first group of metals studied were Al, Be, Co, Cu, Au, In, Fe, Pb, Mg, Mo, Ni, Nb, Pt, Ag, Ta, and Sn.** As in the previous survey, we found many articles describing experimental measurements of electrical resistivity in the open literature. Many presented results of straight-forward temperature-dependent resistivity measurements on wires or rods of high-purity metals. Some dealt with the effects of irradiation, plastic deformation, magnetic fields, and alloying on resistivity, while others showed the variation in resistivity due to unusual shape of the sample, e.g., whiskers or thin films. In the recent literature, superconductivity was also studied extensively. Because the amount of literature in this field is so large, we have restricted this survey to the temperature-dependent resistivity measurements on very pure metals.

All of the data from this one area of resistivity measurements have been organized into a relatively concise and useful form. For the experimentalist, we have tried to present a complete picture of what data are already available so that he may plan his work in such a manner as to fill in "gaps" in existing data or to check or "reinforce" existing measurements. For the engineer, we have presented a method of predicting the electrical behavior of a metallic specimen of known purity. When the purity is not known, the resistivity of the metal may be predicted by measuring its residual resistivity, which can be measured at 4.2 K, and applying Matthiessen's rule, as will be explained below. With these objectives in mind, we have reviewed carefully all of the pertinent articles and noted in a "comments" section the purity of the metals studied, their residual resistivity value, any mechanical treatment of the sample and its final form during measurements, and any other facts which might help explain the character of the experimental data.

---

* This study was supported in part by the National Aeronautics and Space Administration, Office of Advanced Research and Technology, Contract R-06-006-046.

** "Survey of Electrical Resistivity Measurements on 16 Pure Metals in the Temperature Range of 0 to 273 K," L. A. Hall, Natl. Bur. Stds. Tech. Note 365 (Feb 1968).

An earlier compilation* presented experimental resistivity data for 53 metallic elements. From the time of that publication to the present, the Compilation Unit of the Cryogenic Data Center has been actively acquiring electrical resistivity articles. These articles were entered into our Storage and Retrieval System together with all the other cryogenically oriented documents that have come to our attention by a systematic scanning of the primary journals, and secondary publications such as Chemical Abstracts, Physics Abstracts, NASA STAR, Nuclear Science Abstracts, DDC TAB, and International Aerospace Abstracts. A computer search of this Storage and Retrieval System was the basis for this compilation. All pertinent articles from the references listed in this search were obtained and reviewed.

2. GENERAL DISCUSSION OF RESISTIVITY**

The measured resistivity ρ_T is a function of temperature, but on approaching absolute zero it approaches a constant residual resistivity ρ_0. The quantity ρ_0 arises from the presence of impurities, defects, and strains in the metal lattice. However, in pure annealed metals it is only a small fraction of the total resistivity at room temperature. Subtraction of ρ_0 from the measured resistivity gives a value of the resistivity appropriate for a perfectly pure, strain-free specimen. The temperature-dependent resistivity thus obtained is called the ideal or intrinsic resistivity ρ_i. It is caused by the interaction of the conduction electrons with the thermally induced vibrations of the lattice ions, and, if present, with the magnetic structure of the lattice. The separation of the total resistivity ρ_T into temperature dependent (ρ_i) and temperature-independent (ρ_0) contributions in this way is known as Matthiessen's rule, which may be written

$$\rho = \rho_0 + \rho_i \ .$$

This rule is a good approximation for all engineering purposes.

The ideal resistivity due to lattice vibrations may be expressed by the Gruneisen-Bloch relation

$$\rho_i = \frac{C}{M\theta_R} \left(\frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{z^5 dz}{(e^z - 1)(1 - e^{-z})}$$

where M is the atomic weight, C is a constant, and T is in the Kelvin scale. θ_R is an empirical temperature characterizing the metal's lattice resistivity in the same way the Debye temperature θ_D characterizes a solid's lattice specific heat. It is often true that $\theta_R \approx \theta_D$, typically about 300 K for most metals. Below about 0.1 θ_R this relation reduces to $\rho_i \propto T^5$ relation closely. It is found that a few of the metals follow the T^5 relation closely. The exponent of T for most nonmagnetic metals generally lies between 4.5 and 5.

---

* A Compendium of the Properties of Materials at Low Temperatures (Phase II)", R. B. Stewart and V. J. Johnson, editors, Natl. Bur. Standards, Cryogenic Eng. Lab., WADD Tech. Rept. 60-56, Part IV (1961) DDC AD 272 769.

** A more complete discussion of electrical resistivity can be found in Electrical Resistance of Metals by G. T. Meaden, Plenum Press, New York, 1965.

A metal with a cubic crystal structure has the same resistivity whether in polycrystalline or single crystal form, apart from a small extra contribution in a polycrystal that may sometimes be caused by grain boundaries since the cubic structure is isotropic. But in a single crystal of a noncubic metal, the resistivity is often very anisotropic, its value depending on the direction of the flow of current. Likewise, polycrystalline specimens of such metals, if preferentially oriented, as by rolling or drawing, for instance, will have direction-dependent resistive properties.

In anisotropic metals, the electrical resistivity parallel to the principle crystalline axis is designated $\rho_{\parallel}$ and electrical resistivity perpendicular to the principle axis is designated $\rho_{\perp}$. When values for $\rho_{\parallel}$ and $\rho_{\perp}$ have been determined for single crystals, one may calculate a value of $\bar{\rho}$ for a polycrystalline sample using the equation of Voigt*

$$\bar{\rho} = \frac{3\rho_{\perp} \ \rho_{\parallel}}{2\rho_{\parallel} + \rho_{\perp}} \ .$$

Superconductivity is observed in at least 30 elements. At temperatures less than their "superconducting transition" temperatures, these elements lose all resistance to electric current. Articles dealing with superconductivity were not reviewed here and only the transition temperatures are noted for each metal. The curves on our graphs should not be extrapolated below this transition temperature.

In the residual resistance range, approximately below 20 K, trace quantities of certain impurity atoms in a nominally pure metal can cause resistance minima and other temperature dependent effects. These are generally quite small and have been neglected in this survey. Along with related magnetic effects, they are commonly classed as a manifestation of the "Kondo effect," occurring in the neighborhood of the "Kondo temperature." The interested reader should refer to the review article by Daybell and Steyert** for further information.

3. PRESENTATION OF DATA

A separate section has been devoted to each metal. These sections have been prepared in the format of our regular preliminary compilations and have been numbered consecutively with other worksheets dealing with other properties of materials at cryogenic temperatures. With the collection in this format, the user may easily remove any memorandum on a particular metal that he is studying from the group. The sections contain the following:

a) Sources of data - references for the articles from which we have taken the data.

b) Additional references - other articles dealing with electrical resistivity of the metal which may be of interest to the reader.

c) Comments - a concise discussion of any factors influencing the character of the experimenter's resistivity data, such as purity, heat treatment, shape of sample, crystal structure, etc.

---

* Voigt, W., Lehrbuch der Kristallphysik (Teubner, Leipzig, 1928), p. 959.

** M. D. Daybell and W. A. Steyert, Rev. Mod. Phys. 40, 380-89 (1968).

d) Tables - tabulated experimental data. When the experimenters presented their results graphically, an attempt was made to read values from the graphs and put them into tabular form.

e) Graph - the data have been plotted as ratios ρ_T/ρ_{273}, that is, the resistivity at a given temperature divided by the resistivity at 273.15 K. Many of the investigators have not given their ρ_{273} value, and in these instances we have used a value which we believed to be the most accurate value of ρ_{273} in calculating ρ_T/ρ_{273}. Table 1 shows ρ_{273} values given by the investigators and the value chosen as the most accurate. The data are plotted on logarithmic coordinates which tend to emphasize the differences in the values reported by the several experimenters at the lower temperatures.

In Table 1 on pages 6 - 11, all experimental values of ρ_{273} have been tabulated for the eight metals. The "selected" value is in most instances the lowest available value of ρ_{273} for that particular metal.

4. HOW TO USE THE DATA

As has been stated before, this is an attempt to gather all experimental data from temperature-dependent electrical resistivity measurements into a relatively concise form. The graph presents at a glance the amount of work done on a particular metal; however, for some of the more popular metals not all the tabular data are plotted because their curves would be superimposed on others. The annotated bibliography gives an insight into the character of the data.

An engineer, wishing to predict the resistivity of a particular metal, could:

1. review the comments section to find out if measurements have been made on a sample similar to his. If he succeeds in finding such measurements he can then refer to the tabular data and expect his metal to perform similarly.
2. apply Matthiessen's rule, $\rho_T = \rho_o + \rho_i$. The residual resistivity, ρ_o, could be found by measuring the resistivity at 4.2 K of the particular metal being used. The ideal resistivity, ρ_i, would be estimated from the graph by drawing a straight line downward from the portion of the lowest curve where $\rho \propto T^5$ (shown in figure 1).

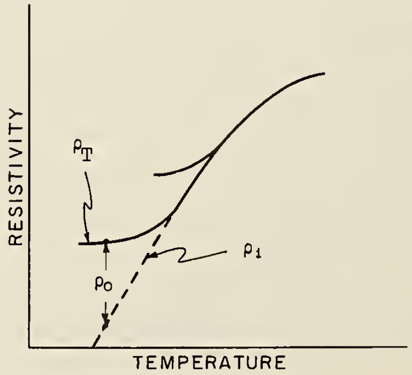


Figure 1. Relationship between ideal resistivity, ρ_i, residual resistivity, ρ_o, and measured resistivity at a given temperature, ρ_T.

It is also possible to estimate the purity of a metal by measuring its residual resistivity at 4.2 K, finding its position on the graph, and referring to the comments section to find statements of purity for curves in the same region of the graph.

On each graph an additional scale in degrees Rankine has been added at the top border. The appropriate conversion is: Kelvin times 1.8 = °R. For example, the ice point 273.15 K is equivalent to 491.67 °R.

Table 1 starts on the following page.

Table 1. Experimental Resistivity Values at 273 K.

metal		our "selected" value at 273 K	other compilations‡ value at 273 K			other values of resistivity at 273 K	articles which did not report a ρ_{273} value	
		$\rho \times 10^6$ ohm cm	Meaden(1965) $\rho_1 \times 10^6$ ohm cm	Gruneisen(1945) $\rho \times 10^6$ ohm cm	Gerritsen(1956) $\rho \times 10^6$ ohm cm	$\rho \times 10^6$ ohm cm	reported R/R_{273}	reported resistivity only
Cadmium	$\rho_\perp$	6.35 Goens & Gruneisen(1932)	6.35	6.35	6.35	6.54 Gruneisen & Goens(1924) 6.289 Bridgman(1933) 6.55 Aleksandrov & D'Yakov (1963), Aleksandrov (1963)	Meissner(1926)	
	$\rho_\parallel$	7.73 Goens & Gruneisen(1932)	7.73	7.73	7.73	7.79 Gruneisen & Goens(1924) 7.593 Bridgman(1933) 7.8 Aleksandrov & D'Yakov (1963), Aleksandrov (1963)(calculated value) 7.05 Tsui & Stark(1967) (calculated value)	Meissner(1926)	
	ρ_{poly}	6.73 Goens & Gruneisen(1932) (calculated value)	6.73	6.73	6.73	7.2 Jaeger & Diesselhorst (1900) 7.76 Eucken & Gelhoff(1912) 6.849 Schott(1916)	Onnes & Holst(1914) Schimank(1914) Holborn(1919) Meissner(1926) Tuyn & Onnes(1926) Tuyn(1929) McLennon & Niven(1927) Meissner & Voigt(1930) Vtorov & Dmitrenko(1967)	

Chromium		12.155	White & Woods (1959) Harper, Kemp, Klemens, Tainsh, & White(1957)	12.1	~15.0	15.0	18.9 Bridgman(1933) 21. Sochtig(1940) 13. Fine, Greiner, & Ellis(1951) 13. Newmann & Stevens(1959) 12.3 Arajs, Colvin, & Marcinkowski(1962) 12.3 Arajs & Dunmyre(1965, 1966) 12.2 Goff(1968) 11.8 Moore, Williams, & McElroy(1968) 12.1 (interpolated values) 12.5 Clinard & Kempter(1968) 12.5 Moore, Williams, & McElroy(1969) (interpolated value)	McLennan & Niven(1927) McLennan, Niven & Wilhelm (1928) Meissner & Voigt(1930) Potter(1941) Semenenko(1966)	
Manganese	γ	22.7	Brunke(1934)	--	39	39	42.038 Jaeger & Diesselhorst (1900) (extrapolated value) 39.2 Erfling(1940)		
	β	91.	Brunke(1934)	--	~90	91	135. Reddeman(1935) (estimated value)	Erfling(1939)	
	α	143.5	Meaden(1965, 1966)	138.5	~600	710	150. Meissner & Voigt(1930) 627. Erfling(1940) 150. White & Woods(1957, 1959) 714. Brunke(1934)		

Table 1. Experimental Resistivity Values at 273 K (con't).

metal		our "selected" value at 273 K	other compilations‡ value at 273 K			other values of resistivity at 273 K	articles which did not report a ρ_{273} value	
		$\rho \times 10^6$ ohm cm	Meaden(1965) $\rho_1 \times 10^6$ ohm cm	Gruneisen(1956) $\rho \times 10^6$ ohm cm	Gerritsen(1956) $\rho \times 10^6$ ohm cm	$\rho \times 10^6$ ohm cm	reported R/R_{273}	reported resistivity only
Titanium	$\rho_\perp$	45.35 Wasilewski (1962)	45.35	--	--	none		
	$\rho_\parallel$	48.0 Wasilewski (1968)	48.0	--	--	none		
	ρ_{poly}	39.4 Clinard & Kempter(1962)	39.0	42	42	82. Clausing & Moubis (1927) 54. Meissner & Voigt(1930) 52.27 Bostrom(1954) 67. Kemp, Klemens, & White(1956) 41. 43.5 Berlincourt(1959) (interpolated value) 41.3 White & Woods(1959) 41. 38. Roesch(1959) 36.5 42.67 Wasilewski(1962)	McLennan, Howlett, & Wilhelm(1929) De Haas & Van Alphen(1931) Meissner, Franz, & Westerhoff(1932) Potter(1941) Webber & Reynolds(1948)	Rosenberg(1955) Cape & Hake(1965) Mendelssohn, Sharma & Yoshida (1965)

Tungsten	4.839 Moore, McElroy & Barison(1967)	4.82	4.9	4.89	4.91 Gruneisen & Goens(1927) 4.98 Kannuluik(1933) 4.94 4.86 Gruneisen & Adenstedt (1938) 5.034 Cox(1943) 5.035 5.423 De Nobel(1957) (calculated value) 4.85 White & Woods(1957, 1959) 4.8 Shukovsky, Rose & Wulff(1966) (calculated value) 5. Backlund(1967) 5.002 Moore, McElroy & Barison(1967) 5. Clinard & Kempter(1968)	Holborn(1919) Henning(1921) Meissner(1928) McLennan, Howlett & Wilhelm(1929) Meissner & Voigt(1930) Van den Berg(1948) Wiese(1963) Berthel(1964) Volkenshtein, et al. (1964) Berthel(1967)	De Haas & De Nobel(1938) Powell, Harden & Gibson(1960)
Vanadium	19.54 Taylor & Smith (1962)	18.3	--	18.2	170. Meissner & Voigt(1930) 18.2 Potter(1941) (estimated value) 21.9 White & Woods(1957, 1959) 26.4 Hren & Wayman(1960) 23. Burger & Taylor(1961) 22.67 Taylor & Smith(1962) 20.34 24.1 Amitin, Kovalevskaya, Kovdrya(1967) 20.5 Westlake(1967), Westlake & Alfred (1968)	Meissner & Westerhoff(1933) Rostoker & Yamamoto(1955) Loomis & Carlson(1959)	Smirnov & Finkel (1966)

Table 1. Experimental Resistivity Values at 273 K (con't).

metal		out "selected" value at 273 K	other compilations‡ value at 273 K			other values of resistivity at 273 K	articles which did not report a ρ_{273} value	
		$\rho \times 10^6$ ohm cm	Meaden(1965) $\rho_1 \times 10^6$ ohm cm	Gruneisen(1945) $\rho \times 10^6$ ohm cm	Gerritsen(1956) $\rho \times 10^6$ ohm cm	$\rho \times 10^6$ ohm cm	reported R/R_{273}	reported resistivity only
Zinc	$\rho_{\perp}$	5.386 Bridgman(1933)	5.39	5.38	5.39	5.39 Gruneisen & Goens(1924) 5.38 Meissner(1926) 5.65 Meissner & Voigt(1930) (calculated value) 5.4 Goens & Gruneisen(1932) (interpolated value) 5.4 Aleksandrov(1963), Aleksandrov & D'Yakov (1963) (interpolated)		
	$\rho_{\parallel}$	5.589 Bridgman(1933)	5.59	5.58	5.59	5.83 Gruneisen & Goens(1924) 5.82 Meissner(1926) 5.99 Meissner & Voigt (1930) (calculated value) 5.57 Goens & Gruneisen(1932) (interpolated value) 5.7 Aleksandrov(1963), Aleksandrov & D'Yakov (1963) (interpolated)		
	ρ_{poly}	5.46 Bridgman(1933) (calculated value)	5.45	5.45	5.45	5.69 ⎤ Jaeger & Diesselhorst (1900) 6.0 ⎦ (extrapolated value) 5.99 Pawlek & Rogalla(1966) 5.56 Wilkes, Powell & DeWitt(1969)	Schimank(1914) Holborn(1919) Meissner(1926) Tuyn & Onnes(1926) Tuyn(1929) Collings, Hedgcock, & Muir(1963)	

Zirconium	38.85 White & Woods (1959)	38.6	41	40.5	42.5 Clausing & Moubis(1927) 42.4 Clausing & Moubis(1927) 41.0 Clausing & Moubis(1927) 60. Meissner & Voigt(1930) 49. Meissner & Voigt(1930) 17.1 Potter(1941) 39.6 Adenstedt(1952) 45. Kemp, Klemens & White (1956) 37. Berlincourt(1959) (interpolated value) 39. Clinard & Kempter(1968)	Clausing(1924) De Haas & Voogd(1928) McLennan, Howlett & Wilhelm(1929) Renucci, Langeron & Lehr(1961)	

‡ G. T. Meaden, Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

E. Gruneisen, Ergebn. exakt. Naturw. 21, 50-116 (1945).

A. N. Gerritsen, Handbuch der Physik, 19, 137-226 (1956).

5. ELECTRICAL RESISTIVITY DATA SHEETS

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422 **FILE NO.** M-26

ELECTRICAL RESISTIVITY OF CADMIUM, Cd
(Atomic Number 48)

(page 1 of 10)

Sources of Data:

Aleksandrov, B. N., "Size effect in electrical resistivity of high-purity metals," Soviet Phys. JETP 16, No. 2, 286-94 (Feb 1963).

Aleksandrov, B. N., and D'Yakov, I. G., "Variation of the electrical resistance of pure metals with decrease of temperature," Soviet Phys. JETP 16, No. 3, 603-08 (Mar 1963).

Bridgman, P. W., "The effect of pressure on the electrical resistance of single metal crystals at low temperature," Proc. Am. Acad. Arts Sci. 68, 95-123 (1933).

Eucken, A., and Gehlhoff, G., "Elektrisches, thermisches leitvermogen und Wiedemann-Franzsche zahl der antimon-cadmiunlegierungen zwischen 0 und -190°C," (Electrical, thermal conductivity and the Weidemann-Franz constant for antimony-cadmium alloys between 0 and -190°C), Verhandl. Deut. Physik. Ges. 14, 169-182 (1912).

Goens, E., and Gruneisen, E., "Elektrizitats und warmeleitung in zink und cadmiumkristallen," (Electrical and thermal conductivity in zinc and cadmium crystals), Ann. Physik 14, 164-80 (1932).

Gruneisen, E., "Elektrische leitfahigkeit der metalle bei tiefen temperaturen," (Electrical conductivity of metals at low temperatures), Ergeb. Exakt. Naturw. 21, 50-116 (1945).

Gruneisen, E., and Goens, E., "Untersuchungen an metallkristallen. II. Spezifische warme und elektrischer widerstand von zink und cadmium," (Tests with metal crystals. II. Specific heat and electrical resistivity for zinc and cadmium), Z. Physik 26, 250-73 (1924).

Holborn, L., "Uber die abhangigkeit des widerstandes reiner metalle von der temperatur," (About the dependence of resistance of pure metals on the temperature), Ann. Physik 59, 145-69 (1919).

Jaeger, W., and Diesselhorst, H., "Warmeleitung elektricitatsleitung, warmecapacitat und thermokraft einiger metalle," (Heat conduction, electrical conductivity, specific heat and thermal power in metals), Wiss. Abhandl. Physik.-Tech. Reichasanstalt 3, 269-424 (1900).

Mc Lennan, J. C., and Niven, C. D., "Electrical conductivity at low temperatures," Phil. Mag. 4, 386-404 (1927).

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meissner, W., "Messungen mit hilfe von flussigem helium. 2. Widerstand von gold, zink, cadmium, platin, nickel, eisen und silber bis herab zu 1.3° Abs." (Measurement with the help of liquid helium. 2. Resistance of gold, zinc, cadmium, platinum, nickel, iron and silver down to about 1.3 K), Z. Physik 38, 647-58 (1926) Abbreviated version appearing in Physik. Z. 27, 725-30 (1926).

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. (A) Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 761-97 (1930).

Onnes, H. K., and Holst, G., "On the electrical resistance of pure metals etc. IX. The resistance of mercury, tin, cadmium, constantin and manganin down to temperatures, obtainable with liquid hydrogen and with liquid helium at its boiling point," Commun. Phys. Lab. Univ. Leiden No. 142A (1914) Transl. from Verslag Gewone Vergader. Afdel. Natuurk. Koninkl. Ned. Akad. Wetenschap., 506-11 (Jun 1914).

Schimank, H., "Uber das verhalten des elektrischen widerstands von metallen bei tiefen temperaturen," (The behavior of the electrical resistance of metals at low temperature), Ann. Physik 45, 706-36 (1914).

Schott, R., "Uber das warmeleitvermogen einiger metalle bei tiefen temperaturen," (Thermal conductivity of some metals at low temperatures), Verhandl. Deut. Physik. Ges. 18, No. 1, 27-34 (1916).

Tsui, D. C., and Stark, R. W., "Evidence for anisotropic electron-phonon scattering probabilities from the galvanomagnetic properties of cadmium," Phys. Rev. Letters 19, No. 23, 1317-9 (Dec 1967).

Tuyn, W., "Measurements on the electrical resistance of some metals below the boiling point of oxygen," Commun. Phys. Lab. Univ. Leiden No. 196B (1929) Reprinted from Proc. Kon. Ned. Akad. Wetensch. 32, 115 (Feb 1929).

Tuyn, W., and Onnes, H. K., "Nouvelles experiences avec l'helium liquide. AB. Nouvelles mesures relatives a la resistance electrique des metaux aux temperatures de l'helium liquide," (New experiments with liquid helium. AB. New measurements of the electrical resistance of metals at liquid helium temperatures), Communs. Phys. Lab. Univ. Leiden No. 181 (1926), Reprinted from Arch. Neerl. Sci. IIIA 10, 5-41 (1926).

Vtorov, F. P., and Dmitrenko, I. M., "Superconducting bolometric current modulator," Cryogenics 7, No. 4, 207-8 (Aug 1967) Instr. Exptl. Tech. (USSR), No. 3, 748-50 (May-Jun 1966) Transl. Pribory I Tekhn. Eksperim., No. 3, 223-4 (May-Jun 1966).

Other References:

Aleksandrov, B. N., "Effect of dimensions and purity on the electrical resistance of metals in a longitudinal magnetic field at (liquid) helium temperatures," Soviet Phys. JETP 16, No. 4, 871-8 (Apr 1963), Transl. of Zhur. Eksptl. I Teoret. Fiz. 43, 1231-41 (1962).

Alekseevskii, N. E., and Gaidukov, Yu. P., "Open cross sections of cadmium, zinc and thallium fermi surfaces," Soviet Phys. JETP 16, No. 6, 1481-88 (Jun 1963).

Borovik, E. S., "Change of resistance of metals in a magnetic field at low temperatures," Zh. Eksptl. I. Teoret. Fiz. 23, 91-100 (1952).

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Bridgman, P. W., "Miscellaneous measurements of the effect of pressure on electrical resistance," Proc. Am. Acad. Arts Sci. 82, No. 2, 83-100 (Apr 1953).

Dewar, J., and Fleming, J. A., "The electrical resistance of metals and alloys at temperatures approaching the absolute zero," Phil. Mag. 36, 271-99 (1893).

Hilsch, R., and Von Minnigerode, G., "He^3 cryostat for investigation of condensation films below 1 K," Kaltetechnik 14, No. 12, 394-96 (Dec 1962).

Meissner, W., "Widerstand von metallen bei der temperatur des flussigen heliums," (Resistance of metals at the temperature of liquid helium), Z. Instrumentenk. 46, 103-5 (1926).

Onchi, M., "Conductivity and surface potential change of cadmium films due to adsorption," Transactions of the Natl. Vacuum Symp. of the AVS 10th, 1963, MacMillian Co., New York (1964) 5 pp.

Panova, G. K., and Samoilov, B. N., "Effect of isotopic composition on the electrical conductivity of cadmium," Sov. Phys. JETP 26, No. 5, 888-90 (May 1968) Transl. of Zh. Eksp. Teor. Fiz. 53, 1539-44 (Nov 1967).

Peiffer, H. R., "Effect of deformation and recovery on the subsequent resistivity increase in cold-worked cadmium," Rias, Inc., Baltimore, Md., Tech. Rept. No. 7 (1963) Contr. No. NONR3707(00) 7 pp, DDC AD 435 840.

Peiffer, H., and Maycock, J. N., "An investigation of the defect solid state," Rias, Div. of Martin Co., Baltimore, Md., Final Rept. (1964) Contr. No. NONR-3707(00), 48 pp, NASA N65 19021.

Perez-Albuerne, E. A., Clendenen, R. L., Lynch, R. W., and Drickamer, H. G., "Effect of very high pressure on the structure of some HCP metals and alloys," Phys. Rev. 142, No. 2, 392-99 (Feb 1966).

Ruhl, W., "Zur oxydation von metallen bei sehr tiefen temperaturen," (On the oxidation of metals at very low temperatures), Z. Physik 176, No. 4, 409-20 (Nov 1963).

Sharp, J. V., Mitchell, A., and Christian, J. W., "The recovery of deformed cadmium, magnesium, zinc and cobalt," Acta Met. 13, 965-71 (Sep 1965).

Stevenson, F. R., and Peiffer, H. R., "Recovery of defects following deformation of high purity cadmium at 78 K," Rias, Baltimore, Md., Tech. Rept. No. 4 (Jul 1963) Contr. No. NONR-3707(00) 17 pp, DDC AD 410 358.

Stevenson, F. R., and Peiffer, H. R., "Effect of impurities on the electrical resistivity increase during elongation of cadmium at 78 K," Rias, Baltimore, Md., Tech. Rept. No. 5 (Jul 1963) Contr. No. NONR-3707(00) 5 pp, DDC AD 410 357.

Stevenson, F. R., and Peiffer, H. R., "Effect of impurities on the electrical resistivity increase during elongation of cadmium at 71 K," Nature 200, 771-72 (1963).

Stevenson, F. R., and Peiffer, H. R., "Recovery of defects following deformation of high purity cadmium at 78 K," Phys. Status Solidi 4, 411-18 (1964).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data". The tabular values are ratios of electrical resistivity with respect to the resistivity at the ice point temperature (ρ_{273}).

Since cadmium is an anisotropic metal, we list suggested values of ρ_{273} for Cd $\parallel$, Cd $\perp$, and polycrystalline cadmium to be used in calculating electrical resistivities from the ratios whenever the original investigators did not state such values for their samples. These suggested values are:

$$\rho(\parallel)_{273} = 7.73 \times 10^{-6} \text{ ohm cm}, \qquad \rho(\perp)_{273} = 6.35 \times 10^{-6} \text{ ohm cm},$$

and

$$\rho_{(\text{poly})_{273}} = 6.73 \times 10^{-6} \text{ ohm cm}.$$

These values are from Goens and Gruneisen (1932). It should also be noted that cadmium becomes superconducting below 0.52 K.

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Jaeger and Diesselhorst (1900) gave two experimental values for electrical conductivity at 18°C and 100°C. An extrapolation of the data gives a resistivity value of $\rho_{273} = 7.2 \times 10^{-6}$ Ω cm.

Eucken and Gelhoff (1912) measured the electrical conductivity of a polycrystalline bar.

Onnes and Holst (1914) cast their polycrystalline sample in a glass tube. The impurities were $< 0.01\%$.

Schimank (1914) measured the resistances of two samples of high purity cadmium wire. The first sample (Cd I) was cold drawn and the second (Cd II) was extruded. The impurities were $< 0.01\%$.

Schott (1916) measured the electrical conductivity of a chemically pure rod which had been previously annealed in a vacuum.

Holborn's (1919) samples were 2 mm diameter wires. The cadmium was purified at the Reichsanstalt and taken from the fourth purity stage (impurity was $< 0.01\%$). Cd 2 was heated to 220 K for a lengthy period of time.

Grüneisen and Goens (1924) determined resistivities of very pure cadmium at 84° and 0° angles to the hexagonal axis. No further information is given about the samples.

Meissner (1926) measured resistance ratios of four samples: Cd $\parallel$ was 3.2 mm dia., 5 cm long and the measurements were made at 10° to the hexagonal axis; Cd $\perp$ was 3.9 mm dia., 5 cm long and the measurements were made at 84° to the hexagonal axis; Cd(poly)1 was 0.2 mm dia., 5 cm long and not annealed; Cd(poly)2 was 0.2 mm dia., 5 cm long and annealed.

Tuyn and Onnes (1926) and Tuyn (1929) report measurements on a 99.99% pure polycrystalline cadmium wire which was 0.22 mm dia. The superconducting portions of the curves are probably due to the presence of 0.005% lead in the samples.

Mc Lennan and Niven (1927) wound strips of cadmium on a piece of pyrex glass. The aged samples were annealed for 3.5 hours at 200°C.

Meissner and Voigt (1930) stated that their cadmium samples were impure. The polycrystalline wire was 55 mm long, 0.2 mm dia. and had been aged. The single crystals had the following dimensions: Cd $\parallel$ was 55 mm long, 3.2 mm dia.; Cd $\perp$ was 55 mm long, 3.9 mm dia. The data presented here are the same as the data in Meissner (1926).

Goens and Grüneisen (1932) determined the resistivity of ideal, pure, undeformed cadmium both parallel and perpendicular to the hexagonal axis. Polycrystalline resistivity at 273 K can be calculated from the following: $\rho(\parallel)_{273} = 7.73 \times 10^{-6}$ ohm cm and $\rho(\perp)_{273} = 6.35 \times 10^{-6}$ ohm cm. We find $\rho_{(\mathrm{poly})_{273}} = 6.73 \times 10^{-6}$ ohm cm.

Bridgman (1933) used 1 mm dia. rods of approximately 2.5 cm length which were cast in pyrex tubing by slowly lowering out of a furnace. He used Kahlbaum grade cadmium. The data in the table below were taken at zero pressure.

Grüneisen (1945) used the Goens and Grüneisen (1932) data to determine the resistivity values at 0°C.

$$\rho \parallel = 7.73 \times 10^{-6} \text{ ohm cm},$$

$$\rho \perp = 6.35 \times 10^{-6} \text{ ohm cm},$$

and by averaging the two using Voigt's equation, he calculated for the polycrystal:

$$\rho_{\mathrm{poly}} = 6.73 \times 10^{-6} \text{ ohm cm}.$$

Aleksandrov (1963) and Aleksandrov and D'Yakov (1963) report electrical resistivity measurements on 3.5 mm dia. and 150 mm length samples. The cadmium was purified by zone melting (99.999994% pure) and the samples were annealed in air at 120-130°C for one day following each change of mounting. They present measurements at both parallel and perpendicular orientation to the primary axis. ρ_{273}'s were calculated using the ρ_{293}'s from Aleksandrov (1963). Their values are: Cd $\parallel$ has $\rho_{273} = 7.8 \times 10^{-6}$ ohm cm, Cd$\perp$ has $\rho_{273} = 6.55 \times 10^{-6}$ ohm cm.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Tsui and Stark (1967) measured resistivity of high purity single crystal specimens with residual resistivity ratios in excess of 150,000. The data in the table are for zero magnetic field. ρ_{273} is calculated to be 7.05×10^{-6} ohm cm.

Vtorov and Dmitrenko (1967) measured resistance of a very pure large-grain specimen of cadmium. $R_{(residual)}/R_{293}$ is 1.1×10^{-5}.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm);
R = resistance, (ohm);
ρ_{273} = resistivity at 273 K, (ohm cm).
R_{273} = resistance at 273 K, (ohm).

Eucken and Gelhoff (1912)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
83	1.978	0.254
194	5.45	0.703
273	7.76	1.0

* These values were not plotted on the Electrical Resistivity of Cadmium graph.

Onnes and Holst (1914)

Temp. K	Resistance $R \times 10^3$ ohm	R/R_{273}**
4.2	0.032	0.00045
14.8	0.58	0.00817
20.2	1.45	0.0204
71.9	15.7	0.221
89.9	20.9	0.294
273.1*	71.0 *	1.0

* Interpolated value.
** These values were not plotted on the Electrical Resistivity of Cadmium graph.

Schimank (1914)

Temp. K	R/R_{273} Cd I	R/R_{273} Cd II*
20.2	0.0232	0.0217
82.7	0.2584	-
82.9	-	0.2581
90.0	0.2872	0.2860
133.9	0.4949	0.4637
161.5	-	0.5644
163.6	0.5742	-
180.4	-	0.6376
182.1	0.6434	-
200.6	0.7149	-
202.3	-	0.7200
226.4	-	0.8137
227.3	0.8203	-
273.09	1.0000	1.0000

* These values were plotted on the Electrical Resistivity of Cadmium graph.

Schott (1916)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
20.4	0.1473	0.0215
87.	1.866	0.272
273.	6.849	1.00

Holborn (1919)

Temp. K	R/R_0*	
	Cd 1	Cd 2
80.6	0.2533	-
80.8	-	0.2522
194.7	0.6906	-
194.8	-	0.6917

* These values were not plotted on the Electrical Resistivity of Cadmium graph.

Gruneisen and Goens (1924)

Temp. K	ρ/ρ_{273}*	
	Cd ∥	Cd ⊥
20.4_3	0.0220_4	0.0187
82.0	0.258	0.250
83.0	0.263	-
85.0	-	0.262
88.3	0.282	-
89.7	-	0.283
130	0.439	0.435
195	0.694	0.693

* For Cd ∥ , $\rho_{273} = 7.79 \times 10^{-6}$ ohm cm;
Cd ⊥ , $\rho_{273} = 6.54 \times 10^{-6}$ ohm cm.

These values were not plotted on the Electrical Resistivity of Cadmium graph.

Meissner (1926)

Temp. K	R/R_{273}			
	Cd ∥ *	Cd ⊥ *	Cd (poly) 1* not annealed	Cd (poly) 2* annealed
1.35	0.00015_7	0.00047_5	-	-
1.68	-	-	0.000594	0.000736
4.20	-	-	0.000614	0.000760
4.21	0.00018_8	0.00050_7	-	-
20.42	0.020_0	0.0197_6	0.0209_0	0.0209_1
82.48	0.2617	0.2542	0.2579	0.2575
273.20	1.000	1.000	1.000	1.000

* These values are not plotted on the Electrical Resistivity of Cadmium graph because they are the same data as the Meissner and Voigt (1930) data.

Tuyn and Onnes (1926) and Tuyn (1929)

Temp. K	R/R_{273}		
	Cd-1919-I	Cd-1920-I	Cd-1924-I
1.43			0.0000_4
1.46		0.0014_0	
1.74			0.0000_8
1.87		0.0014_0	
2.01			0.0001_2
2.30	0.00000		
2.40			0.0002_6
2.62	0.0000_6		
2.80			0.0004_6
2.81	0.0006_3		
2.90	0.0009_9		
2.98	0.0014_6		
3.04	0.0015_6		
3.11	0.0017_4		
3.20	0.0019_3		
3.26	0.0020_9		
3.30			0.0008_1
3.39		0.0014_1	
3.42	0.0023_7		
3.42	0.0023_9		
3.46		0.0014_1	
3.48	0.0024_8		
3.51	0.0025_0		
3.77	0.0027_4		
3.96			0.0012_9
4.18			0.0014_6
4.22	0.0029_0	0.0014_3	
4.24	0.0029_2		
14.22	0.00997	0.00907	0.01022
16.53	0.01424	0.01331	0.01450
18.06	0.01759	0.01666	0.01786
20.51	0.02362	0.02267	0.02386
56.77	0.15572	0.15475	0.15581
65.99	0.19251	0.19158	0.19256
73.05	0.22060		0.22061
73.06		0.21967	
81.01		0.25125	
81.02	0.25219		0.25218
90.40			0.28907
90.41	0.28913	0.28820	

McLennan and Niven (1927)

Temp. K	R/R_0		
	Cd I* (unaged)	Cd I* (aged)	Cd II (aged)
3.6			0.000924
3.8	0.00492		
4.2	0.00496	0.00073	0.000939
8.2		0.00087	
9.2		0.00120	
9.8		0.00127	
11.5		0.00221	
20.6	0.0262	0.0207	0.0242
80	0.257		
81			0.311
83		0.270	
273	1.000	1.000	1.000

* These values were plotted on the Electrical Resistivity of Cadmium graph.

Meissner and Voigt (1930)

Temp. K	R/R_{273}		
	Cd (poly)	Cd $\parallel$	Cd $\perp$
1.35	-	0.00015_7	0.00047_5
1.68	0.000736	-	-
4.20	0.000760	-	-
4.21	-	0.00018_8	0.00050_7
20.42	0.0209_1	0.0220_1	0.0197_6
82.47	0.2575	0.2617	0.2542
273.16	1.000	1.000	1.000

Goens and Gruneisen (1932)

Temp. K	$\rho \times 10^6$ ohm cm		ρ/ρ_{273} **	
	Cd $\perp$	Cd $\parallel$	Cd $\perp$	Cd $\parallel$
21.2	0.1346	0.188_1	0.0210	0.0241
83.2	1.62_6	2.02_4	0.254	0.259
273.2	6.35 *	7.73 *	1.000	1.000

* Interpolated value.
** These values have not been plotted on the Electrical Resistivity of Cadmium graph.

Bridgman (1933)

Temp. K	ρ/ρ_{273}	
	Cd $\parallel$	Cd $\perp$
90.35	0.2891	0.2850
194.85	0.6903	0.6899
273.15*	1.000	1.000

* At 273.15 K, $\rho_{\parallel} = 7.593 \times 10^{-6}$ ohm cm and $\rho_{\perp} = 6.289 \times 10^{-6}$ ohm cm.

Aleksandrov (1963) and Aleksandrov and D'Yakov (1963)

Temp. K	ρ/ρ_{273}*	
	Cd $\parallel$	Cd $\perp$
0	0.0000107	0.0000162
1.65	0.0000114	0.0000163
3.4	0.0000144	0.0000208
3.7	0.0000164	0.0000232
4.22	0.0000217	0.0000298
7.2	0.000192	-
14	0.00590	0.00596
20.4	0.0212	0.0197
58	0.161	0.160
63.5	0.185	0.181
77.4	0.243	0.238
90.31	0.291	0.289
111.6	0.376	0.373
273	1.0	1.0

* ρ_{273} was calculated using the ρ_{293} values for Cd $\parallel$ and Cd $\perp$ Aleksandrov (1963).
For Cd $\parallel$, $\rho_{273} = 7.8 \times 10^{-6}$ ohm cm;
Cd $\perp$, $\rho_{273} = 6.55 \times 10^{-6}$ ohm cm.

Vtorov and Dmitrenko (1967) (read from graph)

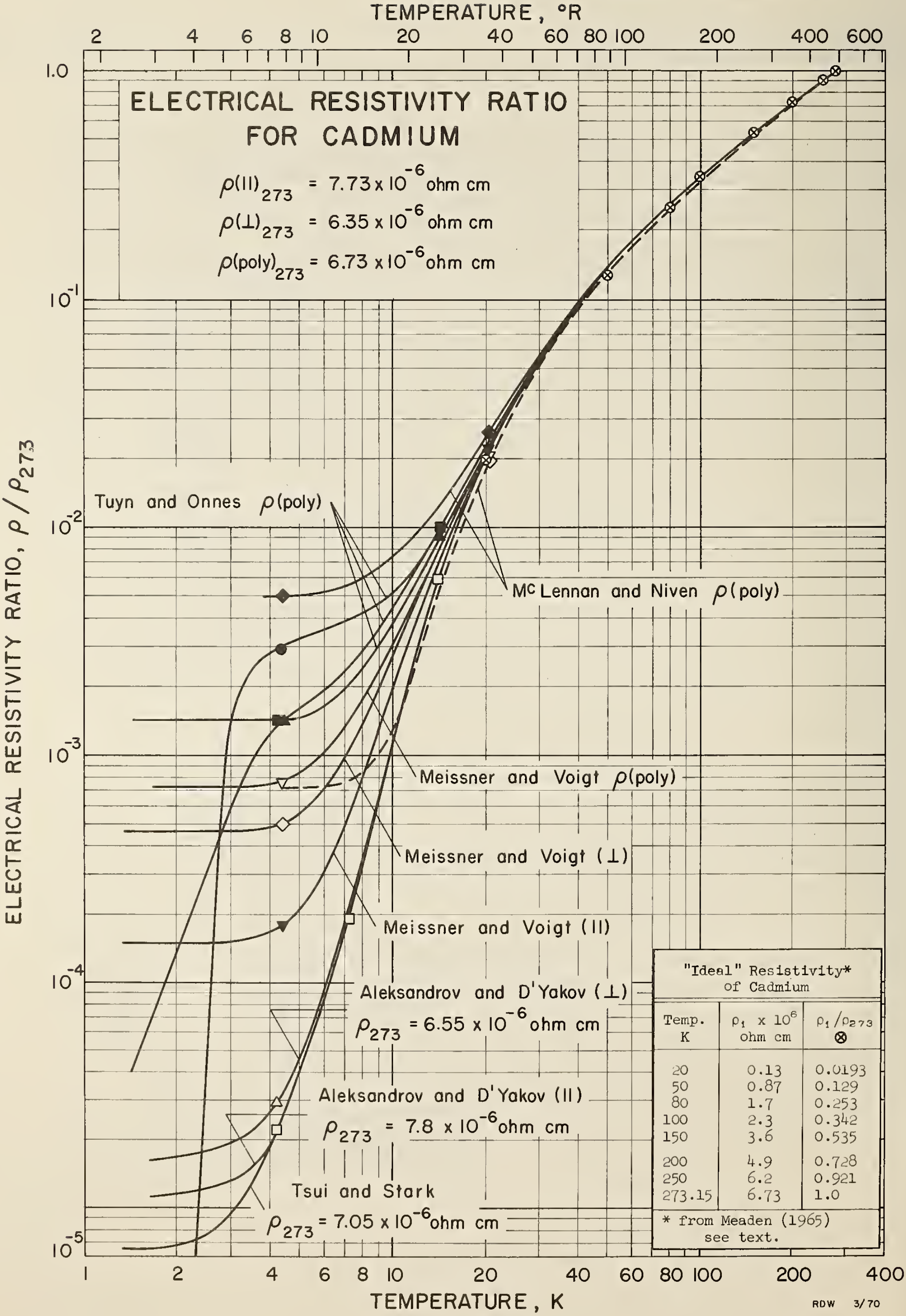
Temp. K	Resistance * R x 10^9 ohms
1.9	2.2
2.4	2.2
3.13	2.5
3.5	2.75
3.7	3.0
293	191818.0

* These data do not appear on the Electrical Resistivity of Cadmium graph.

Tsui and Stark (1967) (read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
	Cd $\parallel$	Cd $\parallel$
1.35	0.000047	0.0000066
2.0	0.000048	0.0000068
3.0	0.000065	0.0000092
3.5	0.00009	0.000013
4.0	0.00013	0.000018
4.2	0.000155	0.000022
273	7.05 *	1.00

* Calculated value.



ELECTRICAL RESISTIVITY RATIO FOR CADMIUM

$\rho(\parallel)_{273} = 7.73 \times 10^{-6}$ ohm cm
$\rho(\perp)_{273} = 6.35 \times 10^{-6}$ ohm cm
$\rho(\text{poly})_{273} = 6.73 \times 10^{-6}$ ohm cm

"Ideal" Resistivity* of Cadmium

Temp. K	$\rho_i \times 10^6$ ohm cm	ρ_i / ρ_{273} ⊗
20	0.13	0.0193
50	0.87	0.129
80	1.7	0.253
100	2.3	0.342
150	3.6	0.535
200	4.9	0.728
250	6.2	0.921
273.15	6.73	1.0

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422 **FILE NO.** M-27

(page 1 of 9)

ELECTRICAL RESISTIVITY OF CHROMIUM, Cr
(Atomic Number 24)

<u>Sources of Data</u>:

Arajs, S., Colvin, R. V., and Marcinkowski, M. J., "Initial study of electrical resistivity of a chromium single crystal," J. Less-Common Metals 4, No. 1, 46-51 (1962).

Arajs, S., and Dunmyre, G. R., "Electrical resistivity and transverse electrical magnetoresistivity of chromium," J. Appl. Phys. 36, No. 11, 3555-59 (Nov 1965).

Arajas, S., and Dunmyre, G. R., "Electrical resistivity of chromium-rich chromium-iron alloys between 4 and 320 K," J. Appl. Phys. 37, No. 3, 1017-19 (1966).

Bridgman, P. W., "Compressibilities and pressure coefficients of resistance of elements, compounds, and alloys, many of them anomalous," Proc. Am. Acad. Arts Sci. 68, 27-93 (1933).

Clinard, F. W., Jr., and Kempter, C. P., "Low-temperature electrical properties of some transition metals and transition-metal carbides," J. Less-Common Metals 15, No. 1, 59-73 (May 1968).

Erfling, H. D., "Studies of the thermal expansion of solids at low temperatures II. (Cr, Beta-Mn, Mo, Rh, Be, Graphite, Tl, Zr, Bi, Sb, Sn, and Beryl). (In German)," Ann. Physik 34, 136-60 (1939).

Fine, M. E., Greiner, E. S., and Ellis, W. C., "Transitions in chromium," J. Metals 189, 56-58 (1951).

Goff, J. F., "The thermal conductivity of chromium above and below the Neel temperature - an analysis," Thermal conductivity (Proc. of the Conference on Thermal Conductivity 7th, Gaithersburg, Md., Nov 13-17, 1967) National Bureau of Standards Spec. Publ. 302 (Sep 1968) pp 311-21.

Harper, A. F. A., Kemp, W. R. G., Klemens, P. G., Tainsh, R. J., and White, G. K., "The thermal and electrical conductivity of chromium at low temperatures," Phil. Mag. 2, 577-83 (May 1957).

Mc Lennan, J. C., and Niven, C. D., "Electrical conductivity at low temperatures," Phil. Mag. 4, 386-404 (1927).

Mc Lennan, J. C., Niven, C. D., and Wilhelm, J. O., "The resistance of caesium, cobalt, and chromium at low temperatures," Phil. Mag. 6, 672-7 (1928).

Meaden, G. T., <u>Electrical Resistance of Metals</u>, Plenum Press, New York (1965) 218 p.

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 892-936 (1930).

Moore, J. P., Williams, R. K., and Mc Elroy, D. L., "Physical properties of chromium from 77 to 400 K," Thermal Conductivity (Proc. of the Conference on Thermal Conductivity 7th, Gaithersburg, Md., Nov 13-17, 1967) National Bureau of Standards Spec. Publ. 302 (Sep 1968) pp 297-310.

Moore, J. P., Williams, R. K., and Mc Elroy, D. L., "Further comments on transport properties of chromium," Thermal Conductivity (Proceedings of the Conference 8th, Purdue Univ., Lafayette, Ind., Oct 7-10, 1968) C. Y. Ho, et al., Eds, Plenum Press, New York (1969) pp 303-13.

Newmann, M. M., and Stevens, K. W. H., "Magnetic susceptibilities of iron-chromium alloys," Proc. Phys. Soc. (London) 74, 290-96 (1959).

Potter, H. H., "Electrical resistance and thermoelectric power of the transition metals," Proc. Phys. Soc. (London) 53, 695-705 (1941).

Semenenko, E. E., "Minimum electric resistivity of antiferromagnetic metal (chromium)," JETP Letters 3, No. 11, 291-3 (Jun 1966) Transl. of Zh. Eksp. I Teor. Fiz., Pisma V Redaktsiyu 3, No. 11, 443-7 (Jun 1966).

Sochtig, H., "Untersuchungen an reinem chrom im anomaliegebiet. Elektrischer und thermischer widerstand, thermokraft, warmetonung, magnetische suszeptibilitat und gitterstruktur," (Research on pure chromium in the anomalous region. Electrical and thermal resistance, thermopower, thermalhue, magnetic susceptibility and lattice structure), Ann. Physik 38, No. 2, 97-120 (1940).

White, G. K., and Woods, S. B., "Electrical and thermal resistivity of the transition elements at low temperatures," Phil. Trans. Roy. Soc. London A251 No. 995, 273-302 (1959).

Other References:

Arko, A. J., Marcus, J. A., and Reed, W. A., "High-field galvanomagnetic effects in antiferromagnetic chromium," Phys. Rev. 176, No. 2, 671-83 (Dec 1968).

Bastow, T. J., and Street, R., "Transverse magnetoresistance of high-purity chromium foils," Phil. Mag. 10, No. 104, 269-76 (1964).

Brenner, A., Burkhead, P., and Jennings, C., "Physical properties of electrodeposited chromium," J. Res. Natl. Bur. Stds. 40, 31-59 (1948).

Bridgman, P. W., "The electric resistance to 30,000 kg/cm^2 of twenty nine metals and intermetallic compounds," Proc. Am. Acad. Arts Sci. 79, 149-79 (1951).

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Erfling, H. D., "Zur anomalie des elektrischen widerstands von chrom. Nachtrag zu untersuchungen von H. Sochtig," (An anomaly in the electrical resistance of chromium. Supplement to studies by H. Sochtig), Ann. Physik 41, 100-2 (1942).

Kostina, T. I., Kozlova, T. N., and Kondorskii, E. I., "Dependence of the electric and magnetic properties of chromium on the magnetic field strength and temperature," Zhur. Eksptl. I Teoret Fiz. 45, No. 5, 1352-55 (1963).

Matsumoto, T., Sambongi, T., and Mitsui, T., "Anomaly in the electrical resistivity of chromium metal in the vicinity of spin-flip temperature," J. Phys. Soc. Jap. 26, No. 1, 209 (Jan 1969).

Mc Whan, D. B., and Rice, T. M., "Pressure dependence of itinerant antiferromagnetism in chromium," Phys. Rev. Letters 19, No. 15, 846-9 (Oct 1967).

Milgram, A. A., and Lu, Chih-Shun , "Field effect and electrical conduction mechanism in discontinuous thin metal films," J. Appl. Phys. 37, No. 13, 4773-9 (Dec 1966).

Milgram, A. A., and Lu, Chih-Shun , "Preparation and properties of chromium films," J. Appl. Phys. 39, No. 6, 2851-6 (May 1968).

Mitsui, T., and Tomizuka, C. T., "Effect of hydrostatic pressure on the Neel temperature in chromium," Phys. Rev. 137, No. 2A, A564-65 (Jan 1965).

Powell, R. W., and Tye, R. P., "The influence of heat-treatment on the electrical resistivity and the thermal conductivity of electrodeposited chromium," J. Inst. Metals 85, 185-92 (1957).

Sambongi, T., and Mitsui, T., "Electrical resistivity of antiferromagnetic chromium," J. Phys. Soc. Jap. 24, No. 5, 1168 (May 1968).

Ulyanov, R. A., and Kovtun, S. F., "Effect of alloying on the volume resistivity of titanium," Phys. Metals Metallog. 17, No. 4, 24-30 (1964) Transl. of Fiz. Metal. I Metalloved. 17, No. 4, 505-11 (1964).

Comments:

The data presented here were taken from the references cited above under "Sources of Data" and are listed as ratios of electrical resistivity with respect to resistivity at the ice point temperature. When actual values of ρ_{273} for the samples used by the investigators are not available, a datum value reported by White and Woods ($\rho_{273} = 12.155 \times 10^{-6}$ ohm cm) is suggested for calculating the values of electrical resistivity from these ratios.

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Mc Lennan and Niven (1927) measured the resistance of 3/16 in. wide and 1-1/2 in. long strips of chromium cut from an electrolytically deposited sheet. The aged sample was heated for 2 hours at high temperatures.

Mc Lennan, Niven and Wilhelm (1928) continued the measurements of Mc Lennan and Niven (1927) adding some low temperature values for the "aged" sample.

Meissner and Voigt (1930) used a 99.5% pure chromium sample with the following dimensions; 21 mm long and 2.5 mm x 2.5 mm cross section. No further information is given for the sample.

Bridgman (1933) reported values (at one atmosphere pressure) of resistance for a swaged rod, 4 cm long and 2.5 mm dia. which was of "exceptional degree of purity". His $\rho_{273} = 18.9 \times 10^{-6}$ ohm cm.

Sochtig (1940) measured resistances of high purity chromium with the following dimensions; 0.58 x 0.23 x 0.21 cm. He also reported $\rho_{273} = 21 \times 10^{-6}$ ohm cm. He also reports values by Erfling (1939) which were made on the same sample and extend to lower temperatures.

Potter (1941) measured resistances of a 99.99% pure chromium rod approximately 1 cm long which had been annealed at 600°C.

Fine, Greiner and Ellis (1951) used a wrought chromium specimen, consisting of powder filings which had been cleaned magnetically and annealed 2 hours at 800°C in vacuum.

Harper, Kemp, Klemens, Tainsh and White (1957) and White and Woods (1959) report resistivity values for a 99.998% pure chromium rod, 8 cm long and 3 mm dia. This recrystallized sample had been annealed in vacuo at 1050°C for 4 hours. The residual resistivity was $\rho_0 = 0.055 \times 10^{-6}$ ohm cm.

Newmann and Stevens (1959) report resistivities for 2 cm long pure chromium rods which had been annealed in vacuum at about 1200 K for a month.

Arajs, Colvin and Marcinkowski (1962) made resistivity measurements on a single crystal specimen parallel to the [100] axis. The sample dimensions were 0.254 cm x 0.235 cm x 0.900 cm. At one time measurements were made on the sample after it had been left overnight at 310 K. Another time the sample was heated to 373 K, then cooled rapidly to 78 K and left for a period of time before measurements were taken. The residual resistivity was 1.04 x 10^{-6} ohm cm.

Arajs and Dunmyre (1965, 1966) used 99.9953% chromium sample cut from an arc-melted ingot and the final shape, 0.478 cm x 0.476 cm cross section and 5 cm long, was obtained by surface grinding. The residual resistivity at 4.2 K was 0.0811 x 10^{-6} ohm cm. The values in the table are for zero magnetic field.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Semenenko (1966) presents data showing resistance minimums below 10 K. No quantitative analysis was made of the impurities in the three samples. He states that "even the purest one contained 0.01% Fe, 6 x 10^{-3} % Ni, and ~ 5 x 10^{-4} % Mn. The samples were annealed in a vacuum of less than 10^{-7} mm Hg at ~ 1300°C. The data were not plotted on the Electrical Resistivity of Chromium graph.

Goff (1968) measured ideal resistivities of a 99.92% pure sample (4 mm x 4 mm x 35 mm) which had been annealed in vacuum at 900°C for 24 hrs prior to measurement. The residual resistivity was 0.1834 x 10^{-6} ohm cm.

Moore, Williams and Mc Elroy (1968) made resistivity measurements on two samples Cr A and Cr B. Cr A was prepared by using vacuum compacted crystals for extruding a rod 60 cm long and 1.6 cm dia. This sample had a purity of 99.986%. Cr B was prepared by arc melting crystals into an ingot which was drop cast into a rod 15 cm long and 1.6 cm dia. This sample had a purity of 99.992%. The values in the table are smoothed.

Clinard and Kempter (1968) measured resistivity of annealed polycrystalline rods about 0.25 in. dia. and 1 in. long. The purity was 99.656 %.

Moore, Williams and Mc Elroy (1969) borrowed Goff's (1968) sample for these resistivity measurements. There is a large disagreement between Goff's results and these results on the same sample.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

McLennan and Niven (1927)

Temp. K	Resistance R x 10^6 ohm		R/R_{273}	
	Cr (unaged)	Cr (aged)	Cr (unaged)	Cr (aged)
2.35	25.9	-	0.617	-
4.2	26.2	-	0.624	-
20.6	26.7	0.90	0.636	0.060
80	-	2.01	-	0.134
83	29.2	-	0.695	-
273	42.0*	15.0 *	1.00	1.000

* Interpolated value.

McLennan, Niven and Wilhelm (1928)

Temp. K	Resistance $R \times 10^6$ ohm	R/R_{273}
	Cr (aged)	Cr (aged)
2.25	0.79	0.05
4.2	0.79	0.05
20.6	0.80	0.051
80	2.01	0.127
273	15.8 *	1.00

* Interpolated value.

Meissner and Voigt (1930)

Temp. K	R/R_{273}
1.41	0.83_2
4.20	0.83_4
20.45	0.842
78.42	0.8507
86.14	0.8561
273.16	1.000

Bridgman (1933)
(read from graph)

Temp. K	R/R_{273}
193	0.885
213	0.903
233	0.962
253	0.99
273*	1.00

* $\rho_{273} = 18.9 \times 10^{-6}$ ohm cm.

Sochtig (1940) and Erfling (1939)
(measurements on the same sample)

Temp. K	ρ/ρ_{273}	
20.36	0.0188	Erfling
79.00	0.0874	
77.69	0.0868	Sochtig
90.09	0.122	

Potter (1941)

Temp. K	R/R_{273}*
20	0.021
77	0.074
90	0.119
173	0.508
273	1.00

* These values were not plotted on the Electrical Resistivity of Chromium graph.

Fine, Greiner and Ellis (1951)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
78	1.8	0.14
123	4.1	0.32
173	7.0	0.54
223	10.4	0.80
273	13.0	1.00

* These values were not plotted on the Electrical Resistivity of Chromium graph.

Harper, Kemp, Klemens, Tainsh and White (1957)
White and Woods (1959)

Temp. K	Ideal resistivity $\rho_i \times 10^6$ ohm cm	Resistivity $\rho = \rho_i + \rho_o$ $\rho_o = 0.055 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
15	0.002_7	0.0577	0.0047
20	0.007_2	0.0622	0.0051
25	0.015_5	0.0705	0.0058
30	0.02_9	0.084	0.0069
40	0.07_8	0.133	0.0109
50	0.16_5	0.220	0.0181
60	0.3_0	0.355	0.0292
70	0.5_2	0.575	0.0473
80	0.8_1	0.865	0.0712
90	1.1_8	1.235	0.102
100	1.6_2	1.675	0.138
120	2.6_5	2.715	0.223
140	3.9	3.955	0.325
160	5.2	5.255	0.432
180	6.4	6.455	0.531
200	7.7_5	7.805	0.642
220	9.0_5	9.105	0.749
250	10.9_5	11.005	0.905
273	12.1	12.155	1.00

Newman and Stevens (1959)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
90	2.5	0.19
150	6.3	0.48
200	9.	0.69
273	13.	1.00

* These values were not plotted on the Electrical Resistivity of Chromium graph.

Arajs, Colvin and Marcinkowski (1962)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
10	1.04	0.085
50	1.3	0.11
100	2.8	0.23
150	5.7	0.46
200	8.5	0.69
250	11.3	0.92
273	12.3	1.0

Arajs and Dunmyre (1965, 1966)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4.2	0.0811*	0.0066
20	0.085	0.0070
40	0.2	0.016
60	0.4	0.033
100	1.8	0.15
140	4.0	0.33
200	7.9	0.64
273	12.3	1.00

* from text

Semenenko (1966) (read from graph)			
Temp. K	R/R_{300K} *		
	Sample 1	Sample 2	Sample 3
1.5	-	0.00681	0.008006
4.0	0.07617	0.006799	0.008002
6.0	0.07612	0.006798	0.008005
6.5	0.07608	0.006797	0.00801
10.0	0.07602	0.006796	-
12.0	0.07603	0.006797	-
15.0	0.07609	0.006801	-
16.0	0.07616	-	

* These values were not plotted on the Electrical Resistivity of Chromium graph.

Clinard and Kempter (1968) (read from graph)		
Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}
4.2	0.1	0.0080
20	0.1	0.0088
50	0.4	0.032
100	2.0	0.16
150	5.0	0.40
200	8.0	0.64
273	12.5	1.00

Goff (1968) (read from graph)			
Temp. K	ideal resistivity ρ_i x 10^6 ohm cm	resistivity $\rho = \rho_i + \rho_0$ $\rho_0 = 0.1834 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
20	0.011	0.1944	0.016
50	0.2	0.3834	0.032
70	0.7	0.8834	0.073
100	2.0	2.1834	0.18
200	7.6	7.7834	0.64
273	12.0	12.1834	1.00

Moore, Williams and McElroy (1968)

Temp. K	Resistivity ρ x 10^6 ohm cm		ρ/ρ_{273}**	
	Cr A	Cr B	Cr A	Cr B
80	0.860	1.060	0.0729	0.0876
90	1.225	1.445	0.104	0.119
100	1.630	1.860	0.138	0.154
120	2.605	2.860	0.221	0.236
140	3.760	4.050	0.319	0.335
160	5.000	5.295	0.424	0.438
180	6.315	6.575	0.535	0.543
200	7.545	7.830	0.639	0.647
220	8.790	9.100	0.745	0.752
240	10.015	10.300	0.849	0.851
260	11.095	11.385	0.940	0.941
273	11.8 *	12.1 *	1.00	1.00

* Interpolated value.

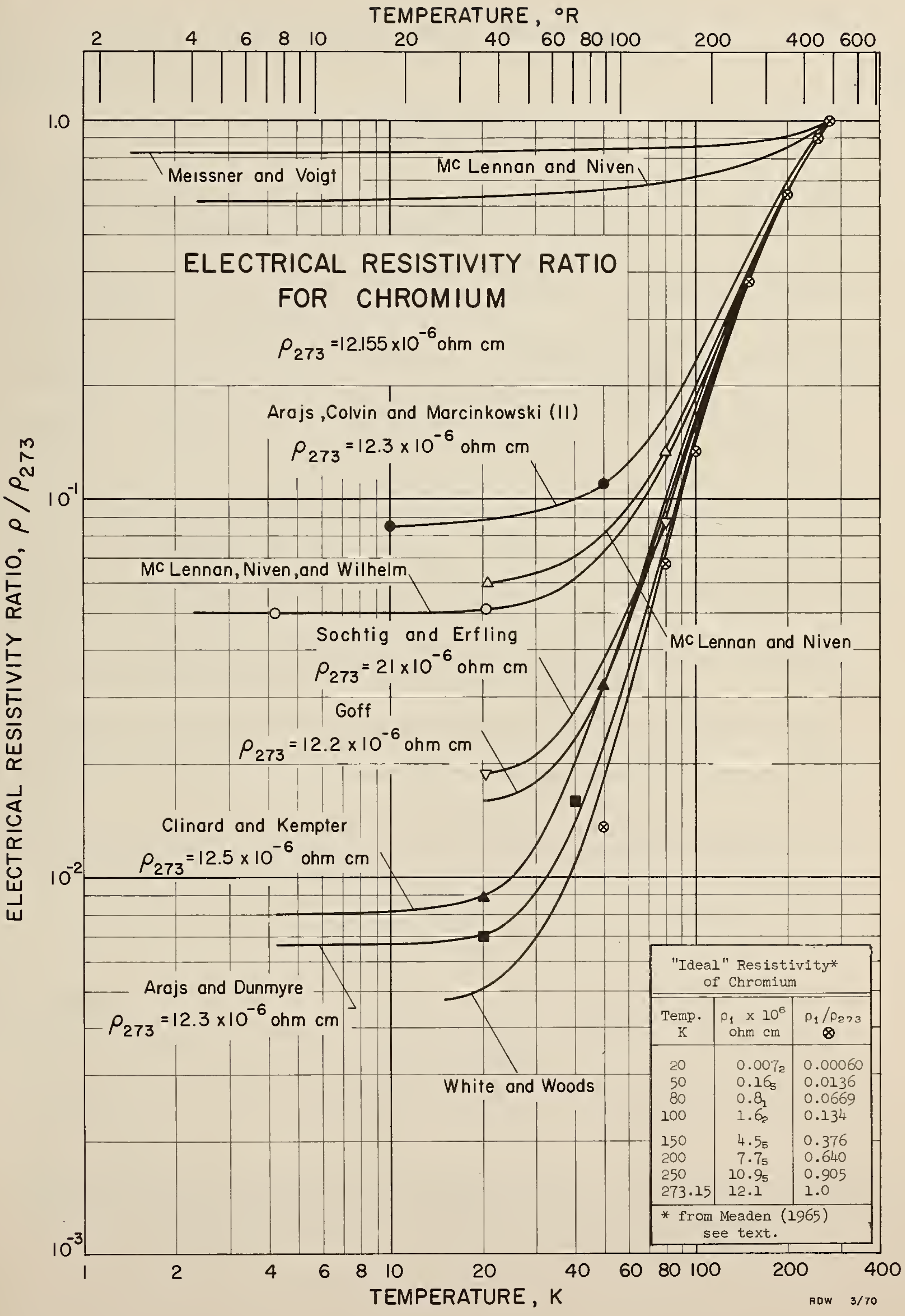
** These values were not plotted on the Electrical Resistivity of Chromium graph.

Moore, Williams and McElroy (1969)
(using Goff's (1968) sample)

Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}**
90	1.495	0.120
100	1.935	0.155
120	2.935	0.235
140	4.190	0.335
160	5.515	0.441
180	6.830	0.546
200	8.130	0.650
220	9.460	0.757
240	10.755	0.860
260	11.895	0.952
273	12.5 *	1.00

* Interpolated value.

** These values were not plotted on the Electrical Resistivity of Chromium graph.



"Ideal" Resistivity*
of Chromium

Temp. K	$\rho_i \times 10^6$ ohm cm	ρ_i / ρ_{273} ⊗
20	0.007_2	0.00060
50	0.16_5	0.0136
80	0.8_1	0.0669
100	1.6_2	0.134
150	4.5_5	0.376
200	7.7_5	0.640
250	10.9_5	0.905
273.15	12.1	1.0

* from Meaden (1965)
see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422 **FILE NO.** M-28

(page 1 of 5)

ELECTRICAL RESISTIVITY OF MANGANESE, Mn
(Atomic Number 25)

Sources of Data:

Brunke, F., "Untersuchungen an reinem alpha-, beta- und gammamangan," (Investigation of pure alpha-, beta- and gamma manganese), Ann. Phys. 21, 139-68 (1934).

Erfling, H. D., "Studies of the thermal expansion of solids at low temperatures II. (Cr, Beta-Mn, Mo, Rh, Be, graphite, Tl, Zr, Bi, Sb, Sn, and beryl). (In German)," Ann. Physik 34, 136-60 (1939).

Erfling, H. D., "Anderung der thermischen ausdehnung und des elektrischen widerstandes vonmangan beim ubergang zur alpha-phase," (Change in thermal expansion and electrical resistance of manganese in transition to alpha-phase), Ann. Physik 37, 162-8 (1940).

Jaeger, W., and Diesselhorst, H., "Warmeleitung elektricitatsleitung, warmecapacitat und thermokraft einiger metalle," (Heat conduction, electrical conductivity, specific heat and thermal power in metals), Wiss. Abhandl. Physik.-Tech. Reichasanstalt 3, 269-424 (1900).

Meaden, G. T., "An alpha-manganese resistance thermometer for the measurement of low temperatures," Cryogenics 6, No. 5, 275-8 (Oct 1966).

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meaden, G. T., and Pelloux-Gervais, P., "The electrical resistivity of alpha-manganese between 2 and 325 K," Cryogenics 5, No. 4, 227-28 (Aug 1965).

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 892-936 (1930).

Reddemann, H., "Wiedemann-Franzsche shal von β-mangan bei -190°C," (The Wiedemann-Franz coefficient of beta-manganese at -190°C), Ann. Physik 22, 28-30 (1935).

White, G. K., and Woods, S. B., "Conductivity of alpha-manganese," Can. J. Phys. 35, 346-8 (1957).

White, G. K., and Woods, S. B., "Electrical and thermal resistivity of the transition elements at low temperatures," Phil. Trans. Roy. Soc. London A251, No. 995, 273-302 (1959).

Other References:

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Griffiths, D., and Coles, B. R., "Magnetic brillouin zone effects in the thermoelectric power and magnetoresistance of alpha-manganese," Proc. Phys. Soc. (London) 82, No. 525, Pt. 1, 127-32 (1963).

Mendelssohn, K., Griffin, G. S., Sutcliffe, P. W., et al., "Low temperature properties of actinide metals," Low Temperature Physics and Chemistry (Proc. of International Conf. on Low Temperature Physics and Chemistry 10th, Moscow, USSR, Aug 31 - Sep 6, 1966) IV. Antiferromagnetism, A. S. Borovik-Romanov, et al., Eds., Viniti, Moscow, USSR (1967) pp 117-21.

Comments:

The data for this graph were taken from the references cited above under "Sources of Data" and are listed as ratios of electrical resistivity with respect to the resistivity at the ice point temperature (ρ_{273}). Manganese is an allotropic metal and measurements have been made on samples of three different crystal structures. The suggested values of ρ_{273}, to be used if the experimenter did not give one for his sample, follow:

For α-Mn, $\rho_{273} = 143.5 \times 10^{-6}$ ohm cm (Meaden 1965, 1966);
for β-Mn, $\rho_{273} = 91.0 \times 10^{-6}$ ohm cm (Brunke 1934);
for γ-Mn, $\rho_{273} = 22.7 \times 10^{-6}$ ohm cm (Brunke 1934).

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Jaeger and Diesselhorst (1900) measured conductivity at 18 and 100°C. By extrapolating the data to 0°C and calculating resistivity we have $\rho_{273} = 42.04 \times 10^{-6}$ ohm cm. They do not describe the crystal structure of their sample.

Meissner and Voigt (1930) used a sample 1.0 mm x 1.8 mm x 11 mm which was 93.65% pure. The values are for α-manganese.

Brunke (1934) measured conductivity of pure α, β, and γ-Mn. The calculated resistivities are in the table.

Reddemann (1935) give one value of resistivity for β-manganese at -190°C. The other values are resistance ratios. The sample was 5 mm dia. and 16 mm long with no statement of purity.

Erfling (1939) states that his β-manganese sample was pure and had been annealed in vacuum at 1100°C.

Erfling (1940) gives two values of ρ_{273} for γ-manganese and α-manganese. The γ-Mn was cut from an electrolytically deposited sample, approximately 2.3 cm long and 0.2 to 0.3 cm wide.

White and Woods (1959) present data based on the experiments of White and Woods (1957) for α-Mn. The table contains smoothed values taken from large-scale graphs. Three samples were used: Mn 1, of high purity, was annealed in vacuo at 600°C for some hours; Mn 2, a 99.99% pure sample, was not annealed; Mn 3, a 99.99% pure sample, was annealed in vacuum at 600°C. Their cross sections were $\sim 3 \times 0.7$ mm, $\sim 3 \times 1.1$ mm, and $\sim 3.3 \times 1.4$ mm, respectively. Only the residual resistivities of Mn 1 and Mn 3 were given. I averaged the two values to obtain ρ_0 to add to the ideal resistivities from their table.

Meaden (1965, 1966) used an electrolytically prepared sample of 99.995% pure manganese which had been annealed under a vacuum of 10^{-6} to 8×10^{-6} torr for 7 hours at 625°C.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

Jaeger and Diesselhorst (1900)
$\rho_{273} = 42.04 \times 10^{-6}$ ohm cm (extrapolated)

Brunke (1934)
α - Mn, $\rho_{273} = 714 \times 10^{-6}$ ohm cm β - Mn, $\rho_{273} = 91 \times 10^{-6}$ ohm cm γ - Mn, $\rho_{273} = 22.7 \times 10^{-6}$ ohm cm

Meissner and Voigt (1930)
α - Manganese

Temp. K	ρ/ρ_{273}
1.41	0.9581
4.20	0.9765
20.46	1.0020
77.82	0.9807
88.9	0.9776
273.16*	1.0

* $\rho_{273} = 150 \times 10^{-6}$ ohm cm.

Reddemann (1935)
β - Manganese

Temp. K	R/R_{273}
78.0	0.731
83.0*	-
90.0	0.750
194.6	0.891
273.1**	1.0

* One experimental value is given at this temperature; $\rho_{83} = 100 \times 10^{-6}$ ohm cm.

** Using the ρ_{83} and reading the ratio from the graph, R/R_{273} or ρ/ρ_{273}, we can estimate $\rho_{273} = 135.5 \times 10^{-6}$ ohm cm.

Erfling (1939)
β - Manganese

Temp. K	R/R_{273}*
78	0.731 (measured in 1935)
78	0.774 (measured in 1937)

* These values are not on the Electrical Resistivity of Manganese graph.

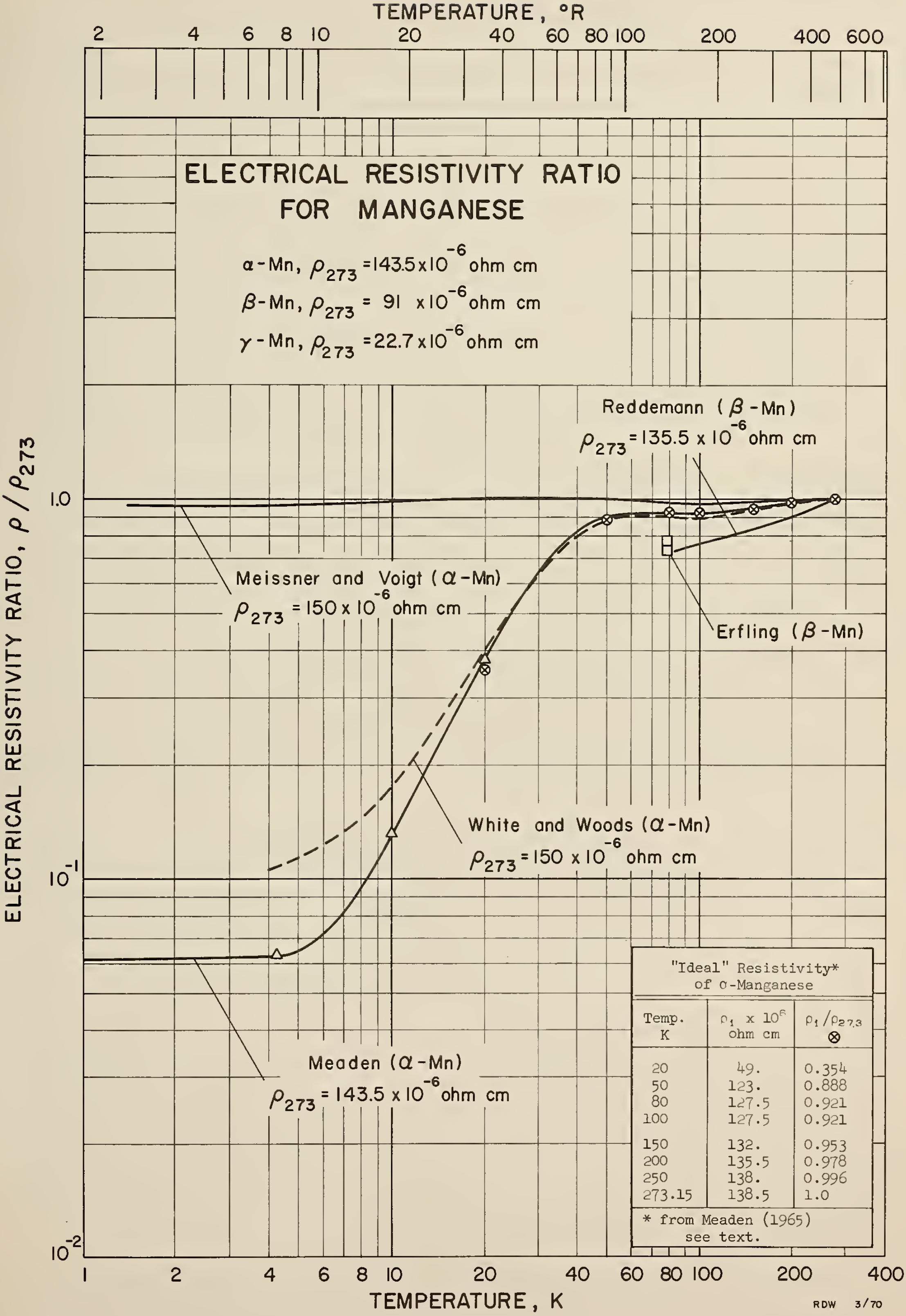
Erfling (1940)
α - Mn, $\rho_{273} = 627 \times 10^{-6}$ ohm cm γ - Mn, $\rho_{273} = 39.2 \times 10^{-6}$ ohm cm

White and Woods (1957, 1959)
α - Manganese

Temp. K	Ideal Resistivity ρ_i x 10^6 ohm cm	Resistivity $\rho = \rho_i + \rho_o$ $\rho_o = 14 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
4	1.9	15.9	0.106
6	4.3	18.3	0.122
8	8	22	0.147
10	12	26	0.173
15	28	42	0.280
20	46	60	0.400
25	65	79	0.527
30	82	96	0.640
40	105	119	0.793
50	117	131	0.873
60	122	136	0.907
70	122	136	0.907
80	121	135	0.900
90	120	134	0.893
100	121	135	0.900
120	123	137	0.913
140	125	139	0.927
160	127	141	0.940
180	130	144	0.960
200	131	145	0.967
220	131	145	0.967
250	133	147	0.980
273	136	150	1.00

Meaden (1965, 1966)
α - Manganese

Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}
0	6.9	0.0481
4.2	9	0.0627
10	19	0.132
20	54	0.376
30	92	0.641
40	118	0.822
50	128	0.892
60	132	0.920
70	133	0.927
80	132.5	0.923
90	132	0.920
100	132.5	0.923
150	137	0.955
200	140.5	0.979
250	143	0.996
273.15	143.5	1.00



"Ideal" Resistivity*
of α-Manganese

Temp. K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20	49.	0.354
50	123.	0.888
80	127.5	0.921
100	127.5	0.921
150	132.	0.953
200	135.5	0.978
250	138.	0.996
273.15	138.5	1.0

* from Meaden (1965)
see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422 **FILE NO.** M-29

(page 1 of 9)

ELECTRICAL RESISTIVITY OF TITANIUM, Ti
(Atomic Number 22)

Sources of Data:

Berlincourt, T. G., "Hall effect resistivity and magnetoresistivity of Th, U, Zr, Ti, and Nb," Phys. Rev. 114, No. 4, 969-77 (1959).

Bostrom, W. A., "Electrical resistance of zirconium and titanium," Westinghouse Elec. Corp., Atomic Power Div., Pittsburgh, Pa., Rept. No. WAPD-T-176 (Apr 1954) Contr. No. AT-11-1-GEN-14, 13 pp.

Cape, J. A., and Hake, R. R., "Localized magnetic impurity states in Ti, Zr, and Hf," Phys. Rev. 139, No. 1A, A142-49 (Jul 1965).

Clausing, P., and Moubis, G., "Over den electrischen weerstandvan titaan en zirkoon bij lage temperaturen," (The electrical resistance of titanium and zirconium at low temperatures), Physica 7, No. 7, 245-50 (1927).

Clinard, F. W., and Kempter, C. P., "Low-temperature electrical properties of some transition metals and transition-metal carbides," J. Less-common Metals 15, No. 1, 59-73 (May 1968).

De Haas, W. J., and Van Alphen, P. M., "The change in resistance of graphite, thorium, titanium-zirconium between 20.4 K and 1.1 K," Commun. Phys. Lab. Univ. Leiden No. 212E (1931) Reprinted from Proc. Kon. Ned. Akad. Wetensch. 34, 70 (1931).

Kemp, W. R., Klemens, P. G., and White, G. K., "Thermal and electrical conductivities of iron, nickel, titanium, and zirconium at low temperatures," Australian J. Phys. 9, 180-88 (Jun 1956).

McLennan, J. C., Howlett, L. E., and Wilhelm, J. O., "On the electrical conductivity of certain metals at low temperatures," Trans. Roy. Soc. Can. Sec. III, 23, Part I, 287-306 (Jan 1929).

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meissner, W., Franz, H., and Westerhoff, H., "Measurements with the help of liquid helium. XV. Resistance of barium, indium, thallium, graphite, and titanium at low temperatures," Ann. Physik (5) 13, 555-63 (1932).

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 892-936 (1930).

Mendelssohn, K., Sharma, J. K. N., and Yoshida, I., "Heat conductivity of pure metals below 1 K," Bull. IIR Annexe 1965-2, pp 49-56 (Meeting of Commission 1, Grenoble, France, Jun 8-11, 1965).

Potter, H. H., "Electrical resistance and thermoelectric power of the transition metals," Proc. Phys. Soc. (London) 53, 695-705 (1941).

Roesch, K. C., "The influence of temperature and preferred orientation on Hall coefficient and resistivity of pure titanium," Calif. Inst. Technol., Pasadena, Rept. (Nov 1962) Contr. AF 49(638) 1034, 111 pp, DDC AD 289 535.

Rosenberg, H. M., "Thermal conductivity of metals at low temperatures," Phil. Trans. Roy. Soc. London A247, No. 933, 441-97 (1955).

Wasilewski, R. J., "Observations on electrical resistivity of titanium," Trans. Met. Soc. AIME 224, 5-8 (1962).

Webber, R. T., and Reynolds, J. M., "Incipient superconductivity in titanium," Phys. Rev. 73, 640 (Mar 1948).

White, G. K., and Woods, S. B., "Electrical and thermal resistivity of the transition elements at low temperatures," Phil. Trans. Roy. Soc. London A251, No. 995, 273-302 (1959).

Other References:

Brehm, C., and Lehr, P., "Influence de la deformation par traction du zirconium et du titane sur la resistivite residuelle et sur la densite de dislocations," (Effect of zirconium and titanium tensile deformation on the residual resistivity and dislocation density), Compt. Rend. Ser. C, 265, No. 18, 974-6 (1967).

Fast, J. D., "Uber die darstellung de reinen metalle der titangruppe durch thermische zersetzung ihrer jodide. V. Titan," (On the preparation of pure metals in the titanium group from thermal dissociation of their iodides. V. Titanium), Z. Anorg. u. allgem. Chem. 241, 42-56 (1939).

Koftun, S. F., and Ulyanov, R. A., "Influence of alloying of the physico-mechanical properties of titanium," Physical Metallurgy of Titanium, Izdatelstvo Nauka, Moscow, SSSR (1964) Transl. by Foreign Technology Div., Wright-Patterson AFB, Ohio, No. FTD-HT-66-354 (Dec 1966) pp 158-81, DDC AD 655 033.

Strothenk, H., "Messungen der differentiellen sorptionswarmen und der elektrischen leitfahigkeit im system titan-wasserstoff in abhangigkeit von der wasserstoff-konzentration," (Measurements of the differential sorption temperatures and electric conductivity of the titanium-hydrogen system as functions of hydrogen concentration), Hannover Technische Hochschule, West Germany, Ph.D. Thesis (1965) 108 pp NASA 68-10909.

Volkenshteyn, N. V., and Galoshina, E. V., "Hall effect in transition metals with low number of d-electrons," Phys. Metals Metallog. 20, No. 3, 166-69 (1965) Transl. of Fiz. Metal. I Metalloved. 20, No. 3, 475-8 (1965).

Wedler, G., Brocker, F. J., Kock, H. G., and Wolfing, C., "Der einfluss von ordnungszustand und schichtdicke auf die struktur und die elektrische leitfahigkeit aufgedampfter metallfilme - nickel, titan, silver," (Influence of the order-disorder state and film thickness on the structure and electrical conductivity of evaporated nickel, titanium, and silver films), Basic Problems in Thin Film Physics (Proc. International Symp., Clausthal-Gottingen, West Germany, Sep 6-11, 1965) Gottingen, Vandenhoeck and Ruprecht (1966) pp 566-73.

Comments:

The data for this graph were taken from the references cited above under "Sources of Data" and are listed as ratios of electrical resistivity with respect to the resistivity at the ice point temperature (ρ_{273}). When the actual values of ρ_{273} are not available for the polycrystalline samples used by the investigators, a datum value reported by Clinard and Kempter (1968) ($\rho_{273} = 39.4 \times 10^{-6}$ ohm cm) is suggested for calculating values of electrical resistivity from these ratios. Only one investigator (Wasilewski, 1962) has determined resistivity for titanium single crystals with directions of the current being both parallel and perpendicular to the primary axis. His results are:

for Ti($\parallel$), $\rho_{273} = (48.0 \pm 0.7) \times 10^{-6}$ ohm cm;

for Ti($\perp$), $\rho_{273} = (45.35 \pm 0.5) \times 10^{-6}$ ohm cm.

It should also be noted that titanium becomes superconducting at 0.39 K.

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Clausing and Moubis (1927) measured the resistivity of a 99.84% pure titanium sample. No further information is given for the preparation of the sample.

Mc Lennan, Howlett and Wilhelm (1929) used a wire specimen which had been baked in vacuo at a high temperature for a number of hours to remove as much as possible of the occluded gases.

Meissner and Voigt's (1930) sample was a rod 2 mm dia. and 33.5 mm long with a purity of 99.77%.

De Haas and Van Alphen (1931) did not report method of preparation or purity of their sample; however, they did state that the purity was not high enough to obtain reproducible data. Their titanium became superconducting at 1.63 K.

Meissner, Franz and Westerhoff (1932) used two very pure single crystals (Ti 3 and Ti 4) which were grown from the gas phase. The lower residual resistance of Ti 4 is probably not due to higher purity but rather due to better crystalline structure of the sample.

Potter (1941) measured resistivities on a 1 cm long specimen. No other information is given about the sample.

Webber and Reynolds (1948) report resistance measurements in zero magnetic field for a 99.89% pure wire sample, 0.055 in diameter.

Bostrom (1954) used a high purity crystal bar 2 to 2-1/2 in. long and ~1/8 in. diameter. He compared the resistivity of this high purity bar to the resistivity of commercial titanium.

Rosenberg (1955) measured resistivities of a single crystal, 0.0306 cm dia. and 1.6 cm long, which had a purity of 99.99%.

Kemp, Klemens and White (1956) used a 98% titanium rod, 3 mm dia., which had been annealed at 950°C for 5 hours in vacuo.

Berlincourt (1959) made five sets of measurements.

sample	size	purity	annealing
Ti 1u	cut from a rolled sheet 2.3 cm long and 0.32 cm wide and 0.0127 cm thick	99.912%	---
Ti 1a	"	99.9024%	1 hr at 1200°C at 7×10^{-7} mm Hg
Ti 2u	"	99.79%	---
Ti 2a	"	99.83%	1 hr at 1200°C at 7×10^{-7} mm Hg
Ti 3	crystal bar 0.0361 cm thick	99.987%	---

White and Woods (1959) measured electrical resistivities of five samples.

sample	purity %	diameter (mm)	treatment
Ti 1	98	3	annealed in vacuo at 950°C
Ti 2	high	2.6 x 0.1	" " " 700°C
Ti 3	99.99	1.6 x 3.1	" " " 800°C,60 hours
Ti 4	99.99	1.6 x 3.1	as rolled.
Ti 5	99.99	4.9 x 3.1	annealed in vacuo at 800°C,60 hours

The residual resistivity was estimated to be 2.3×10^{-6} ohm cm. The values in the table are smoothed (from large-scale graphs) values of ρi.

Roesch (1962) measured resistivities of three specimens. All were cut from the same polycrystalline sheet. No quantitative analysis was made of the impurities. All surfaces were cleaned and samples were placed in pyrex tubes filled with helium. The lower resistivity of specimen 3 is most likely due to fewer lattice defects.

specimen	dimensions, cm	heat treatment
1	l: 12.72 b: 3.86 t: 0.0066	1 hour at 500°C
2	l: 12.08 b: 4.14 t: 0.0093	1 hour at 500°C
3	l: 12.08 b: 4.14 t: 0.0093	Specimen 2 was heated an additional 1 hour at 950°C to produce Specimen 3.

Wasilewski (1962) reports resistivity measurements on zone refined, high purity titanium single crystals. The Ti ∥ and Ti ⊥ samples had a cross section of ~ 2 mm^2 and a length of 15 mm. The polycrystalline sample had the dimensions 50 mm x 5 mm x 0.5 mm. ρ_{273} values are given.

Cape and Hake (1965) used pure titanium specimens, 1 in. x 0.1 in. x 0.01 in., which were cut from buttons arc-cast in an inert atmosphere.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Mendelssohn, Sharma and Yoshida (1965) measured resistivity of a single crystal sample of unknown purity and dimensions.

Clinard and Kempter (1968) made measurements on a polycrystalline sample 1/4 in. dia and 1 in. long, which had been annealed prior to measurement. The titanium was of commercial grade and not specifically of high purity.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

Clausing and Moubis (1927)

Temp. K	ρ/ρ_{273}
78.48	0.2150
90.20	0.2547
158.5	0.5178
194.1	0.6674
222.2	0.7828
273.09*	1.0

* ρ_{273} = 82 x 10^{-6} ohm cm
** These values were not plotted on the Electrical Resistivity of Titanium graph.

McLennan, Howlett and Wilhelm (1929)

Temp. K	R/R_{273}
2.4	0.755
4.2	0.755
20.6	0.772
80.0	0.831
273.1	1.0

Meissner and Voigt (1930)

Temp. K	ρ/ρ_{273}*
1.13	0.0014
1.17	0.154
1.26	0.203
1.30	0.211
4.21	0.215
20.46	0.2180
77.61	0.3180
88.19	0.3505
273.16	1.00

* $\rho_{273} = 54 \times 10^{-6}$ ohm cm.

De Haas and Van Alphen (1931)

Temp. K	R/R_{273}*
1.63	superconducting
1.73	0.0011
1.78	0.0433
1.88	0.1018
2.01	0.1047
4.22	0.1048
20.41	0.1051

* These values were not plotted on the Electrical Resistivity of Titanium graph.

Meissner, Franz and Westerhoff (1932)

Temp. K	R/R_{273}	
	Ti 3	Ti 4
1.21	0.079_7	—
1.30	0.088_8	<0.00001*
1.68	-	0.000086*
1.73	0.11_0	0.00034*
1.75	-	0.0034
1.82	-	0.103_6
3.24	0.159	0.102
20.44	0.158	0.101_5
78.76	-	0.210_6
79.11	0.259_6	0.211
273.16	1.0	1.0

* These three points were not plotted on the Electrical Resistivity of Titanium graph.

Potter (1941)

Temp. K	R/R_{273}
20	0.26
90	0.39
173	0.65
273	1.0

Webber and Reynolds (1948)
(read from graph)

Temp. K	R/R_T*
1.1	0.088**
1.5	0.092
2.0	0.102
2.5	0.150
3.0	0.175
3.5	0.180
4.23	0.180

* R_T is room temperature.

** These values have not been plotted on the Electrical Resistivity of Titanium graph.

Bostrom (1954)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
77	16.94	0.324
273	52.27	1.00

* These values have not been plotted on the Electrical Resistivity of Titanium graph.

Rosenberg (1955) (read from graph)		
Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4.5	2.41	0.0612
10.0	2.42	0.0615
20.0	2.45	0.0622
30.0	2.63	0.0668
37.5	2.88	0.0731

Kemp, Klemens and White (1956) (read from graph)		
Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
2	23	0.343
20	23	0.343
45	25	0.373
70	28	0.418
100	35	0.522
150	44	0.657
200	54	0.806
273	67	1.00

Berlincourt (1959)							
Temp. K	Resistivity $\rho \times 10^6$ ohm cm					ρ/ρ_{273}**	
	Ti 1u	Ti 1a*	Ti 2u	Ti 2a	Ti 3*	Ti 1a	Ti 3
4.2	4.43	3.91	5.83	8.18	1.46	0.095	0.0336
77.0	8.81	8.07	10.5	12.5	6.00	0.197	0.138
273.0	-	41.0	-	-	43.5	1.00	1.00
295.0	-	-	-	50.0	-		
296.0	-	-	48.8	-	-		
296.5	48.7	-	-	-	-		
297.0	-	-	-	-	49.2		
297.5	-	47.3	-	-	-		

* Only the resistivity ratios for Ti 1a and Ti 3 were plotted on the Electrical Resistivity of Titanium graph.

** For Ti 3, $\rho_{273} = 43.5 \times 10^{-6}$ ohm cm and
Ti 1a, $\rho_{273} = 41.0 \times 10^{-6}$ ohm cm. (interpolated values)

White and Woods (1959)			
Temp. K	Ideal resistivity ρ_i x 10^6 ohm cm	Resistivity $\rho = \rho_i + \rho_0$ $\rho_0 = 2.3 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
20	0.02_0	2.32	0.0562
25	0.07_5	2.37_5	0.0575
30	0.2_0	2.5	0.0605
40	0.6_5	2.9_5	0.0714
50	1.4	3.7	0.0896
60	2.3	4.6	0.111
70	3.5	5.8	0.140
80	4.8_5	7.1_5	0.173
90	6.3_5	8.6_5	0.209
100	7.9	10.2	0.247
120	11.2	13.5	0.327
140	14.8	17.1	0.414
160	18.5	20.8	0.504
180	22.1	24.4	0.591
200	25.7	28.0	0.678
220	29.3	31.6	0.765
250	34.8	37.1	0.898
273	39.0	41.3	1.0

Roesch (1962)
(read from graph)

Temp. K	Resistivity ρ x 10^6 ohm cm			ρ/ρ_{273}		
	Specimen 1	Specimen 2	Specimen 3**	1	2	3**
4.2	1.80	1.56	1.23	0.044	0.041	0.034
77.4	6.10	5.85	5.60	0.149	0.154	0.153
273.	41.0	38.0 *	36.5 *	1.00	1.00	1.00

* Interpolated value.
** Only the values for Specimen 3 were plotted on the Electrical Resistivity of Titanium graph.

Wasilewski (1962)

Temp. K	ρ/ρ_{273}*		
	Ti ∥	Ti ⊥	Ti(poly)
4.2	-		0.0306
19.6	-		0.0309
77	0.1786	0.2086	0.15
196	0.6355	0.6450	0.67
273	1.00	1.00	1.00

* For Ti ∥ , $\rho_{273} = (48.0 \pm 0.7) \times 10^{-6}$ ohm cm,
Ti ⊥ , $\rho_{273} = (45.35 \pm 0.5) \times 10^{-6}$ ohm cm,
Ti (poly), $\rho_{273} = (42.67 \pm 0.05) \times 10^{-6}$ ohm cm.
These values have not been plotted on the Electrical Resistivity of Titanium graph.

Cape and Hake (1965)
(read from graph)

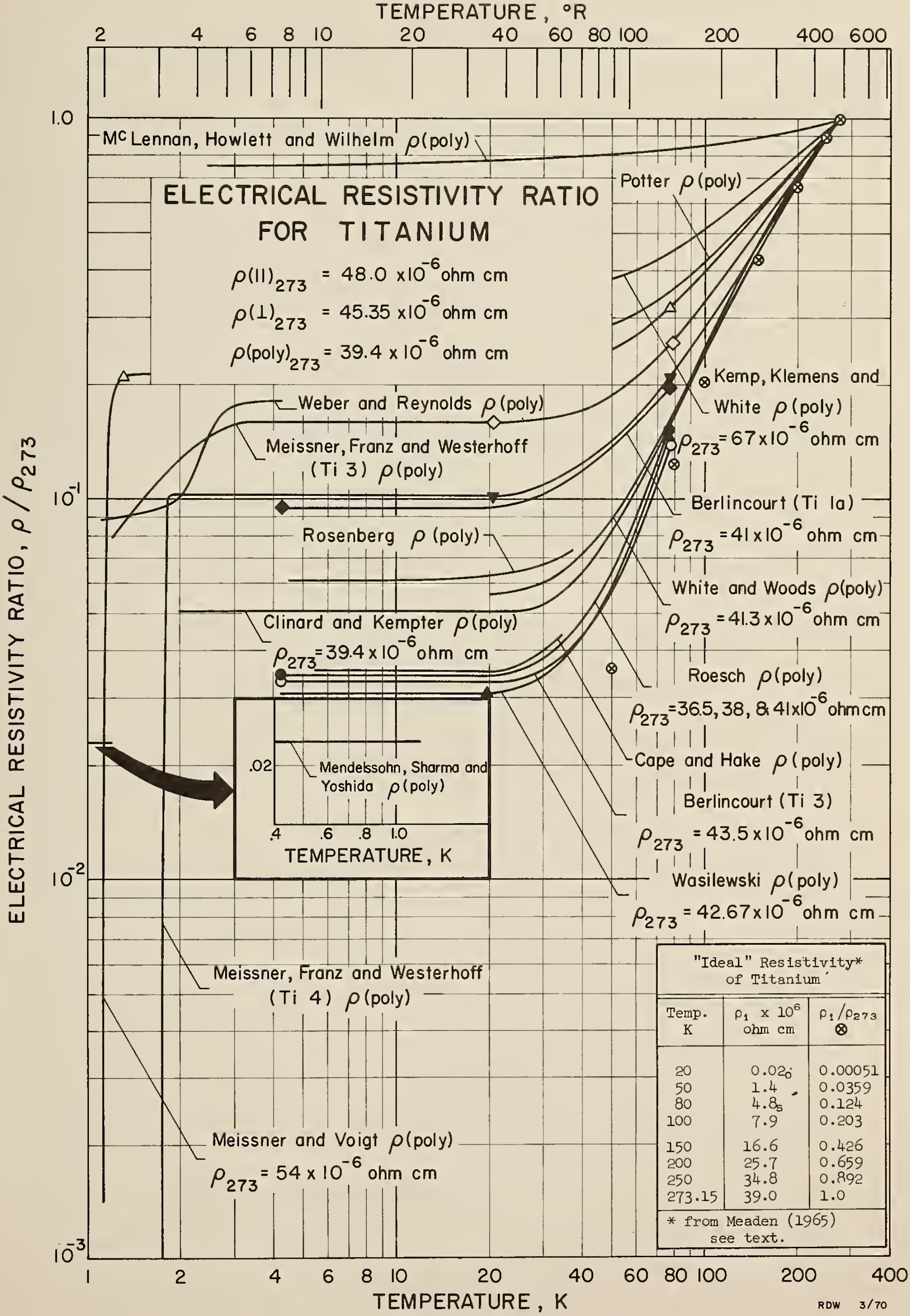
Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
5.5	1.40	0.0355
8.0	1.39	0.0353
15.0	1.38	0.0351
18.5	1.39	0.0353
21.0	1.40	0.0355
24.0	1.43	0.0363
28.5	1.52	0.0386
30.1	1.61	0.0409
35.2	1.75	0.0444

Mendelssohn, Sharma and Yoshida (1965)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
0.4	0.91	0.0231
0.8	0.91	0.0231
1.2	0.91	0.0231

Clinard and Kempter (1968)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
2	2.0	0.0508
10	2.0	0.0508
25	2.0	0.0508
50	3.4	0.086
75	5.8	0.147
100	9.4	0.239
150	18.4	0.467
200	27.5	0.698
250	37.0	0.939
273	39.4	1.0



"Ideal" Resistivity* of Titanium

Temp. K	ρ_1 x 10^6 ohm cm	ρ_1/ρ_{273} ⊗
20	0.02_0	0.00051
50	1.4	0.0359
80	4.8_5	0.124
100	7.9	0.203
150	16.6	0.426
200	25.7	0.659
250	34.8	0.892
273.15	39.0	1.0

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422 **FILE NO.** M-30

ELECTRICAL RESISTIVITY OF TUNGSTEN, W
(Atomic Number 74)

(page 1 of 13)

Sources of Data:

Backlund, N. G., "Measurement and analysis of the thermal conductivity of tungsten and molybdenum at 100-400 K," J. Phys. Chem. Solids 28, No. 11, 2219-23 (Nov 1967).

Berthel, K. H., "Der spezifische elektrische widerstand von elektronen-strahlzonengeschmolzenem wolfram zwischen 1.4 and 27 K," (The specific electrical resistance of electron beam zone melted tungsten between 1.4 and 27 K), Phys. Status Solidi 5, No. 2, 399-406 (1964).

Berthel, K. H., "Uber den einfluss verschiedener streuprozesse auf den spezifischen elektrischen idealwiderstand von reinem wolfram bei tiefen temperaturen," (Influence of various scattering processes on the specific electric ideal resistance of pure tungsten at low temperatures), Realstruktur und Eigenschaften Von Reinststoffen (Internationales Symposium Reinststoffe in Wissenschaft und Technik, Dresden, Germany, 2nd, Sep 28 - Oct 2, 1965, Pt. 3), J. Kunze, et al. Editors, Akademie-Verlag, Berlin, Germany (1967) pp 875-84.

Clinard, F. W., and Kempter, C. P., "Low-temperature electrical properties of some transition metals and transition-metal carbides," J. Less-Common Metals 15, No. 1, 59-73 (May 1968).

Cox, M., "Thermal and electrical conductivities of tungsten and tantalum," Phys. Rev. 64, No. 7/8, 241-47 (Oct 1943).

De Haas, W., and DeNobel, J., "The thermal and the electrical resistance of a tungsten single-crystal at low temperatures and in magnetic fields," Physica 5, 449-63 (1938).

De Nobel, J., "Thermal and electrical resistivity of some tungsten single crystals at low temperatures and in strong magnetic fields," Physica 23, 261-69 (1957).

Gruneisen, E., and Adenstedt, H., "Einfluss transversaler magnetfelder auf elektrizitats und warmeleitung reiner metalle bei tiefer temperatur," (The effect of a transverse magnetic field on the electrical and thermal conduction of pure metals at low temperature), Ann. Physik 31, 714-44 (1938).

Gruneisen, E., and Goens, E., "Unterschungen an metallkristallen. V. Elektrizitats- und warmeleitung von ein- un vielkristallinen metallen des regularen systems," (Investigations of metal crystals V. Electrical and thermal conductivity of single and poly crystalline metals of regular system), Z. Physik 44, 615-42 (1927).

Henning, F., "Gasthermometrische messungen zwischen -193 und -258 degrees," (Gas thermometry measurements between -193 and -258 degrees), Z. Physik 4, 264-79 (1921).

Holborn, L., "Uber die abhangigkeit des widerstandes reiner metalle von der temperatur," (About the dependence of resistance of pure metals on the temperature), Ann. Physik 59, 145-69 (1919).

Kannuluik, W. G., "The thermal and electrical conductivities of several metals between -183°C and 100°C," Proc. Roy. Soc. (London) A141, 159-68 (1933).

Mc Lennan, J. C., Howlett, L. E., and Wilhelm, J. O., "On the electrical conductivity of certain metals at low temperatures," Trans. Roy. Soc. Can. Sec. III, 23, Part I, 287-306 (Jan 1929).

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meissner, W., "Messungen mit hilfe von flussigem helium III. Widerstand von metallen. Supraleitfahigkeit von tantal," (Measurements with the help of liquid helium. III. Resistance of metals. Superconductivity of tantalum), Physik. Z. 29, 897-904 (1928).

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 892-936 (1930).

Moore, J. P., McElroy, D. L., and Barisoni, M., "Thermal conductivity measurements between 78 and 340 K on aluminum, iron, platinum, and tungsten," Proc. 6th Conf. on Thermal Conductivity, Dayton, Ohio (Oct 19-21, 1966) Air Force Materials Lab., Wright-Patterson AFB, Ohio, pp 737-78.

Powell, R. L., Harden, J. L., and Gibson, E. F., "Low-temperature transport properties of commercial metals and alloys. IV. Reactor grade Be, Mo, and W," J. Appl. Phys. 31, No. 7, 1221-24 (Jul 1960).

Shukovsky, H. B., Rose, R. M., and Wulff, J., "The low temperature electrical resistivity of lattice defects in deformed tungsten single crystals," Acta Met. 14, No. 7, 821-30 (Jul 1966).

Van den Berg, G. J., "The electrical resistance of potassium, tungsten, copper, tin, and lead at low temperatures," Physica 14, 111-38 (Apr 1948).

Volkenshtein, N. V., Starostina, L. S., et al., "Temperature dependence of electric conductivity of molybdenum and tungsten mono crystals in low temperature region," Phys. Metals Metallog. 18, No. 1, 85-90 (1964), Fiz. Metal. I Metalloved. 18, No. 6, 888-94 (1964).

White, G. K., and Woods, S. B., "Low temperature resistivity of the transition elements - cobalt, tungsten and rhenium," Can. J. Phys. 35, 656-65 (1957).

White, G. K., and Woods, S. B., "Electrical and thermal resistivity of the transition elements at low temperatures," Phil. Trans. Roy. Soc. London A251, No. 995, 273-302 (1959).

Wiese, J. R., "The flow and fracture of zone refined tungsten," Franklin Inst., Philadelphia, Pa., Labs. for Research and Development, Quart. Prog. Rept. No. Q-B1973-3, Tech. Rept. No. WAL TR 834.2/11-2 (Mar 1963) Contr. No. DA-36-034-ORD-3747 RD, 10 pp, DDC AD 407 426.

Other References:

Berthel, K. H., "Restwiderstandsverhaltnis, durchmesser-effekt und stromabhangigkeit des widerstandsverhaltnisses von zonengeschmolzenem wolfram bei tiefen temperaturen," (Residual resistance ratio, diameter effect and current dependence of the resistance ratio of zone-melted tungsten at low temperatures), Phys. Status Solidi 5, No. 1, 159-68 (1964).

Borovik, E. S., "Change of resistance of metals in a magnetic field at low temperatures," Zh. Eksptl. I Teoret Fiz. 23, 91-100 (1952).

Bridgman, P. W., "Electrical resistance under pressure, including certain liquid metals," Proc. Am. Acad. Arts Sci. 56, 61-154 (1921).

Bridgman, P. W., "The electric resistance to 30,000 kg/cm^2 of twenty nine metals and intermetallic compounds," Proc. Am. Acad. Arts Sci. 79, 149-79 (1951).

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Conte, R. R., and Dural, J., "Dispositif d'irradiation aux neutrons a 20 K," (Apparatus for neutron irradiation at 20 K), Rev. Phys. Appl. 2, No. 1, 1-6 (1967).

De Nobel, J., "Thermal and electrical resistance of a tungsten single crystal at low temperatures and in high magnetic fields," Physica 15, 532-40 (Jul 1949).

Dobson, P. J., and Hopkins, B. J., "Electrical conductance of thin ultrahigh-vacuum evaporated films of tungsten on glass," J. Appl. Phys. 39, No. 7, 3074-81 (Jun 1968).

Engelhardt, J. J., Webb, G. W., and Matthias, B. T., "Superconductivity and the d-shell," Science 155, No. 3759, 191-3 (Jan 1967).

Geiss, W., Van Liempt, J. A. M., "Das erweiterte gesetz von Matthiessen," (The extended law of Matthiessen), Z. Physik 41, 867-71 (1927).

Gibson, J. W., and Hein, R. A., "Superconductivity of tungsten," Phys. Rev. Letters 12, No. 25, 688-90 (Jun 22, 1964).

Goree, W. S., "Electrical conductivity of metals at high pressures and low temperatures," Florida Univ., Gainesville, Ph.D. Thesis (1964) 166 pp (Abstr. in Dissertation Abstr. 12, 7344, Jun 1965). (Available Univ. Microfilms, Ann Arbor, Mich., Order No. 65-5985).

Goree, W. S., and Scott, T. A., "Pressure dependence of electrical conductivity at low temperatures," Proceedings of the Intern. Conf. on Low Temperature Physics 9th, Pt. B, Plenum Press, New York (1965) pp 1205-9.

Goree, W. S., and Scott, T. A., "Pressure dependence of electrical conductivity of metals at low temperatures," J. Phys. Chem. Solids 27, No. 5, 835-48 (May 1966).

Ibragimov, Sh. Sh., "Effect of neutron bombardment on certain properties of tungsten," Phys. Metals Metallog. (USSR) 23, No. 2, 175-8 (1967) Transl. of Fiz. Metal. Metalloved. 23, No. 2, 354-7 (1967).

Justi, E., and Scheffers, H., "Die elektrische anisotropie von wolfram-einkristallen bei tiefen temperaturen in starken magnetischen transversalfeldern," (Electric anisotropy of single crystal tungsten for low temperatures in strong transverse magnetic field), Phys. Z. 37, 700-9 (1936).

Justi, E., and Scheffers, H., "Die elektrische leitfahigkeit von wolframeinkristallen bei tiefen temperaturen in straken magnetischen quer- und langsfeldern," (Electrical conductivity of single crystal tungsten at low temperatures in strong magnetic cross and longitudinal fields), Physik. Z. 38, 891-6 (1937).

Kammerer, O. F., and Strongin, M., "Superconductivity in tungsten films at temperatures near 4 K," Brookhaven National Lab., Upton, N. Y., Rept. No. BNL-9479, (1965) Contr. No. AT(30-2)-GEN-16, 17 pp, Presented at Intern. Symp. on Basic Probl. in Thin Film Phys., 1st, Clausthal-Gottingen, Germany, Paper No. CONF-650936-1, NASA N66-17545.

Kapitza, P. L., "The change of resistance of metals in magnetic fields," Leipziger Vortrage, S. Hirzel, Leipzig, Germany (1933) Reprinted in Collected Papers of P. L. Kapitza. Volume I (1916-1934), Pergamon Press, Ltd., Oxford, England (1964) pp 472-8.

Krautz, E., and Schultz, H., "Der einfluss von gitterbaufehlern auf den elektrischen widerstand und den Hall-effekt von wolfram und tantal," (The influence of lattice structure faults on the electrical resistance and Hall effect of tungsten and tantalum), Z. Angew. Phys. 15, No. 1, 1-4 (Jan 1963).

Kuhlmann, H. H., and Schultz, H., "Erholungsstufe III in entkohltem wolfram nach neutronenbestrahlung bei 4.5 K," (Recovery state III in decarbonized tungsten after neutron irradiation at 4.5 K), Acta Met. 14, No. 6, 798-800 (Jun 1966).

Mimeault, V. J., and Hansen, R. S., "Flash desorption and isotopic mixing of hydrogen and deuterium adsorbed on tungsten, iridium, and rhodium," J. Chem. Phys. 45, No. 6, 2240-50 (Sep 1966).

Mostovetch, N., and Vodar, B., "Variations, en fonction du potentiel applique, de la resistance electrique des depots metalliques tres minces aux basses temperatures," (Variations as function of applied potential of the electrical resistance of very thin metallic deposits at low temperatures), Compt. Rend. 230, 934-6 (Mar 1950).

Nachtigall, E., "Eigenschaften von molybdaen und wolfram bei niedrigen und mittleren temperaturen," (Properties of molybdenum and tungsten at low and medium temperatures), Z. Metallk. 43, No. 1, 23-26 (Jan 1952).

Thomas, J. G., and Mendoza, E., "The electrical resistance of magnesium, aluminum, molybdenum, cobalt, and tungsten at low temperatures," Phil. Mag. 43, 900-10 (Aug 1952).

Tye, R. P., "Preliminary measurements on the thermal and electrical conductivities of molybdenum, niobium, tantalum, and tungsten," J. Less-Common Metals 3, No. 1, 13-18 (Feb 1961).

Van Witzenburg, W., and Laubitz, M. J., "Magnetoresistances and the phonon conductivity of metals," Can. J. Phys. 46, No. 17, 1887-94 (Sep 1968).

Vodar, B., Mostovetch, M., Barbaron, M., and Spondlin, R., "Electrical conductivity of thin metallic films at liquid helium temperatures," Proc. Intern. Conf. Physics Very Low Temp., Mass. Inst. Technol., Cambridge, 113 (Sept 1949).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data" and are listed as ratios of electrical resistivities with respect to the resistivity at the ice point temperature (ρ_{273}). When the actual values of ρ_{273} are not available for the samples used by the various investigators, a datum value reported by Moore, McElroy, and Barison (1967)($\rho_{273} = 4.839 \times 10^{-6}$ ohm cm) is suggested for calculating values of electrical resistivity from these ratios. Gibson and Hein (1964) reported that superconductivity had been observed in a sample of high-purity tungsten at a temperature below 0.011 K.

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Holborn (1919) measured the resistance of 0.1 mm dia. wire which had been annealed a long time in vacuum at temperatures at which the metal glowed. There was no purity statement.

No information is given on the Henning (1921) sample.

The Gruneisen and Goens (1927) sample was a "very pure" single crystal deposited from the vapor. Resistivity values for a less pure sample were determined but have not been included in this compilation.

Meissner (1928) used an annealed tungsten sample 51 mm long and 0.03 mm diameter.

The Mc Lennan, Howlett and Wilhelm (1929) sample was in wire form, baked in vacuo at a high temperature for a number of hours to remove as much as possible of the occluded gases.

Meissner and Voigt (1930) had two samples; W-1 was a wire 0.03 mm dia. and 60 mm long and W-2 had the dimensions 4 mm x 4 mm x 65 mm. Both samples were annealed.

Kannuluik (1933) measured resistivities of 99.83% pure tungsten crystals. W-1 had a cubic configuration, a cross-sectional area of 0.01053 cm^2 and a length of 7.846 cm. W-2 had a hexagonal configuration, a cross sectional area of 0.01022 cm^2 and a length of 7.940 cm.

De Haas and De Nobel (1938) single crystal rod with a hexagonal cross section. They assumed that the axis of the rod was parallel to the (111) direction. The sample was of high purity. All the values in the table were taken in zero magnetic field.

Gruneisen and Adenstedt (1938) measured resistivities of a cubic body centered crystal rod parallel to [100] axis. The cross sectional area was 0.0251 cm^2 and the length was 5.6 cm.

Cox (1943) reported resistivity values for two wires, 0.010 in. diameter and 40 cm long. W-2 was aged at temperatures of 2400° and 2600°C for 370 hours. W-8 was aged at temperatures of 2300°C for 370 hours.

Van den Berg (1948) had two single crystal samples (thick rods) of different orientations. W_v had its length parallel to the rib of the lattice cube. W_z had its length parallel to the body diagonal of the lattice cube.

De Nobel (1957) measured resistivities of a single crystal rod whose axis made an angle of at most 5° with the [100] direction. No purity statement is given. The values in the table were measured with a magnetic field strength of zero.

White and Woods (1957, 1959) measured resistivity values for three samples of 99.99% pure tungsten. W-1a was annealed at 1350°C in vacuo for some hours, then at 600°C for some hours, then cooled. W-1b was the same as W-1a except heavy copper leads were attached instead of thin copper leads. W-2 was electropolished to 1 mm dia. then annealed at 1300°C in vacuo. The smoothed values in the table may have an error of about ± 1% due to uncertainty in the geometry of the specimen.

Powell, Harden and Gibson (1960) had a 98% pure tungsten rod 3.67 mm dia. and 13 cm long. The sample was not annealed after machining.

Wiese (1963) used two electron-beam zone-refined rods of high purity tungsten. Probes were set at varying intervals along the rod. Probes 6-7 were on the polycrystalline ends of the sample. All other probes are on the single crystal portion.

Berthel (1964) made resistance measurements on ten (single crystal) rods with diameters ranging from 1.5 to 4.3 mm. No purity statement was given. They were prepared by electron beam zone melting. The values in the table are the average of all measurements.

Volkenshtein, et al. (1964) measured resistances of both single crystal and polycrystalline samples. The single crystals were produced by zone melting by electron bombardment, with dimensions of 3 to 4 mm dia. and 25 mm long rods. About 100 data points were taken and presented graphically.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Moore, Mc Elroy and Barison (1966) report smoothed values of electrical resistivity for two rod samples; one is stated as "high purity" and the other "radial". The "high purity" sample was prepared by electron-beam melting and has a ratio $\rho_{273}/\rho_{4.2}$ of > 400. The "radial" sample is 99.98% pure.

Shukovsky, Rose and Wulff (1966) measured resistivities of single crystals which were seeded for a [100] axial orientation and were grown by a floating-zone electron-beam technique in vacua of 2×10^{-5} torr and 2×10^{-6} torr at a rate of 2 mm/min. The starting material was 99.99% pure. The values in the table are for an undeformed sample. Residual resistivity $\rho_o = 4.8 \times 10^{-10}$ ohm cm.

Backlund (1967) had two sample bars, 10 cm long and 4 and 5 mm diameters. He does not state the purity of his samples.

Berthel (1967) used 99.999% pure tungsten rods with diameters between 1.5 and 4.5 mm. A residual resistance value was not given.

Clinard and Kempter (1968) measured resistivities of a 99.9% pure tungsten cylinder, 1/4 in. dia. and 1 in. long. The residual resistivity, ρ_o, was 0.1×10^{-6} ohm cm.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

Holborn (1919)

Temp. K	R/R_{273}*
80.4	0.1529
81.1	0.1554
194.85	0.6509
273.0	1.0

* These values were not plotted on the Electrical Resistivity of Tungsten graph.

Henning (1921)

Temp. K	R/R_{273}*
81	0.1564
90	0.1942
197	0.6523
273	1.00

* These values were not plotted on the Electrical Resistivity of Tungsten graph.

Gruneisen and Goens (1927)

Temp. K	ρ/ρ_{273}
21.2	0.00120
83.2	0.1387
273.2*	1.00

* $\rho'_{273} = 4.91 \times 10^{-6}$ ohm cm

Meissner (1928)

Temp. K	R/R_{273}
1.31	0.0307
4.22	0.0307
20.44	0.0317
78.24	0.1478
273.20	1.00

McLennan, Howlett and Wilhelm (1929)

Temp. K	Resistance R x 10^5 ohm	R/R_{273}*
2.4	4.6	0.031
4.6	4.6	0.031
20.6	4.7	0.032
85.0	28.3	0.190
273.1	149.0	1.0

* These values were not plotted on the Electrical Resistivity of Tungsten graph.

Meissner and Voigt (1930)

Temp. K	R/R_{273}	
	W-1*	W-2
0.00	0.0307	0.000516
1.31	0.0307	0.00053
4.21	-	0.00054
4.22	0.0307	-
20.44	0.0317	0.00108
77.60	-	0.1156
78.23	0.1478	-
87.40	-	0.1565
273.16	1.0	1.0

* These values were from Meissner (1929).

Kannuluik (1933)

Temp. K	Resistivity ρ x 10^6 ohm cm		ρ/ρ_{273}*	
	W 1	W 2	W 1	W 2
90.0	0.892	0.843	0.1790	0.1706
194.5	3.22	3.17	0.6464	0.6424
273	4.98	4.94	1.00	1.00

* These values were not plotted on the Electrical Resistivity of Tungsten graph.

De Haas and De Nobel (1938)

Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}*
14.14	0.0023^6	0.000486
17.55	0.0031^5	0.000650
20.36	0.0041^7	0.000860
20.42	0.0042^2	0.000870
50.55	0.142^5	0.0294
63.50	0.323^0	0.0666
65.20	0.347^5	0.0715
65.80	0.356^5	0.0735
68.20	0.394^5	0.0813
69.80	0.423^0	0.0872
71.30	0.446^0	0.0920
74.30	0.499^0	0.103
74.95	0.511^0	0.105
77.40	0.559^5	0.115
80.10	0.606^5	0.125
85.05	0.704^0	0.145
90.15	0.807^0	0.166

* The value of ρ_{273} used in this calculation was 4.839 x 10^{-6} ohm cm. De Haas and De Nobel did not report a ρ_{273} value.

Gruneisen and Adenstedt (1938)

Temp. K	R/R_{273} (W ‖)
20.33	0.00216
78.94	0.1230
273.15*	1.0

* ρ_{273} = 4.86 x 10^{-6} ohm cm

Cox (1943)

Temp. K	Resistivity ρ_{273} x 10^6 ohm cm		ρ/ρ_{273}*	
	W 2	W 8	W 2	W 8
77.36	-	0.6135	-	0.122
77.4	0.6736	-	0.134	-
90.2	0.9132	0.8558	0.181	0.170
193	3.18	-	0.632	-
273.2	5.034	5.035	1.0	1.0

* These values were not plotted on the Electrical Resistivity of Tungsten graph.

Van den Berg (1948)

Temp. K	R/R_{273}	
	W_v*	W_z*
1.29	0.00045^4	-
1.30	-	0.00071^2
2.01	0.00044^5	0.00071^6
3.00	0.00045^7	0.00072^4
4.40	0.00045^8	-
4.49	-	0.00072^3
7.68	0.00047^5	-
8.05	-	0.00074^2
11.27	0.00052^3	-
15.14	0.00062^3	-
18.06	0.00078^3	0.00109^2
20.41	0.00097^1	0.00129^6

* W_v had its length parallel to the rib of the lattice cube.
W_z had its length parallel to the body diagonal of the lattice cube.

De Nobel (1957)

Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}
14.50	0.0123	0.00227
20.42	0.0141	0.00260
55.35	0.2155	0.0397
63.95	0.3551	0.0655
68.51	0.4297	0.0792
72.97	0.5087	0.0938
77.35	0.5921	0.109
273	5.423 *	1.0

* Calculated value

White and Woods (1957, 1959)

Temp. K	Ideal resistivity $\rho_i \times 10^6$ ohm cm	Resistivity $\rho = \rho_0 + \rho_i$ $\rho_0 = 0.0303 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
15	0.002_4	0.0327	0.00674
20	0.005_6	0.0359	0.00740
25	0.011_5	0.0418	0.00862
30	0.02_2	0.0523	0.0108
40	0.06_6	0.0963	0.0199
50	0.15_1	0.1813	0.0374
60	0.27_1	0.3013	0.0621
70	0.42_5	0.4553	0.0939
80	0.60_0	0.6303	0.130
90	0.82_0	0.8503	0.175
100	1.02	1.0503	0.217
120	1.44	1.4703	0.303
140	1.8_8	1.9103	0.394
160	2.3_3	2.3603	0.487
180	2.7_8	2.8103	0.579
200	3.2_2	3.2503	0.670
220	3.6_6	3.6903	0.761
250	4.3_2	4.3503	0.897
273	4.8_2	4.8503	1.0

Powell, Harden and Gibson (1960)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
4	0.16	0.0330
10	0.16	0.0330
20	0.17	0.0350
40	0.22	0.0454
60	0.43	0.0886
80	0.8	0.165
100	1.2	0.249

* The value of ρ_{273} used in this calculation was 4.839×10^{-6} ohm cm. Powell, Harden and Gibson did not report a ρ_{273} value. The values in this column were not plotted on the Electrical Resistivity of Tungsten graph.

Wiese (1963)

Temp. K	Resistance* R x 10^6 ohm				
	probes 1-2	2-3	3-4	4-5	6-7
Sample W-1					
295	61.20	61.57	56.90	44.74	43.91
77	6.37	6.29	5.83	4.62	4.97
4.2	0.039	0.001	0.003	0.033	0.369
Sample W-2					
300	62.22	57.29	59.63	59.80	47.50
77	6.61	6.03	6.28	6.29	5.85
4.2	0.0101	- probes broke -			0.602

* These values have not been plotted on the Electrical Resistivity of Tungsten graph.

Berthel (1964)

Temp. K	R_1/R_{273}*	Temp. K	R_1/R_{273}*
14.00	0.0000785	24.57	0.001028
14.50	0.000090	24.62	0.001036
15.00	0.000103	25.00	0.001126
15.50	0.0001175	25.08	0.001145
16.00	0.0001335	25.51	0.001246
16.50	0.0001525	25.78	0.001319
17.00	0.0001735	25.99	0.001373
17.50	0.000197	26.29	0.001459
18.00	0.000223	26.49	0.001514
18.50	0.000253	26.79	0.001602
19.00	0.0002855	26.98	0.001666
19.50	0.000323	27.06	0.001690
20.00	0.000365		
20.25	0.0003875		

* These values were not plotted on the Electrical Resistivity of Tungsten graph.

Volkenshtein, et al. (1964)
(read from graph)

Temp. K	R/R_{273}	
	single crystal	poly crystal
5	0.0001	-
10	0.0001	-
15	0.0002	-
20	0.00045	0.037
25	0.0009	0.040
30	0.0025	0.042
33	0.0043	-
40	-	0.0525
50	0.03	0.0670
60	-	0.089
70	-	0.16
100	0.22	0.26
150	0.46	0.48
200	0.68	0.68
250	0.9	0.90
273	1.0	1.0

Moore, McElroy and Barison (1966)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273}**	
	"High purity"	"Radial"	"High Purity"	"Radial"
80	0.60	0.76	0.124	0.152
100	1.04	1.20	0.215	0.240
120	1.48	1.64	0.306	0.328
140	1.92	2.08	0.397	0.416
160	2.36	2.52	0.488	0.504
180	2.80	2.96	0.579	0.592
200	3.24	3.40	0.670	0.680
220	3.68	3.84	0.760	0.768
240	4.12	4.27	0.851	0.854
260	4.56	4.71	0.942	0.942
273	4.839*	5.002*	1.0	1.0

* Taken from text.

** These values were not plotted on the Electrical Resistivity of Tungsten graph.

Shukovsky, Rose and Wulff (1966)
(read from graph)

Temp. K	ρ_1 x 10^6 ohm cm	Resistivity $\rho = \rho_0 + \rho_1$ $\rho_0 = 0.0004 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
7.3	0.0000552	0.0005352	0.000111
8	0.000072	0.000552	0.000115
9	0.000096	0.000576	0.000120
10	0.000134	0.000614	0.000128
15	0.00048	0.00098	0.000204
20	0.00163	0.00211	0.000440
25	0.00528	0.00568	0.00118
30	0.0178	0.01828	0.00381
35	0.0408	0.04128	0.00860
40	0.0816	0.08208	0.0171

* $\rho_{273} = 4.8 \times 10^{-6}$ ohm cm

Berthel (1967)
(read from graph)

Temp. K	R_1/R_{273}*
2	0.0000007
4	0.0000027
10	0.000024
16	0.00013
20	0.00035
26	0.0013

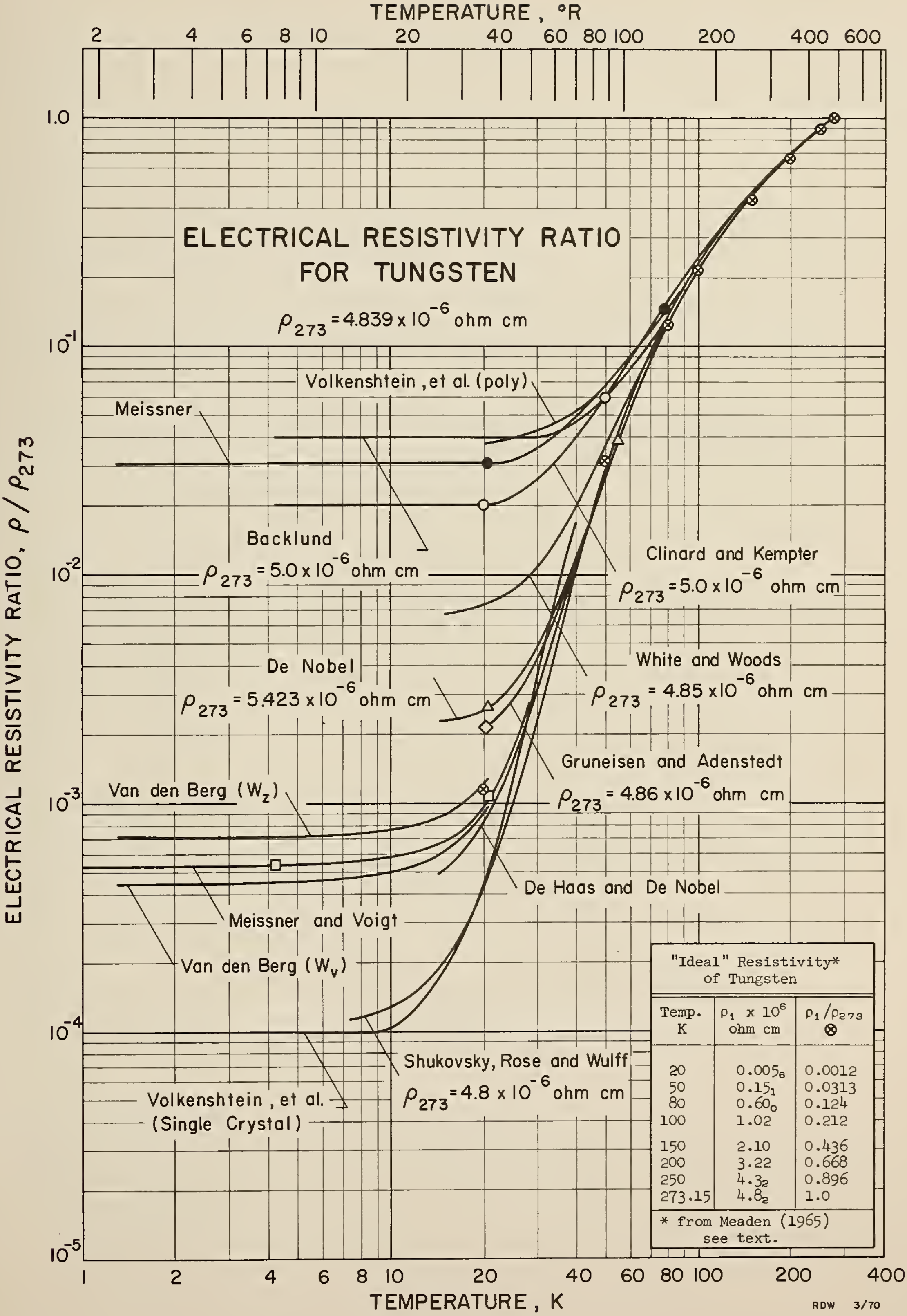
* These values have not been plotted on the Electrical Resistivity of Tungsten graph.

Backlund (1967)
(read from graph)

Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}
4.2	0.2	0.04
20	0.2	0.04
50	0.3	0.06
100	1.1	0.27
150	2.1	0.42
200	3.3	0.66
273	5.0	1.00

Clinard and Kempter (1968)
(read from graph)

Temp. K	Resistivity ρ x 10^6 ohm cm	ρ/ρ_{273}
4.2	0.1	0.02
20	0.1	0.02
50	0.3	0.06
100	1.2	0.24
150	2.2	0.44
200	3.5	0.70
250	4.5	0.90
273	5.0	1.0



"Ideal" Resistivity* of Tungsten

Temp. K	$\rho_i \times 10^6$ ohm cm	ρ_i / ρ_{273} ⊗
20	0.005_6	0.0012
50	0.15_1	0.0313
80	0.60_0	0.124
100	1.02	0.212
150	2.10	0.436
200	3.22	0.668
250	4.3_2	0.896
273.15	4.8_2	1.0

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422

FILE NO. M-31

ELECTRICAL RESISTIVITY OF VANADIUM, V
(Atomic Number 23)

(page 1 of 7)

Sources of Data:

Amitin, E. B., Kovalevskaya, Yu. A., and Kovdrya, Yu. Z., "Hall effect and electrical resistivity of vanadium at 20-300 K," Soviet Phys.-Solid State 9, No. 3, 704-6 (Sep 1967) Transl. of Fiz. Tverd. Tela 9, No. 3, 905-8 (Mar 1967).

Burger, J. P., and Taylor, M. A., "Anomalies in the magnetic susceptibility and electrical resistivity of vanadium," Phys. Rev. Letters 6, No. 4, 185-87 (Feb 1961).

Hren, J. A., and Wayman, C. M., "Some properties of vanadium at subatmospheric temperatures," Trans. Met. Soc. AIME 218, 377-9 (Feb 1960).

Loomis, B. A., and Carlson, O. N., "Investigation of the brittle-ductile transition in vanadium," Reactive Metals (Proceedings of the Annual Conference 3rd, Buffalo, N. Y., May 27-29, 1958) W. R. Clough, Ed., Interscience Publishers, New York (1959) 2, pp 227-43.

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 892-936 (1930).

Meissner, W., and Westerhoff, H., "Messungen mit hilfe von flussigem helium. XXIII. Supraleitfahigkeit von vanadium," (Measurements using liquid helium. XXIII. Superconductivity of vanadium), Z. Physik 87, 206-9 (1933).

Potter, H. H., "Electrical resistance and thermoelectric power of the transition metals," Proc. Phys. Soc. (London) 53, 695-705 (1941).

Rostoker, W., and Yamamoto, A. S., "A contribution to the vanadium-oxygen phase diagram," Trans. Am. Soc. Metals 47, 1002-17 (1955).

Smirnov, Yu. M., and Finkel, V. A., "Crystal structure of tantalum, niobium and vanadium at 110-400 K," Soviet Phys. JETP 22, No. 4, 750-3 (Apr 1966) (Transl. from Zh. Eksperim. I Teor. Fiz. 49, 1077-82, Oct 1965).

Taylor, M. A., and Smith, C. H. L., "The electrical resistivity of vanadium and vanadium-chromium solid solutions," Physica 28, No. 4, 453-60 (Apr 1962).

Westlake, D. G., "Anomalies in the physical properties of vanadium. The role of hydrogen," Phil. Mag. 16, No. 143, 905-8 (Nov 1967).

Westlake, D. G., "A resistometric study of phase equilibria at low temperatures in the vanadium-hydrogen system," Trans. Met. Soc. AIME 239, No. 9, 1341-4 (Aug 1967).

Westlake, D. G., and Alfred, L. C. R., "Determination of the Debye characteristic temperature of vanadium from the Bloch-Gruneisen relation," J. Phys. Chem. Solids 29, No. 11, 1931-4 (Nov 1968).

White, G. K., and Woods, S. B., "Low temperature resistivity of transition elements - vanadium, niobium, and hafnium," Can. J. Phys. 35, 892-901 (1957).

White, G. K., and Woods, S. B., "Electrical and thermal resistivity of the transition elements at low temperatures," Phil. Trans. Roy. Soc. London A251 No. 995, 273-302 (1959).

Other References:

Blades, J. D., Gerber, J., and Thompson, C. T., "Initial studies of the preparation and properties of vanadium thin films," Solid State Electron. 1, No. 4, 319-22 (1960) Office of Naval Research, Washington, D. C., Symposium Rept. No. ACR-50, 121-29 (May 1960) DDC AD 246 916.

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Engelhardt, J. J., Webb, G. W., and Matthias, B. T., "Superconductivity and the d-shell," Science 155, No. 3759, 191-3 (Jan 1967).

Frerichs, R., and Kircher, C. T., "Superconductive films of the transition metals, niobium, titanium and vanadium made by 'protected sputtering'," Low Temperature Physics LT 8, Proc. 8th Intern. Conf. on Low Temp. Phys., London, 1962, 376-77 (1963) Butterworths, Washington, D. C.

Martin, R. B., and Rose-Innes, A. C., "Superconductivity of vanadium," Phys. Letters 19, No. 6, 467-69 (Dec 1965).

Meyers, L., and Little, W. A., "Apparent lack of long-range order in superconducting vanadium," Phys. Rev. Letters 13, No. 11, 325-27 (Sept 1964).

Noer, R. J., and Knight, W. D., "Nuclear magnetic resonance and relaxation in superconducting vanadium," Rev. Mod. Phys. 36, No. 1, 177-85 (Jan 1964).

Sirota, N. N., Ovseichuk, E. A., and Stribuk, E. K., "Effect of the degree of deformation on the superconducting properties of niobium and vanadium," Soviet Phys. Doklady 11, No. 11, 976-8 (May 1967) Transl. of Dokl. Akad. Nauk SSSR 171, No. 1, 88-90 (Nov 1966).

Smirnov, Yu. M., and Finkel, V. A., "Crystal structure of tantalum, niobium and vanadium at 110 - 400 K," Soviet Phys. JETP 22, No. 4, 750-3 (Apr 1966), Transl. of Zh. Eksperim. I Teor. Fiz. 49, 1077-82 (Oct 1965).

Suits, J. C., "Vanadium films evaporated onto liquid-He-cooled substrates in ultra-high vacuum," Natl. Symp. Vacuum Technol. Trans. 9, 74-80 (1962).

Suzuki, H., Minomura, S., and Miyahara, S., "Effect of pressure on the anomaly of vanadium," J. Phys. Soc. Japan 21, No. 10, 2089 (Oct 1966).

Thompson, C. T., and Gerber, J. F., "A note on superconducting vanadium thin films," Burroughs Corp., Paoli, Pa. Rept. No. TR61-20 (Mar 1961) Contr. No. NONR-214500, 4 pp DDC AD 253 747.

Van Gurp, G. J., "The effect of structure on the superconducting properties of vanadium and niobium foils," Philips Res. Repts. 22, No. 1, 10-35 (Feb 1967).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data" and are presented here as ratios of electrical resistivity with respect to the resistivity at the ice point temperature (ρ_{273}). When the actual values of ρ_{273} for the samples used by the several investigators were not available, a datum value reported by Taylor and Smith (1962) (ρ_{273} = (19.54 ± 0.2) x 10^{-6} ohm cm) is suggested for calculating values of electrical resistivity from these ratios. These data should not be extrapolated to temperatures below 5.03 K as vanadium becomes superconducting around that temperature.

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Meissner and Voigt (1930) used a 99.79% pure vanadium rod whose cross section was 2 mm x 2 mm and whose length was 19.5 mm.

Meissner and Westerhoff (1933) made three sets of resistance measurements. Only one set of data is presented in the tables. Their sample was a 99.36% pure vanadium rod which had been pulled from a melt. No further information is given about the sample.

Potter (1941) measured resistance of a specimen about 0.6 mm square and 6 mm long. The resistivity at 273 K is roughly estimated to be 18.2×10^{-6} ohm cm.

In White and Woods (1957, 1959), two of the samples (V2 and V4) were ~99.9% pure vanadium rods with 3.55 mm diameters. One of these (V4) had been annealed at 1300°C in vacuo. A third sample (V1) was 99.7% pure vanadium foil of 0.0005 in. thickness which was rolled into a "rod" about 1-1/2 in. long with an effective cross-sectional area determined by weighing to be 0.0037 cm^2. The change of slope of the curve at about 200 K may be connected with an appreciable oxygen content. The residual resistivity, ρ_0, for each of the three samples was:

Sample	ρ_0, 10^{-6} ohm cm
V1	2.97
V2	3.10
V3	4.83

The values in the table are compiled from the experimental data.

Loomis and Carlson (1959) made electrical resistivity measurements on bomb-reduced vanadium samples of 99.7% purity. The cold rolled bars were recrystallized by annealing at 900°C for 5 hours in vacuo. These samples had an average grain diameter of 0.04 mm. They found a discontinuity in the data at ~ 193 K.

The Hren and Wayman (1960) specimen was a 99.7% pure coiled wire with a 0.025 in. diameter and an 8 cm length. Measurements were made on specimens; 1) with no heat treatment of sample, 2) after annealing at 950°C, and 3) after vacuum degassing at 1500°C. The tabular values were taken from their graph.

Burger and Taylor (1961) used 99.9% pure vanadium specimen. No further information about the specimen is given. The absolute value of the resistivity is only accurate to ± 5%.

Taylor and Smith (1962) had specimens of approximately 10 mm x 1 mm x 1 mm which were annealed at 800°C for 5 hours in a vacuum of about 10^{-6} mm Hg and quickly cooled. Their purities follow:

Sample	% Purity
J.M.	99.63
U.S. B.M.	99.85
B.M.I.	99.92

The resistivity data are believed to be accurate to roughly 1%. An anomaly in the temperature dependence of the resistivity of vanadium was found at 225, 226, and 227 K for specimens B.M.I., J.M. and U.S. B.M.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Smirnov and Finkel (1966) used polycrystalline samples in the form of strips or plates, 0.1 to 0.3 mm thick. Sample V1 had a purity of 99.74%; sample V2 had a purity of 99.20%. A transition of the second type was observed at 195 and 230 K for V1 and V2, respectively.

Amitin, Kovalevskaya and Kovdrya (1967) report resistivity ratios for two samples. Sample 1 was polycrystalline, 99.63% pure vanadium, with dimensions 13.1 x 3.7 x 0.8 mm. It was annealed at $\approx 10^{-6}$ mm Hg vacuum at 850°C for five hours prior to measurements. Sample 1 has $\rho_{273}/\rho_0 = 11.5$. No information is given for Sample 2 except that $\rho_{273}/\rho_0 = 15$. Only data for Sample 1 are tabulated.

Westlake (1967) and Westlake and Alfred (1968) report resistivity measurements on a 99.977% pure strip, 60 mm long, 4.2 mm wide, and 0.4 mm thick. This sample was annealed in a dynamic vacuum of 2×10^{-6} torr for 30 min. at 1073 K. Westlake's Phil. Mag. article states that anomalies similar to those reported by previous investigators were found in the samples having hydrogen present. He suggests that many of the anomalies reported by previous investigators may be attributable to hydrogen content in the sample. The data in the table are for hydrogen-free vanadium.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

Meissner and Voigt (1930)

Temp. K	R/R_{273}
1.25	0.429
1.37	0.511
4.21	0.555
20.45	0.9540
77.59	0.9674
83.57	0.9683
273.16*	1.0

* $\rho_{273} = 17 \times 10^{-5}$ ohm cm.

Meissner and Westerhoff (1933)

Temp. K	R/R_{273}
<4.30	superconducting
4.30	1.7×10^{-3}
4.31	2.9×10^{-3}
4.33	3.1×10^{-3}
4.36	3.6×10^{-3}
4.39	3.8×10^{-3}
4.41	3.7×10^{-3}
20.4	3.05×10^{-3}
77.5	0.162_5
273.16	1.0

Potter (1941)

Temp. K	R/R_{273}
14*	0.326
20*	0.328
77*	0.421
90*	0.455
173	0.71
273**	1.0

* Experimental values were taken at these temperatures.
** Estimated $\rho_{273} = 18.2 \times 10^{-6}$ ohm cm.

Rostoker and Yamamoto (1955)
(read from graph)

Temp. K	R, ohms	R/R_{273}*
221	0.0334	0.841
233	0.0347	0.874
253	0.0373	0.940
273	0.0397	1.0

* These values were not plotted on the Electrical Resistivity of Vanadium graph.

White and Woods (1957, 1959)

Temp. K	Ideal resistivity $\rho_i \times 10^6$ ohm cm	Resistivity $\rho = \rho_o + \rho_i$ where the average $\rho_o = 3.63 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
15	0.01_4	3.644	0.166
20	0.03_7	3.667	0.167
25	0.07_6	3.706	0.169
30	0.1_4	3.77	0.172
40	0.3_8	4.01	0.183
50	0.7_5	4.38	0.200
60	1.2_7	4.90	0.223
70	1.9_0	5.53	0.252
80	2.6_5	6.28	0.286
90	3.5_0	7.13	0.325
100	4.3	7.93	0.362
120	6.0	9.63	0.439
140	7.7_5	11.38	0.519
160	9.5	13.13	0.599
180	11.2	14.83	0.676
200	12.9	16.53	0.754
220	14.5	18.13	0.827
250	16.6_5	20.28	0.925
273	18.3	21.93	1.0

Loomis and Carlson (1959)
(read from graph)

Temp. K	Resistance R x 10^5 ohms	R/R_{273}
83	0.6	0.040
93	1.2	0.080
133	4.0	0.267
173	7.2	0.480
193	8.8	0.587
199	11.0	0.733
233	13.0	0.867
273	15.0	1.0

Hren and Wayman (1960)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
126	13.8	0.523
160	17.0	0.644
200	20.6	0.780
240	23.8	0.901
273	26.4	1.0

Burger and Taylor (1961)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273} *
225	18.57	0.807
230	19.10	0.830
235	19.60	0.852
240	20.08	0.873
245	20.55	0.893
273	23.0	1.0

* These values were not plotted on the Electrical Resistivity of Vanadium graph.

Taylor and Smith (1962)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm			ρ_{273}		
	Sample J.M.	Sample B.M.I.	Sample U.S.B.M.	J.M.	B.M.I.	U.S.B.M.
20	4.00 ± 0.06	0.74 ± 0.01	1.56 ± 0.03	0.176	0.0379	0.0767
77	6.48 ± 0.1	3.18 ± 0.03	3.98 ± 0.07	0.286	0.163	0.196
273	22.67 ± 0.38	19.54 ± 0.20	20.34 ± 0.31	1.0	1.0	1.0

Smirnov and Finkel (1966) (read from graph)

Temp. K	$\frac{R(T) - R(110\ K)}{R(110\ K)}$*	
	V1	V2
110	0	0
125	0.1	0.1
150	0.32	0.32
175	0.53	0.56
200	0.72	0.74
225	0.9	0.92
250	1.04	1.13
273	1.18	1.3

*These data were not plotted on the Electrical Resistivity of Vanadium graph.

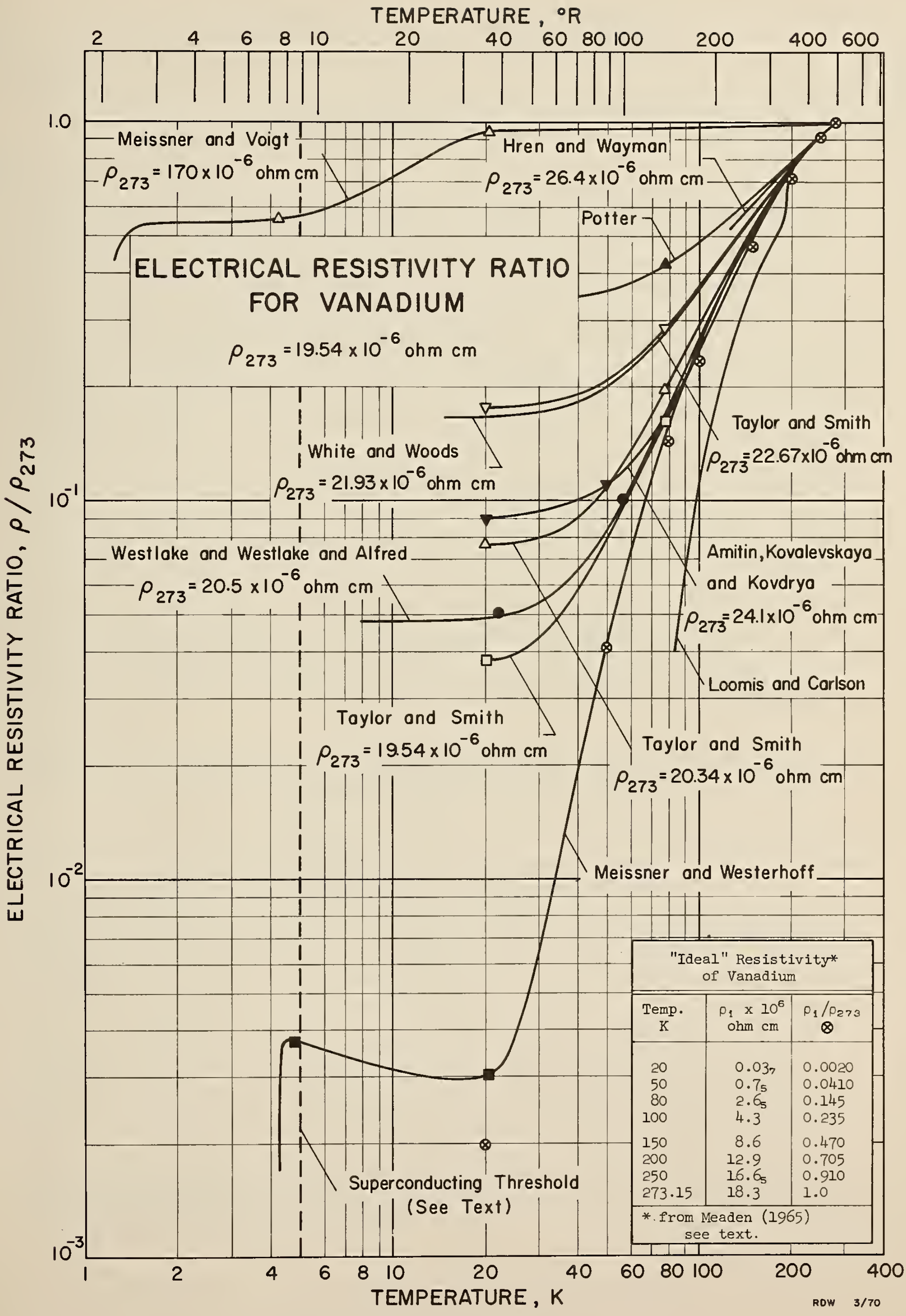
Amitin, Kovalevskaya and Kovdrya (1967) (read from graph)

Temp. K	ρ/ρ_{273}* Sample 1
20	0.09
50	0.11
100	0.30
150	0.51
200	0.72
250	0.92
273	1.0

* $\rho_{273} = 24.1 \times 10^{-6}$ ohm cm.

Westlake (1967) and Westlake and Alfred (1968)

Temp. K	Ideal resistivity $\rho_1 \times 10^6$ ohm cm	Resistivity $\rho = \rho_0 + \rho_1$ where $\rho_0 = 1.0 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
8.0	-	1.0	0.0488
20.0	-	1.0	0.0488
22.0	0.04	1.04	0.0507
56.0	1.08	2.08	0.101
59.0	1.24	2.24	0.109
115.6	6.04	7.04	0.343
134.4	7.75	8.75	0.427
169.8	10.91	11.91	0.581
191.0	12.74	13.74	0.670
198.3	13.40	14.40	0.702
213.5	14.67	15.67	0.764
233.6	16.35	17.35	0.846
242.6	17.08	18.08	0.882
260.8	18.52	19.52	0.952
270.0	19.27	20.27	0.989
273.0	19.5	20.5	1.0



"Ideal" Resistivity*
of Vanadium

Temp. K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20	0.03_7	0.0020
50	0.7_5	0.0410
80	2.6_5	0.145
100	4.3	0.235
150	8.6	0.470
200	12.9	0.705
250	16.6_5	0.910
273.15	18.3	1.0

*. from Meaden (1965)
see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 2750422 **FILE NO.** M-32

ELECTRICAL RESISTIVITY OF ZINC, Zn
(Atomic Number 30)

(page 1 of 8)

Sources of Data:

Aleksandrov, B. N., "Size effect in electrical resistivity of high-purity metals," Soviet Phys. JETP 16, No. 2, 286-94 (Feb 1963).

Aleksandrov, B. N., and D'Yakov, I. G., "Variation of the electrical resistance of pure metals with decrease of temperature," Soviet Phys. JETP 16, No. 3, 603-08 (Mar 1963).

Bridgman, P. W., "The effect of pressure on the electrical resistance of single metal crystals at low temperature," Proc. Am. Acad. Arts Sci. 68, 95-123 (1933).

Collings, E. W., Hedgcock, F. T., and Muir, W. B., "Influence of spin ordering on the low temperature magnetic and electrical properties of the Zn-Mn system," Low Temperature Physics LT 8, Proc. 8th Intern. Conf. on Low Temp. Phys., London, 1962, 253-54 (1963) Butterworths, Washington, D. C.

Goens, E., and Gruneisen, E., "Elektrizitats und warmeleitung in zink und cadmiumkristallen," (Electrical and thermal conductivity in zinc and cadmium crystals), Ann. Physik 14, 164-80 (1932).

Gruneisen, E., "Metallische leitfahigkeit," (Metal conductivity), Handbuch Der Physik 13, 1-75 (1928).

Gruneisen, E., and Goens, E., "Untersuchungen an metallkristallen. II. Spezifische warme und elektrischer widerstand von zink und cadmium," (Studies with metal crystals. II. Specific heat and electrical resistivity of zinc and cadmium), Z. Physik 26, 250-73 (1924).

Holborn, L., "Uber die abhangigkeit des widerstandes reiner metalle von der temperatur," (About the dependence of resistance of pure metals on the temperature), Ann. Physik 59, 145-69 (1919).

Jaeger, W., and Diesselhorst, H., "Warmeleitung elektricitatsleitung, warmecapacitat und thermokraft einiger metalle," (Heat conduction, electrical conductivity, specific heat and thermal power in metals), Wiss. Abhandl. Physik.-Tech. Reichasanstalt 3, 269-424 (1900).

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meissner, W., "Widerstand von metallen bei der temperatur des flussigen heliums," (Resistance of metals at the temperature of liquid helium), Z. Instrumentenk. 46, 103-5 (1926).

Meissner, W., "Messungen mit hilfe von flussigem helium. 2. Widerstand von gold, zink, cadmium, platin, nickel, eisen und silber bis herab zu 1.3 degrees abs," (Measurement with the help of liquid helium. 2. Resistance of gold, zinc, cadmium, platinum, nickel, iron and silver down to about 1.3 K), Z. Physik 38, 647-58 (1926) Abbreviated version appearing in Physik. Z. 27, 725-30 (1926).

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 761-97 (1930).

Pawlek, F., and Rogalla, D., "The electrical resistivity of silver, copper, aluminium, and zinc as a function of purity in the range 4-298 K," Cryogenics 6, No. 1, 14-20 (Feb 1966).

Pawlek, F., and Rogalla, D., "Der elektrische widerstand von silber, kupfer, aluminium, zink und natrium zwischen 4 und 298 K in abhangigkeit von den verunreinigungen," (Electrical resistance of silver, copper, aluminum, zinc and sodium between 4 and 298 K in dependence of the impurities), Metall 20, No. 9, 949-56 (1966).

Schimank, H., "Uber das verhalten des elektrischen widerstands von metallen bei tiefen temperaturen," (The behavior of the electrical resistance of metals at low temperature), Ann. Physik 45, 706-36 (1914).

Tuyn, W., "Measurements on the electrical resistance of some metals below the boiling point of oxygen," Commun. Phys. Lab. Univ. Leiden No. 196B (1929) Reprinted from Proc. Kon. Ned. Akad. Wetensch. 32, 115 (Feb 1929).

Tuyn, W., and Onnes, H. K., "Nouvelles experiences avec l' helium liquide. AB. Nouvelles mesures relatives a la resistance electrique des metaux temperatures de l' helium liquide," (New experiments with liquid helium. AB. New measurements of the electrical resistance of metals at liquid helium temperatures), Commun. Phys. Lab. Univ. Leiden No. 181 (1926), Reprinted from Arch. Neerl. Sci. IIIA 10, 5-41 (1926).

Wilkes, K. E., Powell, R. W., and DeWitt, D. P., "Thermal conductivity measurements on cobalt and zinc between 78 and 373 K," Thermal Conductivity (Proceedings of the Conference 8th, Purdue Univ., Lafayette, Ind., Oct 7-10, 1968) C. Y. Ho, et al., Eds, Plenum Press, New York (1969) pp 3-7.

Other References:

Aleksandrov, B. N., "Effect of dimensions and purity on the electrical resistance of metals in a longitudinal magnetic field at (liquid) helium temperatures," Soviet Phys. JETP 16, No. 4, 871-8 (1963) Transl. of Zhur. Eksptl. I Teoret Fiz. 43, 1231-41 (1962).

Alers, P. B., Spohr, D. A., and Webber, R. T., "The thermal conductivity of metals," Bull. IR Annexe 1955-3 (Presented at Conf. de Physique des Basses Temperatures, Paris, Sept. 2-8, 1955) 3 pp.

Amonenko, V. M., Kruglykh, A. A., and Paperov, I. I., "Production of zinc of high purity and method of purity control," Fiz. Metal. I Metalloved. 11, 633-35 (1961).

Beck, P. A., "Annealing of cold worked metals," Advan. Phys. 3, 245-324 (Jul 1954).

Boato, G., Bugo, M., and Rizzuto, C., "The effect of transition-metal impurities on the residual resistivity of Al, Zn, In, and Sn," Nuovo Cimento 45B, No. 2, 226-40 (Oct 1966).

Borovik, E. S., "Change of resistance of metals in a magnetic field at low temperatures," Zh. Eksptl. I Teoret Fiz. 23, 91-100 (1952).

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Buckel, W., and Hilsch, R., "Influence of condensation at low temperatures on the electrical resistance and superconduction of various metals," Z. Physik 138, No. 2, 109-20 (1954).

Desalvo, A., Gondi, P., Levi, F. A., and Zighani, F., "Purificazione dello zinco oltre al limite di 99,999 percent E determinazione del contenuto di impurita mediante metodi fisici," (Preparation of zinc of purity 99.999 percent and determination of the amount of impurity by physical methods), Metallurgia Italiana 55, No. 10, 511-20 (1963).

Desalvo, A., Gondi, P., Levi, F. A., and Zignani, F., "Electrical conductivity of high-purity zinc." Nuovo Cimento 31, No. 4, 904-13 (1964).

Dewar, J., and Fleming, J. A., "The electrical resistance of metals and alloys at temperatures approaching the absolute zero," Phil. Mag. 36, 271-99 (1893).

Grenier, C. G., Reynolds, J. M., and Zebouni, N. H., "Electron transport phenomena in zinc at liquid helium temperatures," Louisiana State Univ., Baton Rouge, Interin Tech. Rept. No. 2, (Jul 1962) Grant No. DA-ORD-31-124-61-G76, Proj. No. 59901004, 61 pp, NASA N62 14966.

Haager, M., and Siebinger, K., "Orientation dependence of the resistivity increase due to alpha-radiation," Berg. Huettenmaenn. Monatsh. 111, No. 3, 112-6 (1966).

Kan, L. S., and Lazarev, B. G., "Effect of hydrostatic compression on the electrical conductivity of metals at low temperatures," Soviet Phys. JETP 7, No. 1, 180-81 (Jul 1958).

Lucasson, A., and Lucasson, P., "Experimental results obtained in low temperature electron irradiation of Pd, Mo, Zn and alpha-U," J. Phys. Chem. Solids 27, No. 9, 1423-9 (Sep 1966).

Luthi, B., "Longitudinal magnetoresistance of metals in high fields," Phys. Rev. Letters 2, 503-4 (1959).

Luthi, B., "Widerstandsanderung von metallen in hohen magnetfeldern," (Resistance of metals in high magnetic fields), Helv. Phys. Acta 33, 161-82 (1960).

Onnes, H. K., and Tuyn, W., "Data concerning the electrical resistance of elementary substances at temperatures below -80°C," Commun. Phys. Lab. Univ. Leiden Suppl. No. 58 (1926) 88 pp.

Schofield, F. H., "The thermal and electrical conductivities of some pure metals," Proc. Roy. Soc. (London) A107, 206-27 (1925).

Skove, M. J., and Stillwell, E. P., "Size effects in residual resistance ratios for zinc whiskers," Appl. Phys. Letters 7, No. 9, 241-2 (Nov 1965).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data" and are listed as ratios of electrical resistivity with respect to resistivity at the ice point temperature (ρ_{273}). Since zinc is an anisotropic metal, we list suggested values of ρ_{273} for Zn $\parallel$, Zn $\perp$, and polycrystalline zinc to be used in calculating electrical resistivity from the ratios if the ρ_{273} is not stated by the author. These values are:

$$\rho(\parallel)_{273} = 5.589 \times 10^{-6} \text{ ohm cm,}$$

$$\rho(\perp)_{273} = 5.386 \times 10^{-6} \text{ ohm cm, and}$$

$$\rho_{\text{poly}} = 5.46 \times 10^{-6} \text{ ohm cm.}$$

The first and second values are from Bridgman (1933) and the third value was calculated from their data using Voigt's equation:

$$\frac{1}{\rho_{(\text{poly})}} = \frac{1}{3}\left[\frac{1}{\rho_{\parallel}} + \frac{2}{\rho_{\perp}}\right] .$$

It should also be noted that zinc becomes superconducting at 0.85 K.

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

Jaeger and Diesselhorst (1900) used a 99.97% pure zinc rod with dimensions 1.805 cm diameter and 27 cm length. The wire was made from the same starting material. There were no measurements below 0 °C.

Schimank (1914) measured the resistance of an extruded, polycrystalline wire. No further information is given for the sample.

The Holborn (1919) samples were 0.25 mm diameter wires which had been annealed at 200 and 300 °C. The impurities are < 0.01%.

Meissner (1926) (the Z. Instrumentenk. article) measured conductivities of a single crystal sample both parallel and perpendicular to the principle axis. The sample was 99.99% pure.

Meissner (1926) (the Z. Physik article) reported resistance measurements for three samples. The Zn ∥ measurements were made on a single crystal, 0.7 mm diameter and 5 cm length, with its orientation parallel to the hexagonal axis. The Zn ⊥ measurements were for a single crystal, 0.9 mm diameter and 12 cm length, with its orientation perpendicular to the hexagonal axis. $Zn_{(poly)}$ was a drawn polycrystalline wire, 0.25 mm diameter and 12 cm length, which was annealed at 200 °C for 3 hours before measurements were made.

The Gruneisen and Goens (1924) measurements were taken with both orientations, parallel and perpendicular to the hexagonal axis. No information is given on shape or heat treatment of the sample. The samples were of high purity.

Tuyn and Onnes (1926) measured resistances of a wire specimen with impurity content < 0.01%. The specimen was heated for a period of time in the temperature range of 150 to 200 °C.

Tuyn (1929) used the same specimen described by Tuyn and Onnes (1926), designated Zn-1921-I. Another specimen was prepared in the same way, designated Zn-1921-II.

Meissner and Voigt (1930) used Kahlbaum zinc, assuming high purity, to make the single crystal samples. The dimensions were 0.7 mm in diameter and 55 mm long for Zn ∥ , and 1.3 mm diameter and 55 mm long for Zn ⊥.

Goens and Gruneisen (1932) measured resistivities of pure, undeformed single crystal rods. In the actual measurements, the samples' crystal axes were at 3.6°, 4.9°, 8.7°, and 79.7° to the current direction. The values in the table are resistivities extrapolated to the parallel and perpendicular orientations.

Bridgman (1933) determined the effect of pressure on resistivity. The values in the table, however, are his measurements at zero pressure. The crystals were made from spectroscopically pure zinc which was filtered in the molten condition and thoroughly outgassed in a diffusion pump vacuum. The single crystal samples were 1 mm diameter rods, approximately 2.5 cm long, which were cast in pyrex tubing by slow lowering out of a furnace. The measurements were made perpendicular and parallel to the hexagonal axis.

Aleksandrov (1963) and Aleksandrov and D'Yakov (1963) report measurements on single crystals, 4 mm in diameter and 200 mm in length, which were grown from seeds in graphite forms by zone melting. The specimens were annealed 1 to 2 days at 100 to 120 °C prior to measuring resistivities.

Collings, Hedgcock and Muir (1963) measured resistances for pure zinc. No details are given on preparation of sample.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Pawlek and Rogalla (1966) used 99.9959% pure zinc wires with 2 mm diameters which were annealed one hour in argon at 200°C prior to measurements.

Wilkes, Powell, and De Witt (1968) used a 99.999% pure rod which was 1.207 cm in diameter and 10.16 cm long. No further information is given for the sample.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

Schimank (1914)

Temp. K	R/R_{273}*
20.2	0.0154
82.0	0.2185
195.3	0.6982
273.09	1.0

* These values were not plotted on the Electrical Resistivity of Zinc graph.

Holborn (1919)

Temp. K	R/R_{273}*
80.5	0.2180
194.8	0.6856
273	1.0

* These values were not plotted on the Electrical Resistivity of Zinc graph.

Gruneisen and Goens (1924)

Temp. K	ρ/ρ_{273}**	
	Zn ⊥	Zn ∥
20.3_7	0.0074_1	0.0075_7
78.6	-	0.215
81.3	0.207	-
82.0	0.211	0.227
84.0	-	0.236_5
89.7	0.246	0.260
130	0.409	0.418
195	0.684	0.681
273 *	1.0	1.0

* For Zn ⊥, $\rho_{273} = 5.39 \times 10^{-6}$ ohm cm;
Zn ∥, $\rho_{273} = 5.83 \times 10^{-6}$ ohm cm.
** These values were not plotted on the Electrical Resistivity of Zinc graph.

Meissner (1926)
(The Z. Physik article)

Temp. K	R/R_{273}		
	Zn ∥	Zn ⊥	Zn (poly)
1.67	0.00181_3	0.00316	-
4.14	-	-	0.00491
4.20	-	0.00317	-
4.21	0.00183_3	-	-
20.42	-	-	0.01138
20.45	0.00873_6	0.00905	-
82.48	-	-	0.2254
83.74	0.2351	0.2195	-
273.20	1.0	1.0	1.0

Meissner (1926) (the Z. Instrumentenk. article)				
Temp. K	Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273}*	
	Zn $\parallel$	Zn $\perp$	Zn $\parallel$	Zn $\perp$
22.2	0.0788	0.0524	0.0135	0.00974
89.7	1.52	1.33	0.261	0.247
273.2	5.82	5.38	1.0	1.0

* These values were not plotted on the Electrical Resistivity of Zinc graph.

Tuyn and Onnes (1926)	
Temp. K	R/R_{273}
1.40	0.0065_6
3.38	0.0065_6
4.22	0.0065_6
273.09	1.0

Tuyn (1929)		
Temp. K	R/R_{273}	
	Zn-1921-I*	Zn-1921-II
1.40	0.00378	-
4.22	0.00378	-
14.24	0.00838	0.00738
16.45	0.00984	0.00875
17.99	0.01119	0.01006
20.48_5	0.01383	0.01278
57.83	0.12552	-
57.86	-	0.12505
66.10	0.15901	0.15838
72.71	0.18643	0.18581
81.04	0.22136	0.22078
88.72	0.25367	0.25300

* The values for Zn-1921-I were plotted on the Electrical Resistivity of Zinc graph.

Meissner and Voigt (1930)		
Temp. K	R/R_{273}	
	Zn $\parallel$ **	Zn $\perp$
1.67	0.00181_3	0.00174_0
4.21	0.00183_3	0.00175_2
20.42	-	0.00750
20.45	0.00873_6	-
82.47	-	0.2141
83.73	0.2351	-
273.16*	1.0	1.0

* For Zn $\parallel$, $\rho_{273} = 5.99 \times 10^{-6}$ ohm cm;
Zn $\perp$, $\rho_{273} = 5.65 \times 10^{-6}$ ohm cm.
These are calculated values.

** The Zn $\parallel$ values were not plotted because they are identical to the Meissner (1926) (Z. Physik) values.

Goens and Gruneisen (1932)				
Temp. K	Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273} **	
	Zn $\parallel$	Zn $\perp$	Zn $\parallel$	Zn $\perp$
21	0.044_9	0.0366	0.00806	0.00678
83	1.29_3	1.15_5	0.232	0.214
273	5.57 *	5.4 *	1.0	1.0
293	6.05	5.83		

* Interpolated values.
** These values were not plotted on the Electrical Resistivity of Zinc graph.

Bridgman (1933)

Temp. K	ρ/ρ_{273}**	
	Zn $\parallel$	Zn $\perp$
90.35	0.3047	0.2459
194.85	0.6807	0.6794
273.15*	1.0	1.0

* For Zn $\parallel$, $\rho_{273} = 5.589 \times 10^{-6}$ ohm cm;
Zn $\perp$, $\rho_{273} = 5.386 \times 10^{-6}$ ohm cm.
** These values were not plotted on the Electrical Resistivity of Zinc graph.

Aleksandrov (1963) and Aleksandrov and D'Yakov (1963)

Temp. K	ρ/ρ_{293}*		Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273}	
	Zn $\parallel$	Zn $\perp$	Zn $\parallel$	Zn $\perp$	Zn $\parallel$	Zn $\perp$
1.6	$\sim 1.1 \times 10^{-5}$	$\sim 1.1 \times 10^{-5}$	0.000068	0.000064	0.0000119	0.0000118
4.22	1.4×10^{-5}	1.6×10^{-5}	0.000086	0.0000935	0.0000151	0.0000173
14	1.13×10^{-3}	1.08×10^{-3}	0.00695	0.0063	0.00122	0.00117
20.4	6×10^{-3}	4.96×10^{-3}	0.0369	0.0289	0.00647	0.00535
58	0.120	0.103	0.738	0.70	0.129	0.130
63.5	0.137	0.121	0.842	0.80	0.148	0.148
77.4	0.195	0.180	1.20	1.05	0.211	0.194
90.31	0.238	0.227	1.465	1.32	0.257	0.244
111.6	0.325	0.318	2.0	1.855	0.351	0.344
273 **	-	-	5.7	5.4	1.0	1.0

* For Zn $\parallel$, $\rho_{293} = 6.15 \times 10^{-6}$ ohm cm;
Zn $\perp$, $\rho_{293} = 5.83 \times 10^{-6}$ ohm cm.
** Interpolated values for this temperature.

Collings, Hedgcock and Muir (1963)
(read from graph)

Temp. K	R/R_{273}*
1	0.001
5	0.002
10	0.002
20	0.010
30	0.029
40	0.055
50	0.085
57	0.107

* These values have not been plotted on the Electrical Resistivity of Zinc graph.

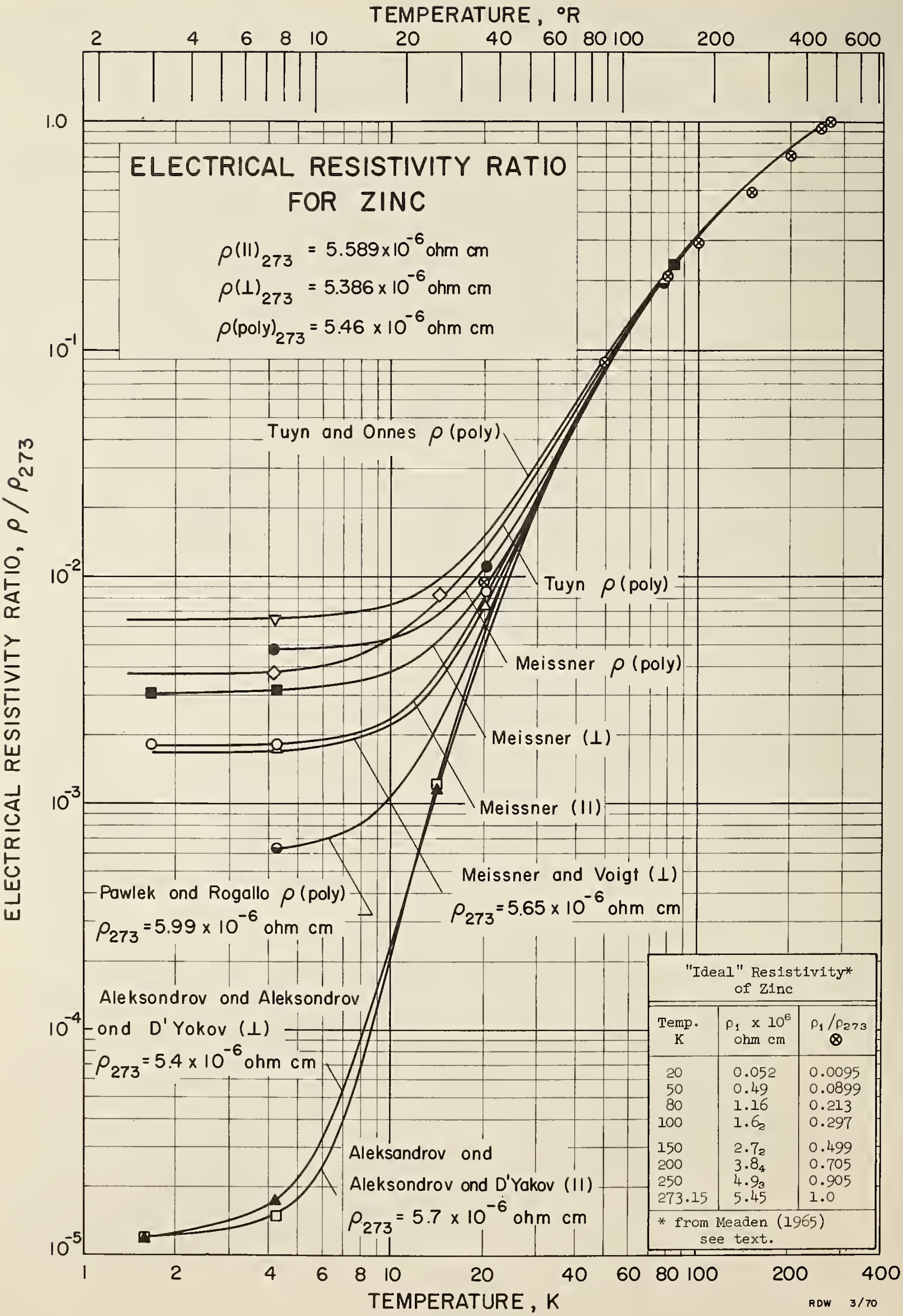
Pawlek and Rogalla (1966)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4.2	0.00381	0.000636
77	1.16	0.194
195	4.01	0.669
273	5.99	1.0

Wilkes, Powell and DeWitt (1969)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
77.8	1.187	0.213
198.7	3.745	0.674
273.2	5.56	1.0
300.9	6.129	

* These values were not plotted on the Electrical Resistivity of Zinc graph.



"Ideal" Resistivity* of Zinc

Temp. K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20	0.052	0.0095
50	0.49	0.0899
80	1.16	0.213
100	1.6_2	0.297
150	2.7_2	0.499
200	3.8_4	0.705
250	4.9_3	0.905
273.15	5.45	1.0

* from Meaden (1965) see text.

ELECTRICAL RESISTIVITY OF ZIRCONIUM, Zr
(Atomic Number 40)

(page 1 of 7)

Sources of Data:

Adenstedt, H. K., "Physical, thermal and electrical properties of hafnium and high purity zirconium," Trans. Amer. Soc. Metals 44, 949-73 (1952).

Berlincourt, T. G., "Hall effect resistivity and magnetoresistivity of Th, U, Zr, Ti, and Nb," Phys. Rev. 114, No. 4, 969-77 (1959).

Clausing, P., "Over den electrischen weerstand van zirkoon," (The electrical resistance of zirconium), Physica 4, 372-5 (1924).

Clausing, P., and Moubis, G., "Over den electrischen weerstandvan titaan en zirkoon bij lage temperaturen," (The electrical resistance of titanium and zirconium at low temperatures), Physica 7, No. 7, 245-50 (1927).

Clinard, F. W., and Kempter, C. P., "Low-temperature electrical properties of some transition metals and transition-metal carbides," J. Less-Common Metals 15, No. 1, 59-73 (May 1968).

De Haas, W. J., and Voogd, J., "The change of the electric resistance of pure hafnium and zirconium between 1.3 K and 90 K," Communs. Phys. Lab. Univ. Leiden No. 194C (1928), Transl. of Verslag Gewone Vergader. Afdeel. Natuurk. Koninkl. Ned. Akad. Wetenschap. 37, 872-4 (Nov 1928).

Kemp, W. R., Klemens, P. G., and White, G. K., "Thermal and electrical conductivities of iron, nickel, titanium, and zirconium at low temperatures," Australian J. Phys. 9, 180-88 (Jun 1956).

Mc Lennan, J. C., Howlett, L. E., and Wilhelm, J. O., "On the electrical conductivity of certain metals at low temperatures," Trans. Roy. Soc. Can. Sec. III, 23, Part I, 287-306 (Jan 1929).

Meaden, G. T., Electrical Resistance of Metals, Plenum Press, New York (1965) 218 p.

Meissner, W., and Voigt, B., "Messungen mit hilfe von flussigem helium. XI. Widerstand der reinen metalle in tiefen temperaturen," (Measurements using liquid helium. XI. Resistance of pure metals at low temperatures), Ann. Physik 7, No. 5, 892-936 (1930).

Potter, H. H., "Electrical resistance and thermoelectric power of the transition metals," Proc. Phys. Soc. (London) 53, 695-705 (1941).

Renucci, L., Langeron, J. P., and Lehr, P., "Etude de la resistivite electrique du zirconium. Application a l'etude de la recristallisation du metal apres ecrouissage. Influence de la purete," (Electric resistivity of zirconium. Application to the study of the recrystallization of the metal after cold working. Influence of purity), Mem. Sci. Rec. Met. 58, 699-715 (1961).

Roberts, L. D., Sartain, C. C., and Dabbs, J. W. T., "Electrical resistance of high-purity zirconium below 300 K," Oak Ridge National Lab., Oak Ridge, Tenn., Progr. Rept. ORNL-1365 (June 1952).

White, G. K., and Woods, S. B., "Electrical and thermal resistivity of the transition elements at low temperatures," Phil. Trans. Roy. Soc. London A251 No. 995, 273-302 (1959).

Other References:

Bridgman, P. W., "The electric resistance to 30,000 kg/cm^2 of twenty nine metals and intermetallic compounds," Proc. Am. Acad. Arts Sci. 79, 149-79 (1951).

Bridgman, P. W., "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2," Proc. Am. Acad. Arts Sci. 81, No. 4, 169-251 (Mar 1952).

Brehm, C., and Lehr, P., "Influence de la deformation par traction du zirconium et du titane sur la resistivite residuelle et sur la densite de dislocations," (Effect of zirconium and titanium tensile deformation on the residual resistivity and dislocation density), Compt. Rend. Ser. C 265, No. 18, 974-6 (1967).

De Boer, J. H., and Fast, J. D., "Uber die darstellung der reinen metalle der titangruppe durch thermische zersetzung ihrer jodide. III. Hafnium," (Concerning the preparation of pure metals of the titanium group by thermal dissociation of their iodides. III. Hafnium), Z. Anorg. Allgem. Chem. 187, 193-208 (1930).

Fehlner, F. P., "Behavior of ultrathin zirconium films upon exposure to oxygen," J. Appl. Phys. 38, No. 5, 2223-31 (Apr 1967).

Finch, R. A., "Measurement of resistivity and heat capacity of metallic conductors," North American Aviation, Inc., Canoga Park, Calif., Rept. No. NAA-SR-MEMO-5819 (1960) 26 pp.

Renucci, L., Langeron, J-P., and Lehr, P., "Sur la conductibilite electrique a basse temperature du zirconium de zone fondue," (On electrical conductivity of zone melted zirconium at low temperatures), Compt. Rend. 249, No. 13, 1113-15 (Sept 1959).

Swanson, M. L., "Low temperature recovery of deformed zirconium," Can. J. Phys. 44, No. 12, 3241-57 (Dec 1966).

Swanson, M. L., Quenneville, A. F., and Schultz, H., "Stage 1 recovery of deformed zirconium," Appl. Phys. Letters 6, No. 3, 49-51 (Feb 1965).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data" and are listed as ratios of electrical resistivity with respect to the resistivity at the ice point temperature (ρ_{273}). When the actual values of ρ_{273} are not available for the samples used by the various investigators, a datum value reported by White and Woods (1959) ($\rho_{273} = 38.85 \times 10^{-6}$ ohm cm) is suggested for calculating values of electrical resistivity from these ratios. **It should also be noted that zirconium becomes superconducting at 0.56 K.**

In instances where data points were quite widely separated or areas where data did not exist, symbols were used to show the available data points so that the reader will know where arbitrary position or shape of the graph was made.

Brief descriptions of sample preparation, purity, etc. for each data source follow in chronological order.

The Clausing (1924) sample had a purity of 99.9%. No further information is given about the sample.

Clausing and Moubis (1927) made three sets of measurements on three wire samples; Zr 5 was 99.88% pure, Zr 6 and Zr 14 were both 99.97% pure. No further information is given about the samples.

De Haas and Voogd (1928) measured resistances of a "very pure" zirconium rod. The rod was, however, too irregularly formed to have its specific resistance determined. No further information is given about the sample.

Mc Lennan, Howlett, and Wilhelm (1929) used a polycrystalline wire which had been baked in vacuo at a high temperature for a number of hours. The purity was not stated.

Meissner and Voigt (1930) report resistance measurements on two zirconium samples. Zr 1 was a 99.69% pure polycrystalling wire with a 5 mm diameter. Zr 2 was a wire of unknown purity, which had been annealed in a vacuum for 2.5 hours at 500°C.

Potter (1941) gave no information on the purity or preparation of the sample.

Adenstedt (1952) used three samples in his resistivity measurements. Two had resistivities measured over a temperature range of 200 to 1000°C, and one had resistivities measured below 0°C. The latter sample was a 0.22 in. diameter rod of 10 in. length which had been cold-swaged, machined and vacuum annealed at 700°C for two hours. The purity was stated to be 99.9% pure zirconium.

The Roberts, et al. (1952) measurements were made with a crystal bar of high purity. One set of values are for the unannealed sample and another set for the same sample after it had been pickled in an aqueous solution of nitric and hydrofluoric acids and then annealed in a vacuum for 40 min. at 796 ± 14°C.

Kemp, Klemens and White (1956) measured resistivities of a 99.99% pure zirconium rod of 3 mm diameter, which had been annealed at 950°C for five hours in vacuo.

Berlincourt (1959) had three crystal bar samples of 99.88% pure zirconium which had been machined from bulk material to a thickness of 0.0378 cm. No mention is made of heat treatment.

White and Woods (1959) present tabular values of ideal resistivity for a 99.95% pure zirconium sample of 0.6 mm diameter. The sample was arc cast, annealed 4 hours at 1100°C, swaged at room temperature, annealed for 15 min. at 1000°C and finally for 15 min. at 800°C in a vacuum of (1 to 2) x 10^{-6} mm Hg.

Renucci, Langeron and Lehr (1961) measured resistivities of three samples. Zr 1 and Zr 2 were prepared by thermal dissociation of ZrI_4 and had a purity of 99.85%. Zr 1 was recrystallized at 600°C for a 15 hour period whereas Zr 2 was used after cold-working with no heat treatment. Zr 3, resulting from magnesium thermal reduction of $ZrCl_4$, was 99.71% pure and had been recrystallized at 700°C for 15 hours.

The "ideal" resistivity values tabulated in the lower right-hand corner of the graph were taken from Meaden (1965). His book presents a comprehensive review of the literature dealing with experimental determinations of electrical resistivity together with a relatively concise account of the modern theory of the electrical resistance of metals and alloys.

Tables of Values of Electrical Resistivity

ρ = resistivity, (ohm cm); ρ_{273} = resistivity at 273 K, (ohm cm).
R = resistance, (ohm); R_{273} = resistance at 273 K, (ohm).

Clausing (1924)
(read from graph)

Temp. K	R/R_{273}
80	0.74
100	0.775
150	0.875
200	0.92
250	0.975
273	1.0

De Haas and Voogd (1928)

Temp. K	R/R_0
1.35	0.0383_6
3.63	0.0383_6
4.21	0.0383_2
14.17	0.0392_6
18.00	0.0403_9
20.32	0.0416_7
61.27	0.1318
78.19	0.1926
90.01	0.2379

Meissner and Voigt (1930)

Temp. K	ρ/ρ_{273}*	
	Zr 1	Zr 2
1.13	0.0388	-
1.23	-	0.108_9
1.36	0.0403	-
4.21	-	0.109_0
4.22	0.0421	-
20.45	-	0.1124
20.46	0.0443_6	-
77.61	0.1971	-
78.42	-	0.2648
83.57	0.2214	-
86.14	-	0.2924
88.19	0.2380	-
273.16	1.0	1.0

* For Zr 1, $\rho_{273} = 60 \times 10^{-6}$ ohm cm,
Zr 2, $\rho_{273} = 49 \times 10^{-6}$ ohm cm.

Clausing and Moubis (1927)

Temp. K	ρ/ρ_{273}*		
	Zr 5	Zr 6**	Zr 14
77.40	-	-	0.1777
78.16	0.2185	-	-
78.20	-	0.2264	-
90.20	-	0.2704	-
90.22	0.2626	-	-
144.8	-	0.4769	-
178.0	-	0.6084	-
217.6	-	0.7692	-
273.09	1.0	1.0	1.0

* For Zr 5, $\rho_{273} = 42.5 \times 10^{-6}$ ohm cm,
Zr 6, $\rho_{273} = 42.4 \times 10^{-6}$ ohm cm,
Zr 14, $\rho_{273} = 41.0 \times 10^{-6}$ ohm cm.

** Values for Zr 6 were plotted on the Electrical Resistivity of Zirconium graph.

Mc Lennan, Howlett, and Wilhelm (1929)

Temp. K	Resistance $R \times 10^4$ ohms	R/R_{273}
2.4	77.9	0.0722
4.2	78.1	0.0724
20.6	83.0	0.0769
84.0	305.	0.283
273.1	1079.	1.0

Potter (1941)

Temp. K	R/R_{273}**
20	0.0385
77	0.196
90	0.237
173	0.567
273*	1.0

* $\rho_{273} = 17.1 \times 10^{-6}$ ohm cm.
** These values were not plotted on the Electrical Resistivity of Zirconium graph.

Adenstedt (1952)	
Temp. K	ρ/ρ_{273}*
90	0.228
273	1.0

* $\rho_{273} = 39.6 \times 10^{-6}$ ohm cm.

Roberts, Sartain, and Dabbs (1952)				
unannealed crystal			pickled and annealed crystal	
Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}	Temp. K	R/R_{273}
4.2	2.14	0.051	14.01	0.02279
73.3	8.68	0.207	20.33	0.02514
273.2	42.0 *	1.0	68.52	0.14076
295.7	45.6	1.1	77.50	0.17356
			273.2	1.00

* Interpolated value

Kemp, Klemens and White (1956)		
Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
5	2	0.0445
15	2	0.0445
50	5	0.111
80	9	0.20
100	12	0.267
130	17	0.378
170	24	0.533
200	31	0.689
250	39	0.867
273	45	1.0

Berlincourt (1959)						
Temp. K	Resistivity $\rho \times 10^6$ ohm cm			ρ/ρ_{273}		
	Zr 1	Zr 2	Zr 3	Zr 1	Zr 2	Zr 3**
4.2	0.224	0.213	0.216	0.00605	0.00576	0.00584
77	6.11	6.08	6.08	0.165	0.164	0.164
273	37. *	37. *	37. *	1.0	1.0	1.0
298.6	42.6	-	-			
300.0	-	-	42.6			
300.1	-	42.6	-			

* Interpolated value
** The values for Zr 3 were plotted on the Electrical Resistivity of Zirconium graph.

White and Woods (1959)

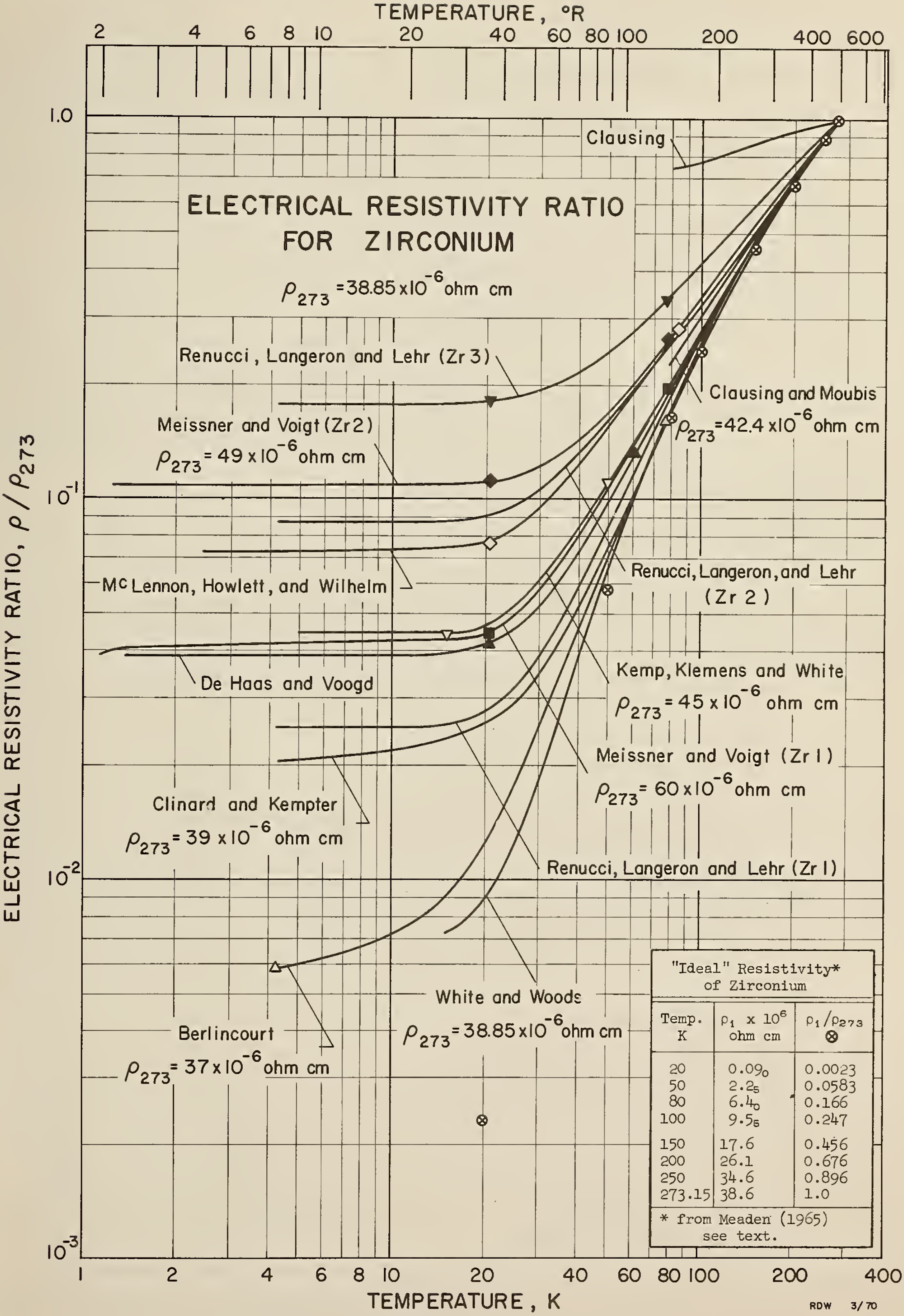
Temp. K	Ideal resistivity $\rho_i \times 10^6$ ohm cm	Resistivity $\rho = \rho_i + \rho_0$ where $\rho_0 = 0.25 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
15	0.02_5	0.28	0.00721
20	0.09_0	0.34	0.00875
25	0.23_5	0.49	0.0126
30	0.4_7	0.72	0.0185
40	1.2_0	1.45	0.0373
50	2.2_5	2.50	0.0644
60	3.5_0	3.75	0.0965
70	4.9_0	5.15	0.133
80	6.4_0	6.65	0.171
90	7.9_0	8.15	0.210
100	9.5_5	9.80	0.252
120	12.8	13.05	0.336
140	16.0	16.25	0.418
160	19.3	19.55	0.503
180	22.6	22.85	0.588
200	26.1	26.35	0.678
220	29.4	29.65	0.763
250	34.6	34.85	0.897
273	38.6	38.85	1.0

Renucci, Langeron and Lehr (1961)

Temp. K	R/R_{273}		
	Zr 1	Zr 2	Zr 3
4.2	0.025	0.0865	0.1785
14.0	0.0254	0.0870	0.1790
20.4	0.0278	0.0905	0.1815
77.4	0.182	0.2495	0.3460
273	1.0	1.0	1.0

Clinard and Kempter (1968)
(read from graph)

Temp. K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4.2	0.8	0.0205
20	1.0	0.0256
40	2.0	0.0513
50	3.5	0.0897
100	9.8	0.250
150	18.0	0.462
200	27.0	0.692
250	35.0	0.897
273	39.0	1.0



"Ideal" Resistivity* of Zirconium

Temp. K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20	0.09_0	0.0023
50	2.2_5	0.0583
80	6.4_0	0.166
100	9.5_5	0.247
150	17.6	0.456
200	26.1	0.676
250	34.6	0.896
273.15	38.6	1.0

* from Meaden (1965) see text.

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National ureau of Standards research and development in hysics, mathematics, chemistry, and engineering. omprehensive scientific papers give complete details the work, including laboratory data, experimental ocedures, and theoretical and mathematical analy- s. Illustrated with photographs, drawings, and arts.

blished in three sections, available separately:

Physics and Chemistry

pers of interest primarily to scientists working in ese fields. This section covers a broad range of ysical and chemical research, with major emphasis standards of physical measurement, fundamental nstants, and properties of matter. Issued six times ear. Annual subscription: Domestic, $9.50; for- n, $11.75*.

Mathematical Sciences

dies and compilations designed mainly for the thematician and theoretical physicist. Topics in thematical statistics, theory of experiment design, merical analysis, theoretical physics and chemis- ical design and programming of computers omputer systems. Short numerical tables. ued quarterly. Annual subscription: Domestic, 00; foreign, $6.25*.

Engineering and Instrumentation

porting results of interest chiefly to the engineer d the applied scientist. This section includes many the new developments in instrumentation resulting m the Bureau's work in physical measurement, ta processing, and development of test methods. will also cover some of the work in acoustics, plied mechanics, building research, and cryogenic gineering. Issued quarterly. Annual subscription: mestic, $5.00; foreign, $6.25*.

TECHNICAL NEWS BULLETIN

e best single source of information concerning the reau's research, developmental, cooperative and blication activities, this monthly publication is igned for the industry-oriented individual whose ily work involves intimate contact with science and hnology—*for engineers, chemists, physicists, re- rch managers, product-development managers, and npany executives.* Annual subscription: Domestic, 00; foreign, $4.00*.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitive data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

CLEARINGHOUSE

The Clearinghouse for Federal Scientific and Technical Information, operated by NBS, supplies unclassified information related to Government-generated science and technology in defense, space, atomic energy, and other national programs. For further information on Clearinghouse services, write:

Clearinghouse
U.S. Department of Commerce
Springfield, Virginia 22151

fference in price is due to extra cost of foreign mailing.

der NBS publications from:

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

U.S. DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20230

OFFICIAL BUSINESS

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE