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Survey of Electrical Resistivity Measurements on 16 Pure Metals In the Temperature Range 0 to 273° K

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SURVEY OF ELECTRICAL RESISTIVITY MEASUREMENTS ON 16 PURE METALS IN THE TEMPERATURE RANGE 0 TO 273°K

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L. A. Hall

Experimental electrical resistivity data for 16 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: electrical resistivity, compilation, low temperature, aluminum, beryllium, cobalt, copper, gold, indium, iron, lead, magnesium, molybdenum, nickel, niobium, platinum, silver, tantalum, tin.

1. INTRODUCTION

Many articles describing experimental measurements of electrical resistivity are found in the open literature. Many present results of straight-forward temperature-dependent resistivity measurements on wires or rods of high-purity metals. Some deal with the effects of irradiation, plastic deformation, magnetic fields, and alloying on resistivity, while others show the variation in resistivity due to unusual shape of the sample, e.g., whiskers or thin films. In the recent literature, superconductivity has also been 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, with the exception of the pressure-dependent measurements by Bridgman.

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

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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.

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-

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* "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.

dependent resistivity thus obtained is called the <u>ideal</u> or <u>intrinsic</u> 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

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

This rule is a good approximation for all engineering purposes.

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

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

where M is the atomic weight, C is a constant, and T is in °K. 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 $\rho_i \propto T^5$. 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 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 <u>anisotropic</u>, 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*

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

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. Some data for lead, however, do appear in the superconducting region. These measurements were made in the presence of a magnetic field, large enough to surpress the superconductivity.

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

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.

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 8 - 11, all experimental values of ρ_{273} have been tabulated for the 16 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, $\rho_T = \rho_0 + \rho_i$. The residual resistivity, ρ_0, 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).

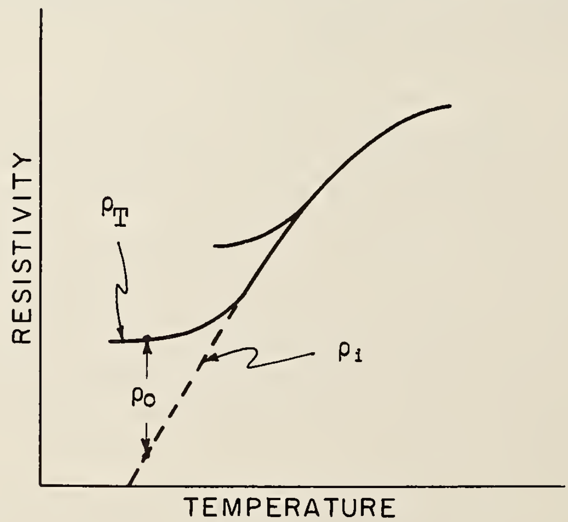

Figure 1. Relationship between ideal resistivity, ρ_i, residual resistivity, ρ_0, and measured resistivity at a given temperature, ρ_T.

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.

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
Aluminum	2.44 Broom(1952)	2.50	2.50	2.50	2.50 Grüneisen & Goens(1927) 2.6 Meissner & Voigt(1930) 2.53 Aleksandrov & D'Yakov(1962) 2.46 Pawlek & Rogalla(1966)	Holborn(1919) Justi & Scheffers(1938) Thomas & Mendoza(1952) Caron(1953) Maimoni(1963)	De Sorbo(1958) Powell et al. (1960) Ottensmeyer et al.(1964)
Beryllium $\rho_\perp$	3.12 Grüneisen & Erfling(1940)	3.12	3.12	3.12			
Beryllium $\rho_\parallel$	3.56 Erfling & Grüneisen(1942)	3.58	3.58	3.58	3.58 Grüneisen & Adenstedt (1938)		
Beryllium ρ_{poly}	2.7 Powell(1953) extrapolated value 2.74 Reich et al. (1963)	2.71	3.25	2.78	17.0 McLennan & Niven (1927) 5.88 Lewis (1929) 7.9 Meissner & Voigt (1930) 3.5 Denton(1947) 4.6, 4.3 White & Woods(1955)	Mac Donald & Mendelssohn (1950)	
Cobalt	5.24 White & Woods (1959)	5.15	5.2	5.2	5.94 Meissner & Voigt(1930) 5.57 Bridgman (1940)	Schimank(1914) Semenenko et al.(1963)	Radhakrishna & Nielsen(1965)
Copper	1.545 Powell et al. (1959)	1.55	1.55	1.55	1.55 Meissner(1915) 1.59 Broom(1952) 1.55 White & Woods(1959) 1.58 Domenicali & Christenson(1961) 1.58 Pawlek & Rogalla(1966) 1.546 Moore et al. (1967)	Holborn(1919) Henning(1921) Meissner & Voigt(1930) de Haas et al.(1934) Sekula(1959) Gniewek & Clark(1965)	Berman & MacDonald(1952)

Gold	2.02 White & Woods (1959)	2.01	2.04	2.04	2.06 Meissner(1915) 2.09 Domenicali & Christenson(1961)	Onnes & Clay(1907) Cath, Onnes & Burgers(1918) Holborn(1919) Meissner(1925) Meissner & Voigt(1930) de Haas & Van den Berg(1936) Van der Leeden(1940) Justi(1940) Van den Berg & Franklin (1958)	
Indium ρ_{poly}	8.00 Powell et al. (1962)	8.0	8.2	8.2	8.19 Meissner et al.(1932) 8.17 Olsen(1958) interpolated value 8.37 Aleksandrov & D'Yakov(1962) 8.21 Kaznoff et al.(1967)	Tuyn & Onnes(1923,1924) Meissner & Voigt(1930) Swenson(1955) Aleksandrov(1962) Orlova et al.(1963)	Protopopescu et al.(1962)
Indium $\rho_{\parallel}$		7.9					
Indium $\rho_{\perp}$		8.3					
Iron	8.7 Backlund(1961)	8.7	8.7	8.71	8.71, 9.11, 9.95 Grüneisen & Goens (1927) 9.11 Meissner & Voigt(1930) 9.57 Kannuluik(1931) 9.06 Broom(1952) 9.28 Kemp et al.(1956) 9.27 Kemp et al.(1959) interpolated value 8.80 White & Woods(1959) 8.94 Soffer et al.(1965) interpolated value	Holborn(1919) Semenenko & Sudovtsov(1962) Semenenko et al.(1962)	Kondorsky et al. (1958)
Lead	19.2 Aleksandrov & D'Yakov(1962)	19.3	19.3	19.3	19.26 Meissner(1915) 19.3 Grüneisen(1945) 19.9 Buckel & Hilsch(1954)	Onnes & Clay(1907) Holborn(1919) Onnes & Tuyn(1926) Meissner & Franz(1930) Meissner & Voigt(1930) Meissner(1932) Van der Leeden(1940) Van den Berg(1948)	

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(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
Magnesium	$\rho_{\parallel}$	3.48 Grüneisen(1945)	3.47	3.48	3.50		Goens & Schmid(1936)	
	$\rho_{\perp}$	4.18 Grüneisen(1945)	4.17	4.18	4.22		Goens & Schmid(1936)	
	ρ_{poly}	3.94 Gruneisen(1945)	3.94	3.94	3.94	5.0 Meissner & Voigt(1930)	Dewar & Fleming(1893) Yntema(1953)	Rosenberg(1954) Spohr & Webber (1957) Hein & Falge (1957)
Molybdenum		5.00 Holmwood & Glang(1965)	4.84	5.0	5.03	4.4 Blom(1919) 5.22 Meissner & Voigt(1930) 5.17, 5.25 Kannuluik(1931) 5.1 White & Woods(1959)	Holborn(1919) McLennan et al.(1929)	
Nickel		6.23 White & Woods (1959)	6.20	6.58	6.58	7.07 Meissner & Voigt(1930) 7.37 Broom(1952) 6.2 Kemp et al.(1956) interpolated value	Dewar & Fleming(1900, 1904) Sudovtsov & Semenenko(1957)	Kondorsky et al. (1958) Greig & Harrison(1965)
Niobium		13.96 White & Woods (1959)	13.5		23.3†	16.1 Reimann & Grant(1936) 13.96 White & Woods(1957)	Meissner et al.(1933)	

Platinum	9.60 White & Woods (1959)	9.59	9.81	9.81	9.81 Meissner(1915) 9.53*Meissner & Voigt(1930) 9.81 White & Woods(1957)	Cath et al.(1917) Holborn(1919) Onnes & Tuyn(1926) Van der Horst et al.(1929) Henning(1926) Meissner & Grassmann(1933) de Haas & de Boer(1933-1934) Hoge & Brickwedde(1939) Van der Leeden(1940)	Powell et al. (1967)
Silver	1.48 White & Woods (1959)	1.47	1.50	1.50	1.48 Meissner & Voigt(1930) 1.51 Kannuluik(1931) 1.48 Gerritsen & Linde (1956) 1.50 Pawlek & Rogalla(1966)	Onnes & Clay(1908) Holborn(1919) de Haas & Van den Berg(1936) Van der Leeden(1940)	
Tantalum	12.3 White & Woods (1959)	12.1	12.4	12.4	15.2 Meissner & Voigt(1930) 12.4 Burgers & Basart(1934) 12.41 Cox (1943)	Holborn(1919) McLennan et al.(1929)	
Tin ρ_{poly}	10.05 Aleksandrov & D'Yakov(1963)	10.1	10.1	10.1	11.15 Jaeger & Diesselhorst (1900) 15.0 Kunzler & Renton(1957)	Onnes & Tuyn(1923) Meissner(1925) Van der Leeden(1940)	
Tin $\rho_{\parallel}$	13.08 Aleksandrov & D'Yakov(1963)	13.08	13.13	13.08	13.08 Bridgman(1933)		
Tin $\rho_{\perp}$	9.01 Aleksandrov & D'Yakov(1963)	9.09	9.05	9.09	9.09 Bridgman(1933)		

* This value is quite a bit lower than the accepted value.

† at 303°K.

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

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

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5. ELECTRICAL RESISTIVITY DATA SHEETS

CRYOGENIC DATA MEMORANDUM

ELECTRICAL RESISTIVITY OF ALUMINUM, Al
(Atomic Number 13)

Sources of Data:

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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).

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 a datum temperature of 273°K. When the actual values of ρ_{273} are not available for the samples used by the investigators, a datum value reported by Broom (1952) ($\rho_{273} = 2.44 \times 10^{-6}$ ohm cm) is suggested for calculating values of electrical resistivity from the ratios. These curves should not be extrapolated to lower temperatures since aluminum becomes superconducting at 1.175°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.

The values listed in the Landolt-Börnstein tables are those reported by Grüneisen and Goens; Holborn (1919); Justi and Scheffers; and Meissner and Voigt; and Thomas and Mendoza, while those values listed by the International Critical Tables are from Holborn (1902, 1919). These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The samples used by Holborn are reported in Landolt-Börnstein as polycrystalline with 0.4% impurities of unknown composition. The Holborn sample was annealed at 250°C. The value of ρ_{273} to be used with Holborn data in calculating values of electrical resistivity is $\rho_{273} = 2.53 \times 10^{-6}$ ohm cm. Grüneisen and Goens are reported to have used a polycrystalline sample with a small amount of impurities present. Their ρ_{273} value was 2.50×10^{-6} ohm cm. The sample used by Meissner and Voigt is reported as a polycrystalline sample with undetermined impurities, which had been annealed at 300°C for 2.5 hours.

A single crystal with a small amount of impurities present is reported as the sample used by Justi and Scheffers. The sample used by Thomas and Mendoza was a polycrystalline sample with 0.005% impurities of unknown composition which had been annealed at 300°C for two hours in vacuo. No other pertinent information was presented about any of the samples from the above experimenters.

Broom (1952) measured resistivities of wire samples at the annealing temperatures and the effect of deformation on the resistivity at the two higher temperatures, 0 and 100°C. His attempts to measure effects of deformation on resistivity at lower temperatures were unsuccessful because of repeated fractures of the wire between the surface of the refrigerant and the chuck. His aluminum was 99.9965% pure.

Bridgman (1952) studied pressure effects on electrical resistivity at room temperature. The results are reported as a ratio of the resistivity at the given pressure to the resistivity at one atmosphere here. His sample was annealed in vacuum to 400°C. The purity of the sample is not given.

The samples used by Caron (1953) were 99.99 and 99.998% pure. He reported his results as the ratio R_{290}/R. As Caron did not give a value of R_{290}, the value of $\rho_{293} = 2.75 \times 10^{-6}$ ohm cm and $\rho_{273} = 2.53 \times 10^{-6}$ ohm cm from Aleksandrov and D'Yakov (1963) were used in determining the ratio R/R_{273}.

The sample of very pure aluminum, annealed at 550°C and then cooled at rates of 2 - 3°C/min., was used by De Sorbo (1958) in his initial resistivity measurements. He then studied the effects of rapid quenching on the resistivity of the specimen.

The 3.66 mm diameter rod used by Powell et al. (1960) was initially 99.995% pure; however, the residual electrical resistivity was not as low as one would expect from a crystal of that purity. This single crystal rod was annealed in vacuum at about 400°C for two hours.

In Maimoni (1962), data are tabulated for the resistance of eight specimens in the temperature range 2 to 26°K. Data for the specimen exhibiting the largest $R_{300}/R_{4.2}$ value (6,630) are given in the table below. This specimen had 1 mm square cross-section, and was machined from an ingot of 99.9999% pure 'zone-refined' aluminum. It was annealed about 100 hours at 400°C, then stored for one week at room temperature before measurements were made. No value is given for the residual resistance. These values do not appear on the Electrical Resistivity of Aluminum graph.

A cylindrical single crystal sample of 99.9998% purity was used by Aleksandrov and D'Yakov (1962) in their measurements in the temperature range 0 to 273°K. In the lower temperature range (<4.2°K) the error in a single measurement amounted to 6 - 7%. All samples were annealed 1.5 to 2 days in air at 300°C. The residual resistivity was $\rho_0 \simeq 10^{-10}$ ohm cm.

Measurements were made by Ottensmeyer, et al. (1964) on 99.995% pure rods before and after tensile strain. Their graph shows the effect of strain on the resistivity.

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.

The wire sample used by Pawlek and Rogalla (1966) was 99.999% pure aluminum which had been annealed at 400°C for one hour.

Stevenson (1967) studied the effects of strain and purity on resistance and magnetoresistance. He used aluminum wire of 59 and 69 purity which had received extensive deformation in the wire drawing process and further deformation when wound on mandrels of 1/2-inch diameter in making the samples for experiment. The mounted samples were annealed at 150°C for 4 hours. The data can be fitted to 35°K, with a maximum deviation of 6% by $\rho - \rho_0 = 7.5 \times 10^{-14}\ T^3 + 7.6 \times 10^{-17}\ T^5$ ohm cm. Below 20°K the 69 purity sample showed a $T^{2.8}$ temperature variation, and the 59 sample a $T^{3.1}$ variation. Between 20 and 35°K, they showed $T^{4.1}$ and $T^{4.4}$ variations respectively.

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 (1902, 1919)					
Temp. °C	$100R/R_{273}$	Temp. °C	$100R/R_{273}$	Temp. °C	$100R/R_{273}$
- 78.3*	64.80*	-140	37.7	-200	12.0
- 80	64.1	-160	28.9	-220	7.1
-100	55.2	-180	20.2	-240	4.9
-120	46.4	-191.9*	14.85*	-253*	4.27*
		-192.9*	14.49*		
* Observed values. All other values have been interpolated.					

Justi and Scheffers (1938)		Meissner and Voigt (1930)		Thomas and Mendoza (1952)	
Temp. °K	ρ/ρ_{273}	Temp.* °K	R/R_{273}	Temp. °K	R/R_{273}
14	0.0014	1.32†	0.0067	4	0.0026
20	0.0018	4.21	0.0065		
		20.44	0.0075		
		77.73	0.1008		
		273.16†	1.0000		

* The second decimal place of the temperature values is somewhat in doubt.
† ρ_{273} = 2.60 x 10^{-6} ohm cm; $\rho_{1.32}$ = 0.0174 x 10^{-6} ohm cm.

Broom (1952)			
Temp. °K	Temp. °C	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
90	-183	0.352	0.144
194.5	- 78.5	1.55	0.635
273	0	2.44	1.00
373	100	3.59	1.47

Caron (1953)			
[Using ρ_{293} = 2.75 x 10^{-6} ohm cm (Aleksandrov, 1962) and ρ_{273} = 2.53 x 10^{-6} ohm cm (Aleksandrov & D'Yakov, 1963)			
Temp. °K	Resistance Ratio		
	R_{290}/R	R/R_{290}	R/R_{273}
	Purity - 99.998%		
78	12.35	0.08097	0.089
63	26.0	0.0385	0.042
20.4	1050	0.00095	0.00105
14.0	1530	0.00065	0.00072

De Sorbo (1958) (read from graph)		
Temp. °K	$\rho \times 10^9$ ohm cm	ρ/ρ_{273}
2	2.94	0.0012
4	2.95	0.0012
14	3.5	0.0014
16	3.77	0.0015
18	4.06	0.0017
20	4.4	0 0018

Bridgman (1952)	
(Room Temperature) (Data compared with the resistance at one atmosphere taken as unity.)	
Pressure kg/cm²	Resistance Ratio R/R_0
0	1.000
10000	0.959
20000	0.923
30000	0.892
40000	0.865
50000	0.843
60000	0.824
70000	0.808
80000	0.794
90000	0.782
100000	0.770

Powell, Hall, and Roder (1960) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4	0.025	0.010
6	0.025	0.010
10	0.0255	0.010
15	0.026	0.011
20	0.0285	0.017
30	0.041	0.019
40	0.064	0.026
60	0.135	0.055
70	0.185	0.076
75	0.22	0.090

Maimoni (1962)			
Temp. °K	$\frac{R - R^o}{R_{300} - R^o}$ *	Temp. °K	$\frac{R - R^o}{R_{300} - R^o}$ *
		11	5.51×10^{-5}
2	1.0×10^{-7}	12	6.84×10^{-5}
3	8.0×10^{-7}	13	8.38×10^{-5}
4	2.7×10^{-6}	14	1.01×10^{-4}
5	6.0×10^{-6}	15	1.19×10^{-4}
6	1.13×10^{-5}	16	1.43×10^{-4}
7	1.70×10^{-5}	17	1.69×10^{-4}
8	2.46×10^{-5}	18	2.01×10^{-4}
9	3.32×10^{-5}	19	2.39×10^{-4}
10	4.33×10^{-5}	20	2.86×10^{-4}

* R^o = residual resistance. These values are not plotted on the Electrical Resistivity of Aluminum graph.

Aleksandrov and D'Yakov (1962)					
Temp. °K	R/R_{293}^*	R/R_{273}^*	Temp. °K	R/R_{293}^*	R/R_{273}^*
1.65	3.4×10^{-5}	3.7×10^{-5}	58	0.032	0.035
3.4	3.4×10^{-5}	3.7×10^{-5}	63.5	0.043	0.047
3.7	3.4×10^{-5}	3.7×10^{-5}	77.4	0.086	0.093
4.22	3.4×10^{-5}	3.7×10^{-5}	90.31	0.129	0.140
14	9.6×10^{-5}	10.4×10^{-5}	111.6	0.226	0.246
20.4	2.7×10^{-4}	2.9×10^{-4}	273	0.92	1.0

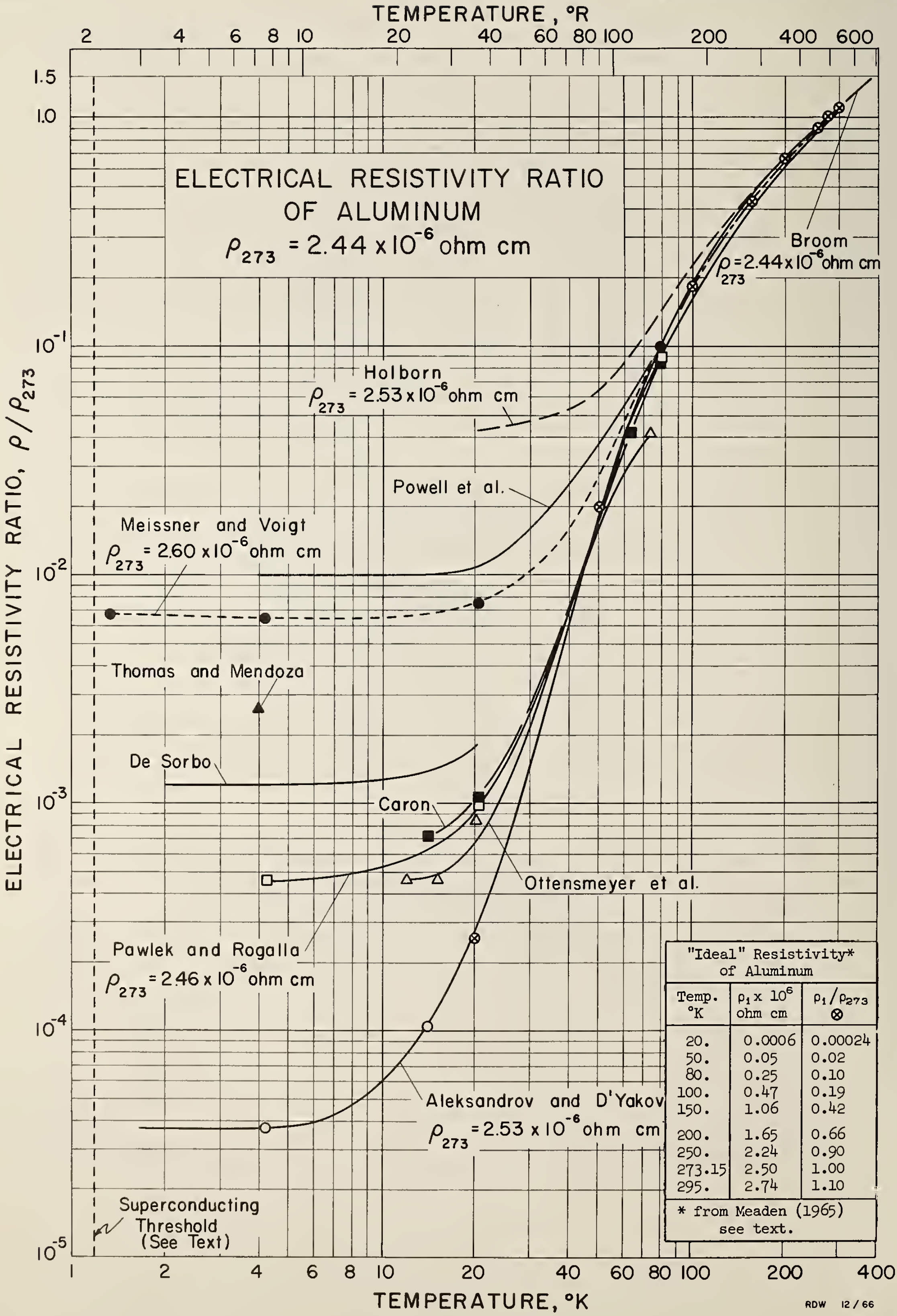
* $\rho_{293} = 2.75 \times 10^{-6}$ ohm cm, from Aleksandrov (1962)
$\rho_{273} = 2.53 \times 10^{-6}$ ohm cm.

Ottensmeyer, Bratsberg, Graham, and Hollis Hallet (1964) (read from graph - unstrained specimen)				
Temp. °K	ρ_{ideal}/ρ_{70}	"ideal resistivity" $\rho_i \times 10^9$ ohm cm (using $\rho_{70} = 10^{-7}$ ohm cm)	$\rho \times 10^9$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 10^{-9}$ ohm cm)	ρ/ρ_{273}
12	0.00151	0.151	1.15	0.00047
15	0.00161	0.161	1.16	0.00048
20	0.011	1.1	2.1	0.00086
30	0.05	5	6	0.00246
41	0.18	18	19	0.00779
50	0.4	40	41	0.01680
60	0.7	70	71	0.02910
71	1.0	100	101	0.04139

Pawlek and Rogalla (1966)		
Temp. °K	Resistivity $\rho \times 10^9$ ohm cm	ρ/ρ_{273}
4.2	1.11	0.000451
20.4	2.38	0.000967
77	221	0.0898
195	1440	0.586
273	2460	1.000

Stevenson (1967) (read from graph)		
Temp. °K	Resistivity* $\rho \times 10^9$ ohm cm 99.999%	99.9999%
4.2	5.74	2.27
5.	5.8	2.3
10.	5.8	2.4
15.	6.1	2.7
20.	6.7	3.2
25.	7.7	4.2
30.	10.1	6.2
34.	14.5	9.3
300.	2512.	2349.

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



"Ideal" Resistivity* of Aluminum

Temp. °K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20.	0.0006	0.00024
50.	0.05	0.02
80.	0.25	0.10
100.	0.47	0.19
150.	1.06	0.42
200.	1.65	0.66
250.	2.24	0.90
273.15	2.50	1.00
295.	2.74	1.10

* from Meaden (1965) see text.

ELECTRICAL RESISTIVITY OF BERYLLIUM, Be
(Atomic Number 4)

Sources of Data:

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Other References:

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Dyakov, I. G., Papirov, I. I., and Tikhinskiy, G. F. "Residual Electrical Resistance of Beryllium" Phys. Metals Metallog. 19, No. 5, 135-6 (1966), transl. of Fiz. Metal. i Metalloved. 19, No. 5, 788-90 (1965).

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Lillie, D. W., "The physical and mechanical properties of beryllium metal," The Metal Beryllium, Chapt. 6, 304-27 (1955).

Marder, A. R., "Beryllium, Effect of Ultra-High Pressure on Resistance," Science 142, No. 3593, 664 (Nov 1963).

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 273.15°K (ρ_{273}). The ρ_{273} value used by each investigator is listed in the tables and on the graph.

Since beryllium is an anisotropic metal, resistivity values will vary according to the relation of the hexagonal c crystal axis to the direction of the resistivity measurements. Grüneisen and co-workers are the only investigators who have made measurements on single crystals. They report

$$\rho(\parallel)_{273} = 3.56 \times 10^{-6} \text{ ohm cm and } \rho(\perp)_{273} = 3.12 \times 10^{-6} \text{ ohm cm.}$$

The lowest values of ρ_{273} for polycrystalline beryllium were reported by Reich, et al. and Powell. They reported

$$\rho(\text{poly})_{273} = 2.7 \times 10^{-6} \text{ ohm cm.}$$

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.

The measurements by McLennan and Niven (1927) were made on thin sheets of beryllium. No information is given on purity or heat treatment of the sample.

Lewis (1929) used a rod of cross-sectional area 0.792 cm^2 made from 99.5% pure beryllium in his measurements. He found that the amount of heat treatment greatly affected the resistivity and that the best results were obtained after the sample had been slowly heated over a period of 24 hours to about 700°C and held there for 12 hours and then cooled slowly to room temperature.

The Meissner and Voigt (1930) sample was a rod with a length of 1.5 cm and hexagonal cross-section 0.18 x 0.15 cm. The 98% pure sample was electrolytically prepared.

Grüneisen and Adenstedt (1938) measured resistivity of single crystals $Be_{\parallel}1$ and $Be_{\parallel}2$ in a direction parallel to the hexagonal c axis. The quality of crystal structure and purity of $Be_{\parallel}1$ were not as high as those of $Be_{\parallel}2$; therefore the values for $Be_{\parallel}1$ were not tabulated. The density of $Be_{\parallel}2$ was 1.84. The length was 1.55 cm and cross-section area was 0.00648 cm^2. The values for $Be_{\parallel}2$ in the tables below were taken with zero magnetic field.

The Grüneisen and Erfling (1940) measurements were made with single crystals $Be_{\perp}3$, $Be_{\perp}4$, and $Be_{\perp}8$ in a direction perpendicular to the hexagonal c axis (at 12°, 2°, and 30° angles to the secondary axis). Crystal sizes are: for $Be_{\perp}4$, ℓ_1 = 0.91 cm and ℓ_2 = 0.83 cm; and for $Be_{\perp}8$, ℓ_1 = 1.40 cm and ℓ_2 = 0.94 cm. $Be_{\perp}3$ dimensions were not given. The values in the tables below were taken with zero magnetic field. Their results show that deviation from the secondary axis has little effect on the resistivity.

Erfling and Grüneisen (1942) made measurements on single crystals $Be_{||}$ 2 and $Be_{||}$ 6 in a direction parallel to the hexagonal c axis. Crystal sizes are: for $Be_{||}$ 2, ℓ_1 = 0.55 cm and ℓ_2 = 0.45 cm; and for $Be_{||}$ 6, ℓ_1 = 0.57cm, ℓ_2 = 0.33cm. $Be_{||}$ 2 is the same sample used in the Grüneisen and Adenstedt (1938) determinations with a change in mounting. $Be_{||}$ 6 sample is a six sided prism of very regular cross-section and of somewhat higher purity than $Be_{||}$ 2. The values in the tables below were taken with zero magnetic field.

Powell (1953) in a literature review of experimental electrical resistivity studies cites the Denton (1947) measurements on rods 3.5 cm long and 0.3 cm diameter from a block of American G.E.C. sintered beryllium. The values in the tables below were made on the samples after a 715°C heat treatment.

The analytical purities of the samples used by MacDonald and Mendelssohn (1950) were not available but they were stated to be of comparatively high purity. The samples were in the form of thin strips. No mention is made of heat treatment.

Powell's (1953) resistivity measurements on beryllium were made on a bar 1.884 cm long by 0.865 cm diameter with a density of 1.84. This specimen was subsequently heated in a vacuum for 1 hour at 700°C and furnace cooled. The original material was from Brush Beryllium Company's crude reactor product. No chemical analysis was made on the sample. The value for ρ_{293} is 3.2×10^{-6} ohm cm.

The specimens used by White and Woods (1955), Be 1 and Be 2, were sintered polycrystalline rods (5 mm and 4 mm diameters) with approximately 2% and 0.1% impurities, respectively. Up to a temperature of about 130°K, the resistance of the two specimens may be represented by

$$\rho = (\rho_0 + 6.4 \times 10^{-8}\ T^{3.2}) \times 10^{-6} \text{ ohm cm.}$$

Reich, et al. (1963) made measurements on polycrystalline beryllium wire which was annealed at 800°C for one hour in a vacuum. The beryllium was electrolytically prepared and the analysis before wiredrawing showed ~ 99.8% pure beryllium. The specimen had a fine grain structure very close to the direction [1010]. ρ_0 for this sample was 0.033×10^{-6} ohm cm.

Reich (1965) studied the influence of impurities on the resistivity of polycrystalline beryllium wires at 4.2°K. In his article the type and amount of each impurity are given. His results are presented in the table below.

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)

McLennan and Niven (1927)	
Temp. °K	Specific Resistance* micro ohm
4.2	13.6
20.6	13.6
81	13.7
273	17.0**
293	17.6

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

** Interpolated value.

Lewis (1929)			
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
-189	84.15	1.50	0.255
- 77	196.15	3.22	0.548
0	273.15	5.88	1.00
+ 21	294.15	6.45	1.10
+ 25	298.15	6.50	1.11

Meissner and Voigt (1930)	
Temp. °K	ρ/ρ_{273} *
273.16	1.00
81.73	0.3229
20.44	0.3075
2.38	0.3075
1.35	0.3077

* $\rho_{273} = 7.9 \times 10^{-6}$ ohm cm.

Grüneisen and Adenstedt (1938)			
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
		$Be_{\parallel} 2$	$Be_{\parallel} 2$
-252.82	20.33	0.00458	0.00128
-194.13	79.02	0.0454	0.01268
0.	273.15	3.58	1.00

Grüneisen and Erfling (1940)							
Temp. °K	Temp. °C	Resistivity $\rho \times 10^6$ ohm cm			ρ/ρ_{273}		
		$Be_{\perp} 3$	$Be_{\perp} 4$	$Be_{\perp} 8$	$Be_{\perp} 3$ *	$Be_{\perp} 4$	$Be_{\perp} 8$
273.15	0	3.12	3.13	3.12	1.00	1.00	1.00
90.29	-182.86	—	0.0868	—	—	0.02775	—
90.17	-182.98	0.0755	—	—	0.02422	—	—
89.86	-183.29	—	—	0.0770	—	—	0.02467
78.05	-195.10	—	—	0.0473	—	—	0.01515
78.00	-195.15	0.0452	—	—	0.01443	—	—
77.83	-195.32	—	0.0537	—	—	0.01717	—
20.37	-252.78	—	0.0124	—	—	0.00396	—
20.36	-252.79	0.0078	—	—	0.00251	—	—
20.34	-252.81	—	—	0.0076	—	—	0.00243

* $Be_{\perp} 3$ values were plotted.

Erfling and Grüneisen (1942)					
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273}	
		$Be_{\|\|}$ 2	$Be_{\|\|}$ 6	$Be_{\|\|}$ 2*	$Be_{\|\|}$ 6
-194.86	78.29	—	0.0404	—	0.01135
-194.20	78.95	0.0450	—	0.01257	—
-193.52	79.63	—	0.04125	—	0.01159
-183.03	90.12	0.0763	0.0728	0.02131	0.02045
0.	273.15	3.58	3.56	1.00	1.00

* $Be_{||}$ 2 values were plotted.

Denton (1947)			
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
0	273.15	3.50	1.00
-183	90.15	0.297	0.085
-253	20.15	0.21	0.06

MacDonald and Mendelssohn (1950)		
Temp. °K	R/R_{273} Be 1	R/R_{273} Be 2*
273	1.000	1.000
90	0.397	0.322
20.4	0.384	0.276
4.2	0.384	0.276

* Be 2 values were plotted.

Powell (1953)	
Temp. °C	Resistivity* $\rho \times 10^6$ ohm cm
0	2.7**
20	3.2
50	4.1
100	5.3
200	8.1
300	11.1
400	13.5
500	16.7
600	20.4

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

** Extrapolated value.

White and Woods (1955) (read from graph)				
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273}	
	Be 1	Be 2	Be 1**	Be 2
0	1.11	1.21	0.241	0.281
10	1.11	1.21	0.241	0.281
30	1.11	1.21	0.241	0.281
50	1.12	1.22	0.243	0.284
70	1.18	1.28	0.257	0.298
90	1.25	1.35	0.272	0.314
273	4.6 *	4.3 *	1.00	1.00
295	5.08	4.93	1.10	1.15

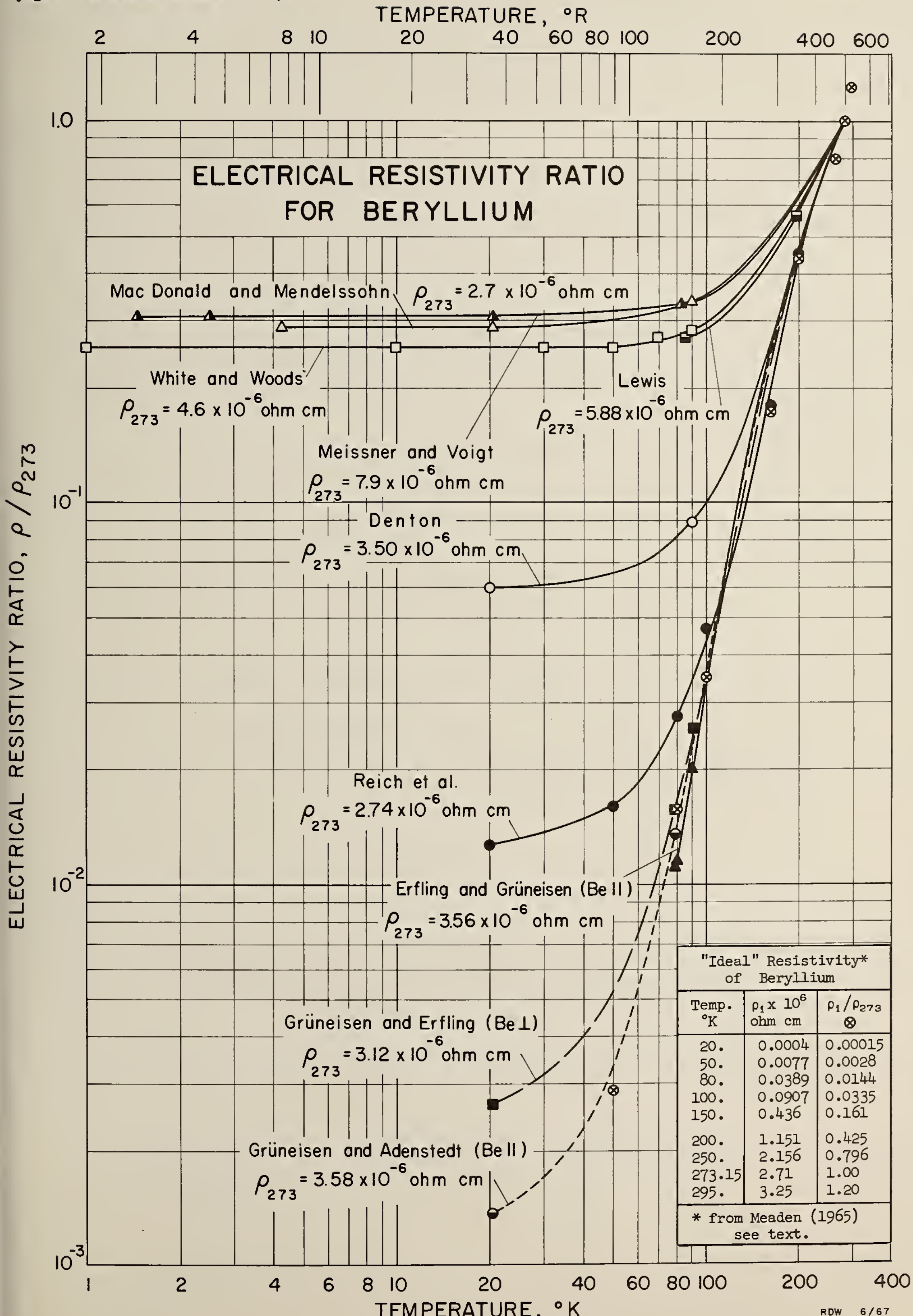
* ρ_{273} values were interpolated. ** Be 1 values were plotted.

Reich, Kinh, and Bonmarin (1963)		
Temp. °K	Resistivity* $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
20	0.0334	0.0122
50	0.0407	0.0148
80	0.0719	0.0262
100	0.1237	0.0451
150	0.4690	0.1710
200	1.184	0.432
250	2.189	0.798
273.15	2.743	1.00
295	3.283	1.20

* These values were actually taken from Meaden (1965) who received the experimental values directly from Reich. The ρ_0 value in Meaden (1965) should be 0.033×10^{-6} ohm cm.

Reich (1965)				
Sample	Purity %	Resistivity at 4.2°K* $\rho \times 10^6$ ohm cm		
		After drawing	After annealing in a 10^{-s} Torr vacuum for 1 hour	After annealing in a 10^{-s} Torr vacuum for 150 hours
H 1209/SR	99.99785	0.0375	0.0332	0.0361
H 978/CR	99.997586	0.512	0.465	0.492
F 887/CR	99.987469	0.598	0.399	0.492
F 671/CR	99.989032	1.050	0.938	1.008

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



"Ideal" Resistivity* of Beryllium

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.0004	0.00015
50.	0.0077	0.0028
80.	0.0389	0.0144
100.	0.0907	0.0335
150.	0.436	0.161
200.	1.151	0.425
250.	2.156	0.796
273.15	2.71	1.00
295.	3.25	1.20

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-10

ELECTRICAL RESISTIVITY OF COBALT, Co
(Atomic Number 27)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

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

Meissner, W., and Voigt, B., "Messungen mit Hilfe von flüssigem Helium. XI. Widerstand der reinen metalle in tiefen Temperaturen," (Measurements with the Help of Liquid Helium. XI. Resistance of Pure Metals at Low Temperatures), Ann. Physik 7, 892-936 (1930).

Radhakrishina, P., and Nielsen, M., "Transport Properties of Cobalt at Low Temperatures," Phys. Status Solidi 11, No. 1, 111-15 (1965).

Semenenko, E. E., Sudovtsov, A. I., and Volkenshtein, N. V., "Temperature Dependence on the Electrical Resistance of Cobalt between 1.3 and 4.2°K," Soviet Phys. JETP 18, No. 4, 957-58 (1964), Transl. from Zh. Eksperim. i Teor. Fiz. 45, 1387-88 (1963).

White, G. K., and Woods, S. B., "Low Temperature Resistivity of the Transition Elements: Cobalt, Tungsten, 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 Temperature," Phil. Trans. Roy. Soc. (London) A251, 273-302 (1959).

Other References:

Bridgman, P. W., "The Electric Resistance to 30,000 kg/cm² of Twenty Nine Metals and Intermetallic Compounds," Proc. Am. Acad. Arts Sci. 79, 149-79 (1951)

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Holborn, L., Z. Physik 8, 58 (1921).

Olsen-Bär, M., Univ. of Oxford, Ph. D. Thesis (1956).

Meissner, W., Physik. Z. 29, 897-904 (1928).

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 a datum temperature of 273°K. When actual values of ρ_{273} for the samples used by the investigators are not available, a datum value reported by White and Woods ($\rho_{273} = 5.24 \times 10^{-6}$ ohm cm) is suggested for calculating 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.

The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; and Bridgman (1951); while those values appearing in the International Critical Tables are from Holborn. These primary sources are cited above under "Other References." The original authors are used in labeling the curves on the graph.

The Landolt-Börnstein tables list the sample used by Meissner and Voigt as an annealed, sintered polycrystalline specimen with no mention made of impurities present. The sample used by Bridgman was reported as polycrystalline with a very small amount of impurities. Bridgman reported only $\rho_{273} = 5.57 \times 10^{-6}$ ohm cm. No information is given on the amount of impurity or nature of the Holborn sample, and no further information is available on the mechanical strain or heat treatment for either of the samples.

White and Woods' (1957) measurements were with 99.999% pure cobalt rods. They report values of ideal resistivity $\rho_i = \rho - \rho_o$ (ρ_o = resistivity due to impurity scattering; ρ_o values for the two cobalt samples were 0.0902×10^{-6} and $0.0907_5 \times 10^{-6}$ ohm cm). Their data are reported graphically with tabular values taken from the graph. These tabular values may have an error of about ± 1% due to uncertainty in the geometry of the specimens.

White and Woods' (1959) review paper gives values of resistivity based on their earlier measurements (1957) between 15 and 295°K and the results obtained by Olsen-Bär (1956) for temperatures below 20°K.

Semenenko, et al. (1963) used rods of 99.9984% pure cobalt. No mention is made of mechanical strain or heat treatment of the sample prior to measurement.

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.

A polycrystalline wire of pure cobalt was annealed at 1040°C in vacuo by Radhakrishina and Nielsen (1965) prior to resistance measurements. They do not state the percent purity of the sample. The data were presented graphically and were fitted to the expression $R = R_0 + R_1 T + R_2 T^2$, where $R_0 = 870.004 \times 10^{-10}$ ohm cm, $R_1 < 3.13 \times 10^{-12}$ ohm cm/°K, $R_2 = 0.9892 \times 10^{-11}$ ohm cm/(°K)^2. ρ_{273} (5.24×10^{-6} ohm cm) used in the resistance ratio was taken from White and Woods (1957).

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}*
1.5	0.0431
4.2	0.0426
20.4	0.0463
77.8	0.1516
86.9	0.1829
273.16	1.0000

* $\rho_{273} = 5.94 \times 10^{-6}$ ohm cm, $\rho_{1.5} = 0.256 \times 10^{-6}$ ohm cm.

Holborn (1921)	
Temp. °C	$100\rho/\rho_{273}$
- 80*	57.4
-100*	48.2
-120*	40.0
-160*	24.8
-180*	17.4
-192	13.5

* Values from interpolation

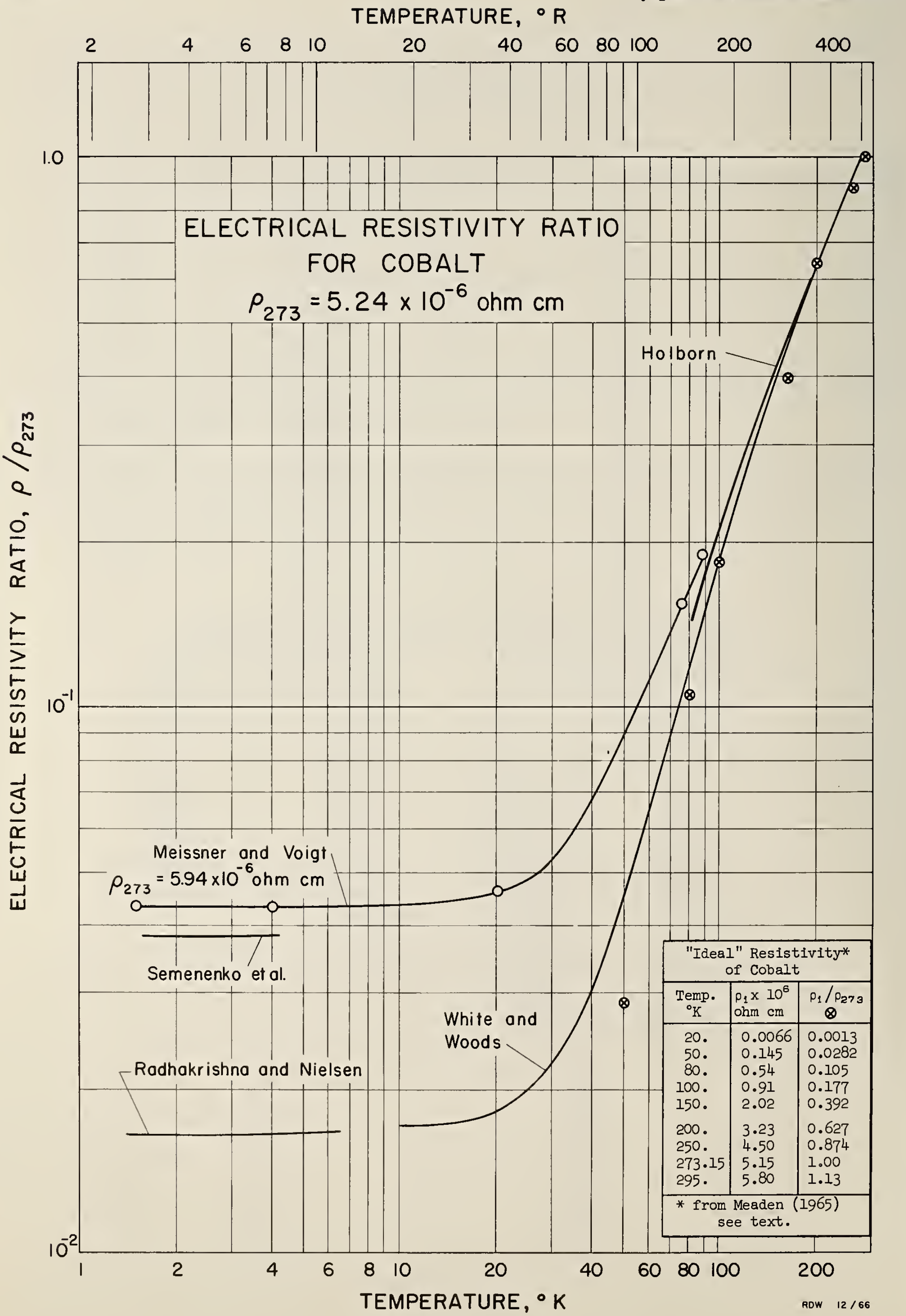
White and Woods (1957)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 0.0905 \times 10^{-6}$ ohm cm)	ρ/ρ_{273}
15	0.0025	0.0930	0.0177
20	0.0065	0.0970	0.0185
30	0.030	0.1205	0.0230
40	0.079	0.1695	0.0323
50	0.150	0.2405	0.0459
75	0.460	0.5505	0.1050
100	0.90	0.9905	0.1890
150	1.98	2.0705	0.3951
200	3.23	3.3205	0.6336
273	5.15	5.2405	1.000
295	5.80	5.8905	1.1239

White and Woods (1959)			
Temp. °K	"Ideal Resistivity"* $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 0.089 \times 10^{-6}$ ohm cm)	ρ/ρ_{273}
10	0.0011	0.0901	0.0172
15	0.0027	0.0917	0.0175
20	0.0066	0.0956	0.0182
25	0.014	0.103	0.0197
30	0.027	0.116	0.0221
40	0.072	0.161	0.0307
50	0.145	0.234	0.0447
60	0.25	0.339	0.0647
70	0.38	0.469	0.0895
80	0.54	0.629	0.120
90	0.72	0.809	0.154
100	0.91	0.999	0.191
120	1.32	1.409	0.269
140	1.78	1.869	0.357
160	2.26	2.349	0.448
180	2.75	2.839	0.542
200	3.23	3.319	0.634
220	3.72	3.809	0.727
250	4.50	4.589	0.876
273	5.15	5.239	1.000
295	5.80	5.889	1.124

* There is uncertainty in the last digit of the resistivity data

Radhakrishna and Nielsen (1965) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^9$ ohm cm	ρ/ρ_{273}
1.4	87.145	0.01663
1.9	87.160	0.01663
2.3	87.175	0.01664
2.8	87.200	0.01664
3.2	87.220	0.01665
3.6	87.246	0.01665
4.0	87.282	0.01666
4.6	87.336	0.01667
5.1	87.380	0.01668
5.5	87.423	0.01668
5.9	87.465	0.01669
6.2	87.495	0.01670
6.4	87.520	0.01670

Semenenko, et al. (1963) (read from graph)	
Temp. °K	R/R_{273}
1.55	0.038196
2.0	0.038201
2.5	0.038206
2.8	0.038210
3.2	0.038215
3.55	0.038221
4.2	0.038233



"Ideal" Resistivity* of Cobalt

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i / ρ_{273} ⊗
20.	0.0066	0.0013
50.	0.145	0.0282
80.	0.54	0.105
100.	0.91	0.177
150.	2.02	0.392
200.	3.23	0.627
250.	4.50	0.874
273.15	5.15	1.00
295.	5.80	1.13

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-11

ELECTRICAL RESISTIVITY OF COPPER, Cu (page 1 of 8)

(Atomic Number 29)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Berman, R., and MacDonald, D. K. C., "The Thermal and Electrical Conductivity of Copper at Low Temperatures", Proc. Roy. Soc. (London) 211, 122-8 (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, 165-251 (Mar 1952).

Broom, T., "The Effect of Temperature of Deformation on the Electrical Resistivity of Cold-worked Metals and Alloys," Proc. Phys. Soc. (London) B65, 871-81 (1952).

Domenicali, C. A., and Christenson, E. L., "Effects of Transition Metal Solutes on the Electrical Resistivity of Copper and Gold Between 4 and 1200°K," J. Appl. Phys. 32, No. 11, 2450-6 (1961).

Gniewek, J. J., and Clark, A. F., "Preparation of Copper Crystals with Low Electrical Resistivity," J. Appl. Phys. 36, No. 10, 3358-59 (1965).

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Meissner, W., and Voigt, B., "Messungen mit Hilfe von flüssigem Helium. XI. Widerstand der reinen Metalle in tiefen Temperaturen," (Measurements with the Help of Liquid Helium), Ann. Physik (5) 7, 761- 97 (1930).

Moore, J. P., McElroy, D. L., and Graves, R. S., "Thermal Conductivity and Electrical Resistivity of High-Purity Copper from 78 to 400°K," Can. J. Phys. 45, 3849-65 (1967).

Onnes, H. K., and Tuyn, W., "Data Concerning the Electrical Resistance of Elementary Substances at Temperatures below -80°C," Communs. Phys. Lab. Univ. Leiden Suppl. 58 (1926).

Pawlek, F., and Rogalla, D., "The Electrical Resistivity of Silver, Copper, Aluminum, and Zinc as a Function of Purity in the Range 4 - 298°K," Cryogenics 6, No. 1, 14-20 (1966) and Metall. 20, No. 9, 949-56 (1966).

Powell, R. L., Roder, H. M., and Hall, W. J., "Low-Temperature Transport Properties of Copper and Its Dilute Alloys: Pure Copper, Annealed and Cold-Drawn," Phys. Rev. 115, No. 2, 314-23 (1959).

Sekula, S. T., "Resistance Minimum and Resistivity of Copper at Low Temperatures," Phys. Rev. Letters 3, No. 9, 416-18 (1959).

White, G. K., "The Thermal and Electrical Conductivity of Copper at Low Temperatures," Australian J. Phys. 6, No. 4, 397-404 (1953).

White, G. K., and Woods, S. B., "Electrical and Thermal Resistivity of the Transition Elements at Low Temperatures," Phil. Trans. Roy. Soc. (London) A251, 273-302 (1959).

Other References:

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Buck, O., "Verformung und elektrischer Widerstand von Kupfer-Einkristallen bei tiefsten Temperaturen," (The Deformation and Electrical Resistivity of Copper Single Crystals at Low Temperatures), Phys. Status Solidi 2, 535-57 (1962).

de Haas, W. J., de Boer, J. H., and Van den Berg, G. J., Physica II, 1115 (1934).

Dauphinee, T. M., and Preston-Thomas, H., "A Copper Resistance Temperature Scale," Rev. Sci. Instr. 25, 884-6 (1954).

Dolecek, R. L., and Schultz, D. J., "Residual Resistance of Copper Annealed in an O_2 Atmosphere," Acta Met. 8, 664 - 65 (1960).

Dugdale, J. S., and Gugan, D., "The Effect of Pressure on the Electrical Resistance of Copper at Low Temperatures," Proc. Roy. Soc. (London) A241, 397-407 (1957).

Franck, J. P., Manchester, F. D., and Martin, D. L., "The Specific Heat of Pure Copper and of some Dilute Copper and Iron Alloys Showing a Minimum in the Electrical Resistance at Low Temperatures," Proc. Roy. Soc. (London) A263, 494-507 (1961).

Grüneisen, E., "Elektrische Leitfähigkeit der Metalle bei tiefen Temperaturen," (Electrical Conductivity of Metals at Low Temperatures), Ergebn. exakt. Naturw. 21, 50-116 (1945).

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Henning, F., "Gasthermometrische Messungen zwischen -193 und -258°," (Gas Thermometry Measurements between -193 and -258°), Z. Physik 5, 264-79 (1921).

Holborn, L., Ann. Physik 59, 145 (1919).

Kannuluik, W. G., and Laby, T. H., "The Thermal and the Electrical Conductivity of a Copper Crystal at Various Temperatures," Proc. Roy. Soc. (London) A121, 640-53 (1928).

Kovacs-Csetenyi, E., Vassel, C. R., and Kovacs, I., "The Effect of Impurity Content and Heat Treatment on the R_{273}/R_{78} Resistivity Ratio of Aluminum and Copper," Acta Phys. Acad. Sci. Hung. 21, No. 2, 195-8 (1966).

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Mac Donald, D. K. C., and Berman, R., "The Thermal and Electrical Conductivity of Copper," Proc. Roy. Soc. (London) A211, 122 (1952).

Meissner, W., "Thermische und elektrische Leitfähigkeit einiger Metalle zwischen 20 und 373° Abs," (Thermal and Electrical Conductivity of Some Metals between 20 and 373°K), Ann. Physik 47, No. 16, 1001-58 (1915).

Meissner, W., Physik. Z. 29, 897 (1928).

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Niccolai, G., "Über den elektrischen Widerstand der Metalle zwischen sehr hohen und sehr tiefen Temperaturen," (The Electrical Resistance of a Metal between Very High and Very Low Temperatures), Physik. Z. 9, 367 (1908).

Pearson, W. B., "CIII. Electron Transport in Copper and Dilute Alloys at Low Temperature. III. Solid Solutions of Iron in Copper," Phil. Mag. 46, 911 (1955).

Roder, H. M., Powell, R. L., and Hall, W. J., "Thermal and Electrical Conductivity of Pure Copper," Low Temperature Physics and Chemistry, Univ. of Wisconsin Press, p. 364-6 (Aug 1958).

Verel, D. J., "Recovery of the Resistivity of Copper Cold Worked at Low Temperatures," Physica 29, 562-64 (1963).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by de Haas, de Boer and Van den Berg; Holborn; and Meissner (1928); while those values in the International Critical Tables are from Henning. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

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.

The data in the Landolt-Börnstein tables and the International Critical Tables tabulated here are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. When the actual values of ρ_{273} for the samples used by the original investigators are not available, a datum value determined by Powell, et al. (1959) ($\rho_{273} = 1.545 \times 10^{-6}$ ohm cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables report the samples used by the authors appearing in their compilation as annealed polycrystalline specimens with a small amount of impurities present. No other pertinent information is given about the data reported in Landolt-Börnstein tables or International Critical Tables.

The Meissner (1915) paper gave $\rho_{273} = 1.55 \times 10^{-6}$ ohm cm.

Onnes and Tuyn (1926) measurements were made on "natural copper crystals".

Meissner and Voigt (1930) present the same data as Meissner (1928).

Berman and Mac Donald (1952) used 99.9988% pure copper wires which were annealed for 6 hours at 450°C in helium.

Bridgman (1952) used 99.9999% pure 0.001 inch thick copper sheets to measure the effect of pressure on the electrical resistivity. He reported room temperature measurements as ratios of the resistance at a given pressure to the resistance at one atmosphere.

A 99.99% pure copper wire used by Broom (1952) was annealed for two hours at 600°C prior to resistivity measurements. The tabular data are for the specimen before deformation (wire drawing). Broom's graphs show the effect of deformation on the resistivity.

White (1953) and White and Woods (1959) used wires of 99.999% purity which were annealed in vacuum at 550 and 530°C for three hours prior to measurement.

Sekula (1959) studied the effect of oxidizing or reducing atmosphere on the electrical resistivity minimum. The 99.999% pure copper wire specimen was first annealed in a vacuum of 2×10^{-5} mm Hg at 950°C for two hours before measurements were made. Then the specimen was reheated in 10 microns of air at 750°C for two hours before a second set of measurements was made. The resistance ratio $R/R_{20°C}$ is reported graphically for both sets of measurements; the value of $R_{20°C}$ is not given. The ratio $\rho_{293}/\rho_{273} = 1.7027/1.5527$ from White and Woods was used in determining the ratio R/R_{273}.

Powell, et al. (1959) used 99.999% pure copper rods which were annealed in vacuum at 400°C prior to measurement at 4.2°K; the resistivity of the sample was $(1.01 \pm 0.02) \times 10^{-9}$ ohm cm. The values in the table below are read from their graph.

The copper used by Domenicali and Christenson (1961) contains 10^{-4} to 10^{-3}% impurities. The copper was shaped in the form of square cross-section wires which were annealed at 500°C for several hours in vacuo.

Gniewek and Clark (1965) used 99.999% pure copper in growing crystals in a 10^{-5} Torr vacuum. Their crystals were heated at 1000°C under a pressure of 5×10^{-5} Torr for approximately 15 hours and then cooled at a maximum rate of 150°C/hr.

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.

The samples used by Pawlek and Rogalla (1966) were 99.9943% and 99.9994% pure copper wires which had been annealed at 600°C for one hour and cooled no faster than 50°C/hr. The data in the table below are for the 99.9994% pure sample.

The Moore et al. (1967) measurements were made with 99.999% pure, polycrystalline copper rods 5 - 8 cm long.

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 (1915)		Holborn (1919)		Henning (1921)		Onnes and Tuyn (1926)	
Temp. °K	ρ/ρ_{273} **	Temp. °K	R/R_{273}	Temp. °C	$100R/R_{273}$	Temp. °C	R/R_{273} **
20.7	0.0026_6	81	0.1502	- 76	65.739	-184.53	0.1749
90.7	0.186_7	195	0.6602	-183	18.868	-192.04	0.1440
273.1*	1.000			-252.8	0.6291	-199.98	0.1103
						-206.94	0.0840
						-218.09	0.0469
						-252.57	0.00154
						-255.07	0.00129
						-256.63	0.00109
						-258.77	0.00097

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

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

Meissner and Voigt (1930) Meissner (1928)		de Haas, et al. (1934)		Broom (1952) (before deformation)		
Temp.* °K	R/R_{273} **	Temp. °K	ρ/ρ_{273}	Temp. °C	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
1.32	0.00029	1.55	0.00117	-183	0.291	0.183
1.97	0.00028	4.23	0.00119	- 78.5	1.06	0.67
4.20	0.00029	14.26	0.00128	0	1.59	1.00
20.42	0.00078	20.47	0.00176	100	2.23	1.40
81.6	0.144					
273.16	1.000					

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

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

Berman and Mac Donald (1952) (read from graph)			
Temp. °K	Conductivity $\sigma \times 10^{-6}$ (ohm cm)$^{-1}$	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
2.5	150	0.0067	0.0043
10.	154	0.0065	0.0042
16.	150	0.0067	0.0043
20.	135	0.0074	0.0048
24.5	109	0.009	0.0058
30.	79	0.013	0.0084
33.	60	0.017	0.011
40.	36	0.028	0.018
48.	21	0.048	0.031
53.5	15	0.067	0.043
64.	9	0.11	0.071
72.	6	0.17	0.11
80.	5	0.20	0.13
90.	3	0.33	0.21

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

Bridgman (1952) (room temperature) (Data compared with the resistance at one atmosphere taken as unity)	
Pressure kg/cm^2	R/R_0
0	1.000
10000	0.981
20000	0.965
30000	0.949
40000	0.934
50000	0.920
60000	0.907
70000	0.895
80000	0.884
90000	0.875
100000	0.866

White (1953) (read from graph)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 4.6 \times 10^{-9}$ ohm cm)	ρ/ρ_{273}
14	0.00035	0.00495	0.00319
20	0.00098	0.00558	0.00360
25	0.0030	0.00760	0.00490
30	0.0066	0.0112	0.00722
34	0.014	0.0186	0.0120
41	0.028	0.0326	0.0210
55	0.074	0.0786	0.0507
62	0.11	0.1146	0.0739
78	0.19	0.1946	0.1255
91	0.28	0.2846	0.1835
100	0.38	0.3846	0.2480
120	0.55	0.5546	0.3576
190	0.98	0.9846	0.6348

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 2.7 \times 10^{-9}$ ohm cm)	ρ/ρ_{273}
15	0.00017	0.00287	0.00185
20	0.0008	0.0035	0.0023
25	0.0025	0.0052	0.0034
30	0.0063	0.0090	0.0058
40	0.022	0.0247	0.015
50	0.050	0.0527	0.034
60	0.095	0.0977	0.063
70	0.153	0.1557	0.100
80	0.215	0.2177	0.140
90	0.280	0.2827	0.182
100	0.350	0.3527	0.227
120	0.490	0.4927	0.318
140	0.635	0.6377	0.411
160	0.775	0.7777	0.501
180	0.92	0.9227	0.595
200	1.06	1.0627	0.685
220	1.20	1.2027	0.775
250	1.40	1.4027	0.904
273	1.55	1.5527	1.00
295	1.70	1.7027	1.10

Sekula (1959)

(read from graph)

Temp. °K	$R/R_{20°C}$ Vacuum Annealed	$R/R_{20°C}$ Air Annealed	R/R^*_{273} Air Annealed
1.7	8.95×10^{-4}	3.10×10^{-4}	0.000340
4.6	8.85×10^{-4}	3.18×10^{-4}	0.000349
6.0	8.81×10^{-4}	3.21×10^{-4}	0.000352
7.6	8.81×10^{-4}	3.27×10^{-4}	0.000359
9.0	8.85×10^{-4}	3.31×10^{-4}	0.000363
11.1	9.00×10^{-4}	3.46×10^{-4}	0.000379
13.5	9.37×10^{-4}	3.90×10^{-4}	0.000428
15.0	9.70×10^{-4}	4.28×10^{-4}	0.000469
16.5	10.10×10^{-4}	4.80×10^{-4}	0.000526
18.0	11.00×10^{-4}	-----------	--------

* using the ratio $\rho_{293}/\rho_{273} = 1.7027/1.5527$ from White and Woods (1959).

Powell, et al. (1959)
(read from graph)

Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4.2	0.00101	0.000654
5.0	0.00105	0.000680
6.5	0.0011	0.000712
7.7	0.00115	0.000744
10.3	0.0013	0.000841
20.4	0.0021	0.00136
22.0	0.0030	0.00194
78.0	0.190	0.123
273.15	1.545	1.000

Domenicali and Christenson (1961)
(read from graph)

Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273} *
1	0.01	0.0063
25	0.02	0.013
50	0.05	0.032
75	0.2	0.13
100	0.35	0.22
150	0.7	0.40
200	1.05	0.66
250	1.4	0.89
273	1.58	1.00
300	1.75	1.11

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

Gniewek and Clark (1965)

Crystal	$R_{300°K}/R_{4.0°K}$	$R_{4.0°K}/R^*_{273°K}$
A polycrystalline	20000	0.0000548
B single	23000	0.0000477
C single	15600	0.0000703

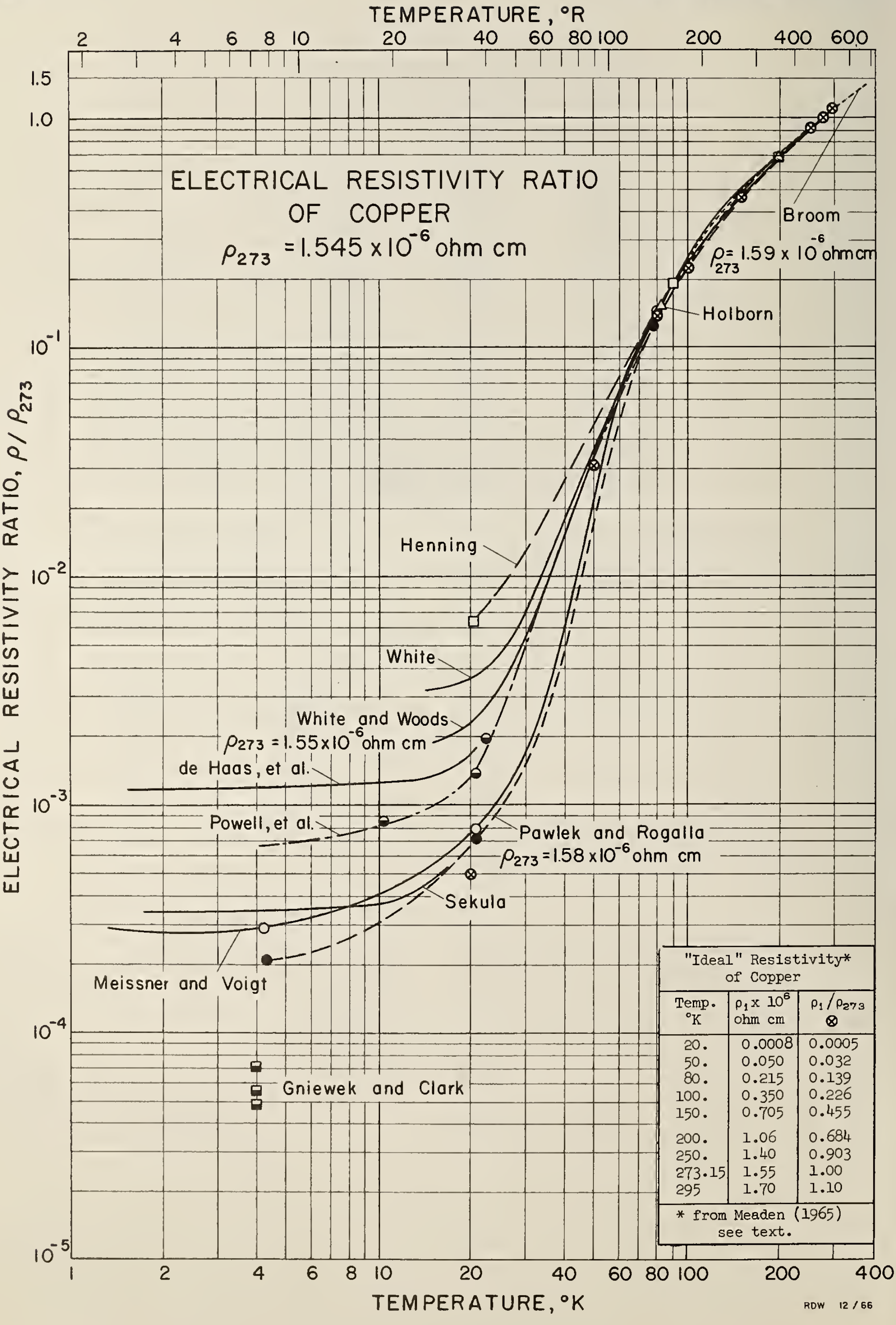
* Calculated using the values of White and Woods (1959) for $\rho_{293} = 1.7027 \times 10^{-6}$ ohm cm and $\rho_{273} = 1.5527 \times 10^{-6}$ ohm cm.

Pawlek and Rogalla (1966)

Temp. °K	Resistivity $\rho \times 10^9$ ohm cm	ρ/ρ_{273}
4.2	0.336	0.000213
20.4	1.11	0.000703
77	192	0.122
195	996	0.630
273	1580	1.000

Moore, McElroy and Graves (1967)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
4.2	0.00172	0.0011
85	0.248	0.160
90	0.282	0.182
100	0.350	0.226
110	0.418	0.270
120	0.488	0.316
130	0.558	0.361
140	0.631	0.408
150	0.702	0.454
175	0.876	0.567
200	1.047	0.677
225	1.219	0.788
250	1.389	0.898
273.16	1.546	1.000

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



"Ideal" Resistivity* of Copper

Temp. °K	ρ_i x 10^6 ohm cm	ρ_i / ρ_{273} ⊗
20.	0.0008	0.0005
50.	0.050	0.032
80.	0.215	0.139
100.	0.350	0.226
150.	0.705	0.455
200.	1.06	0.684
250.	1.40	0.903
273.15	1.55	1.00
295	1.70	1.10

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-13

ELECTRICAL RESISTIVITY of GOLD, Au
(Atomic Number 79)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

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, 165-251 (1952).

de Haas, W. J., and Van den Berg, G. J., "The Electrical Resistance of Gold and Silver at Low Temperatures," Physica 3, No. 6, 440-9 (1936) and Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 241 D (1936).

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Other References:

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Holborn, L., Ann. Physik 59, 145 (1919).

Justi, E., Physik. Z. 41, 486 (1940).

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 (1958), Transl. of Zh. Eksperim. i Teor. Fiz. 34, 258-59 (1958).

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Meissner, W., Physik. Z. 27, 725 (1926).

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 a datum temperature of 273°K. 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) ($\rho_{273} = 2.02 \times 10^{-6}$ ohm cm) is suggested for calculating 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.

The values listed in the Landolt-Börnstein tables are those reported by Holborn, Justi, and Meissner, while the values appearing in the International Critical Tables are those from Cath, Onnes, and Burgers. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph. The Cath et al.measurements were made on "pure minting gold" wires. Meissner (1915) reported $\rho_{273} = 2.065 \times 10^{-6}$ ohm cm.

Onnes and Clay (1907) made their measurements on 0.1 mm diameter wires which were heated in an "annealing furnace for a long time and slowly cooled". The purity of the samples follows; Au_{III} was ~ 99.985%, Au_{IV} and Au_{V} were ~ 99.995%. Their 1908 measurements were on Au_{V}.

Onnes and Tuyn (1926) list values taken by Meissner (1925) [see other references] on single crystal gold. Onnes and Tuyn give no other information about the sample.

Meissner and Voigt (1930) present the same data as that found in the earlier Meissner paper (1926).

The 99.9999% pure gold used by de Haas and Van den Berg (1936) was in the form of a wire which was annealed at 480°C for 5 hours prior to measurement.

Van der Leeden (1940) measured the resistivity of single crystal wires which were annealed at 480°C for 2 hours. The purity was not stated.

The material used by Bridgman (1952) was specified as "highest purity" but with no analysis. The sample was rolled to 0.001 inch thickness and annealed. The measurements were made at room temperature and the resistance ratio is the resistance at the given pressure compared to the resistance at one atmosphere.

The purity of the two single crystal samples used by Van den Berg and Franken (1958) was 99.998%. These single crystal samples were not prepared in high vacuum and were not annealed.

White and Woods (1959) used wire samples of 99.999% purity which had been previously annealed in vacuo at 530 and 700°C.

The gold used by Domenicali and Christenson (1961) contains 10^{-4} to 10^{-3}% impurities. The gold was shaped in the form of square cross-section wires which were annealed at 500°C for several hours in vacuo.

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).

Onnes and Clay (1907)

Temp. °C	Temp. °K	R/R_0		
		Au_{III}	Au_{IV}	Au_V*
0	273.09	1.	1.	1.
-103.83	169.26	0.59601	0.59389	0.59306
-183.00	90.09	0.27653	0.27177	0.27096
-197.87	75.22	0.21456	0.20963	0.20871
-205.01	68.08			0.17897
-215.34	57.75	0.14058	0.13407	0.13337
-252.93	20.16	0.01602	0.008743	0.008103
-255.13	17.96			0.005691
-258.81	14.28	0.01095	0.004265	0.003601
-261	12.09			0.002713
-262	11.09		0.003257	0.002526

* These are the values plotted on the Electrical Resistivity of Gold graph.

Meissner (1915)

Temp. °K	R/R_{273}**
21.5	0.00836
91.5	0.2764
273.1*	1.0000

* $\rho_{273} = 2.06_5 \times 10^{-6}$ ohm cm.
** These values are not plotted on the Electrical Resistivity of Gold graph.

Holborn (1919)

Temp. °K	R/R_{273}
81	0.2375
195	0.6955

Cath, Onnes and Burgers (1918)

Temp. °C	Temp. °K	$100R/R_{273}$
0.0	273.09	100.
- 84.97	188.12	66.443
-102.22	170.87	59.628
-130.28	142.81	48.507
-145.86	127.23	42.273
-164.37	108.72	34.764
-183.95	89.14	26.660
-195.88	77.21	21.622
-205.31	67.78	17.596
-208.18	64.91	16.365
-216.26	56.83	12.906
-222.78	50.31	10.130
-228.73	44.36	7.680
-233.62	39.47	5.804
-236.80	36.29	4.667
-240.25	32.84	3.538
-243.68	29.41	2.553
-245.80	27.29	2.039
-252.57	20.52	0.845
-255.01	18.08	0.594
-258.35	14.74	0.379
-268.88	4.21	0.223
-269.57	3.52	0.223
-271.61	1.48	0.223

Meissner (1925)	
Temp. °C	R/R_{273}
-191.37	0.2320
-193.14	0.2252
-200. *	0.195 *
-220. *	0.109 *
-240. *	0.033 *
-252.69	0.00642
-260. *	0.0010*
-268.89	0.00039
-269.38	0.00038
-271.48	0.00039

* Interpolated values.

Meissner and Voigt (1930) Meissner (1926)	
Temp. °K	R/R_{273}
1.61	0.00109
4.20	0.00109
20.41	0.00707
81.75	0.2341
84.87	0.2480
273.16	1.0000

Justi (1940)	
Temp. °K	R/R_{273}
4.2	0.00085
14.0	0.00227
20.4	0.00709
79.0	0.219

de Haas and Van den Berg (1936)			
Temp. °K	$100R/R_{0°C}$	Temp. °K	$100R/R_{0°C}$
20.44	0.9048	9.38	0.2890
18.08	0.6573	8.83	0.2826
17.03	0.5730	7.28	0.2714
16.05	0.5076	6.54	0.2685
15.17	0.4564	6.08	0.2674
12.10	0.3386	4.81	0.2651
11.95	0.3348	4.23	0.2644
11.84	0.3320	3.77	0.2644
10.00	0.2967	3.12	0.2646
9.95	0.2959	2.39	0.2652
		1.63	0.2666

Van der Leeden (1940)			
Au 1		Au 2	
Temp. °K	$100R/R_0$	Temp. °K	$100R/R_0$*
20.43	0.9960	20.41	2.108
18.23	0.7537	18.215	1.854
17.38	0.6767	17.365	1.774
16.32	0.5964	16.61	1.721
15.18	0.5240	15.37	1.624
14.13	0.4720	14.23	1.560

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

Bridgman (1952)

(room temperature)

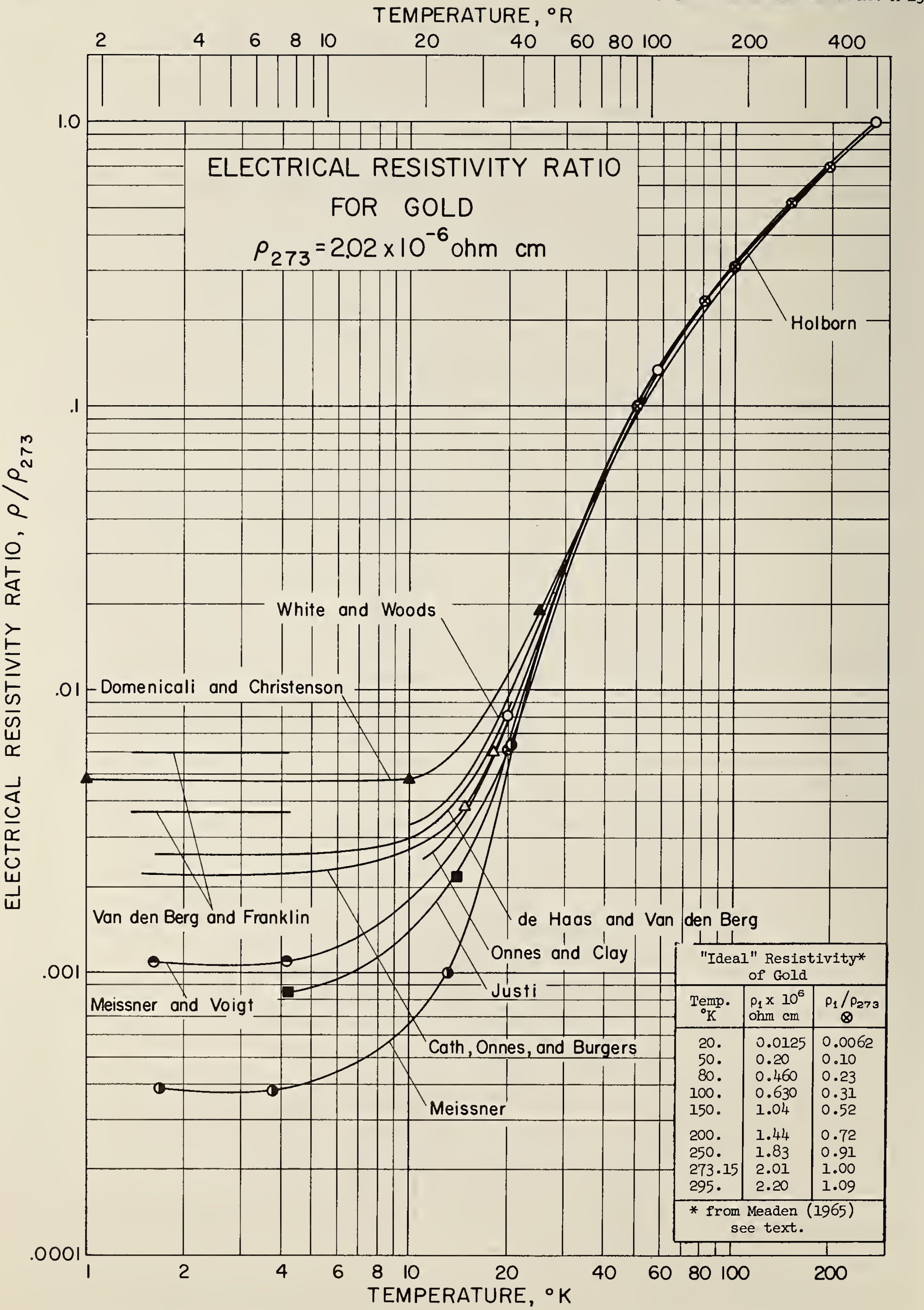
(Data compared with the resistance at one atmosphere taken as unity)

Pressure kg/cm^2	R/R_0	Pressure kg/cm^2	R/R_0
0	1.000	60000	0.855
10000	0.971	70000	0.840
20000	0.944	80000	0.829
30000	0.919	90000	0.821
40000	0.896	100000	0.816
50000	0.874		

Van den Berg and Franken (1958)				
Temp. °K	$R_I \times 10^6$ ohm	$R_{II} \times 10^6$ ohm	R_I/R_{273}	R_{II}/R_{273}
1.365	1.1684	2.4227	0.003686	0.005953
1.762	1.1659	2.4217	0.003678	0.005950
1.968	1.1648	2.4211	0.003674	0.005949
2.229	1.1633	2.4209	0.003670	0.005948
2.719	1.1619	2.4207	0.003665	0.005948
3.196	1.1602	2.4205	0.003660	0.005947
3.713	1.1604	2.4214	0.003661	0.005949
4.240	1.1599	2.4223	0.003659	0.005952
273.0	317.0	407.0	1.0	1.0

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ (where $\rho_0 = 6.23 \times 10^{-9}$ ohm cm)	ρ/ρ_{273}
10	0.0006	0.0068	0.00337
15	0.0037	0.0099	0.00491
20	0.0125	0.0197	0.00977
25	0.027	0.0332	0.0165
30	0.050	0.0562	0.0279
40	0.12	0.1262	0.0626
50	0.20	0.2062	0.102
60	0.29	0.2962	0.147
70	0.38	0.3862	0.192
80	0.46_0	0.4662	0.231
90	0.54_5	0.5512	0.273
100	0.63_0	0.6362	0.316
120	0.79_0	0.7962	0.395
140	0.95_6	0.9612	0.477
160	1.12	1.1262	0.559
180	1.28	1.2862	0.638
200	1.44	1.4462	0.717
220	1.60	1.6062	0.797
250	1.83	1.8362	0.911
273	2.01	2.0162	1.000
295	2.20	2.2062	1.094

Domenicali and Christenson (1961) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
1	0.01	0.005
10	0.01	0.005
25	0.04	0.020
50	0.2	0.099
75	0.4	0.20
100	0.6	0.30
150	1.08	0.53
200	1.45	0.71
250	1.86	0.92
273	2.02	1.00
300	2.3	1.14



"Ideal" Resistivity* of Gold

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.0125	0.0062
50.	0.20	0.10
80.	0.460	0.23
100.	0.630	0.31
150.	1.04	0.52
200.	1.44	0.72
250.	1.83	0.91
273.15	2.01	1.00
295.	2.20	1.09

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-14

ELECTRICAL RESISTIVITY of INDIUM, In
(Atomic Number 49)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Aleksandrov, B. N., "Size Effect in Electrical Resistivity of High-Purity Metals," Soviet Phys. JETP 16, No. 2, 286-94 (1963), Transl. from Zh. Eksperim. i Teor. Fiz. 43, 399-410 (Aug 1962).

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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, 165-251 (1952).

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Comments:

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner, Franz, and Westerhoff; and Meissner and Voigt; while those values appearing in the International Critical Tables are from Tuyn and Onnes. These primary sources are listed above under "Other References". The original authors are used in labeling the three curves on the graph. The curves should not be extrapolated to lower temperatures since indium becomes a superconductor between 3.374 and 3.432°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.

The data in the Landolt-Börnstein tables and the International Critical Tables, tabulated here, are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. The actual values of ρ_{273} were not available for the samples used by Meissner and Voigt; and Tuyn and Onnes, so a datum value reported by Powell, Woodman, and Tye (ρ_{273} = 8.00 x 10^{-6} ohm cm) is suggested for calculating values of electrical resistivity from these ratios.

The Landolt-Börnstein tables list the samples of both references as polycrystalline with 0.2% impurities in the sample used by Meissner and Voigt and a very small amount of impurity in the samples used by Meissner, Franz and Westerhoff. No mention is made of the amount of impurities in the sample used by Tuyn and Onnes, and no information was given on the mechanical strain or heat treatment for any of the samples from any of the above authors.

Bridgman (1952) studied the effect of pressure on electrical resistivity. The sample was rolled and cut into strips and was believed to be 99.9% pure.

The purity of the indium wire samples used by Swenson (1955) was 99.9%. The wires were extruded and not annealed. The values of resistance ratio in the table below for 60, 40, 20, and 4.2°K are extrapolated; all others are experimental.

Olsen's (1958) measurements were made on ten wire specimens with diameters varying from 0.2 to 2.54 mm in diameter from three different sources. No statement of purity was made. Below 3.37°K, where indium becomes superconducting, the zero field resistance was obtained by extrapolating from measurements in fields greater than the critical. The values in the table below are for the 2.0 mm diameter wire; this wire having the lowest residual resistivity ρ_0 = 0.27 x 10^{-9} ohm cm.

The cylindrical indium samples used by Aleksandrov (1962) had a purity of 99.9993% and were annealed 1-2 days at 25-50°C before measurements were made. He observed the effect of sample size on the resistivity of indium and estimates the error in a single measurement on the thickest and purest sample at 4.2°K to be 1.5%. He found $\rho_{293} = 9 \times 10^{-6}$ ohm cm. The samples of indium used by Aleksandrov and D'Yakov (1962) were the same as those of Aleksandrov (1962) with the exception that they were all polycrystalline. They found $\rho_{273} = 8.37 \times 10^{-6}$ ohm cm, $\rho_0 = 3 \times 10^{-10}$ ohm cm.

Powell, et al. (1962) used 99.9997% pure rods in their measurements. No mention is made of heat or mechanical treatment to the sample. The experimental data were plotted on a graph and the following tabular values are taken from that graph.

Protopopescu, et al. (1962) reported the influence of purity on the electrical resistivity of indium. The samples range from 96.05 to 99.998% pure. The table below presents values for the four purest samples.

Wire samples of 99.9994% purity were used by Orlova, et al. (1963) in constructing resistance thermometers. The thermometers were annealed at $\sim$ 100°C for 3 hours prior to resistivity measurements.

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.

Kaznoff et al. (1967) used 99.999% pure polycrystalline rods which were 0.3" in diameter. The table below gives smoothed values.

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).

Tuyn and Onnes (1923, 1924)					
Temp. °C	Temp. °K	$100R/R_{273}$	Temp. °C	Temp. °K	$100R/R_{273}$
-182.79	90.30	28.75	-254.95	18.14	5.173
-194.06	79.03	24.92	-256.61	16.48	4.796
-202.07	71.02	22.20	-258.89	14.20	4.317
-209.98	63.11	19.52	-268.87	4.22	3.394
-218.30	54.79	16.71	-269.49	3.60	3.392
-252.65	20.44	5.739	-269.61	3.48	3.387

Meissner and Voigt (1930)	
Temp. °K	R/R_{273}
4.21	0.00387
20.46	0.0256
77.82	0.2177
88.90	0.2567
273.16	1.0000

Meissner, Franz and Westerhoff (1932)	
Temp. °K	R/R_{273}
4.23	0.0015
20.4	0.0216
77.8	0.212
273.16*	1.000

* $\rho_{273} = 8.19 \times 10^{-6}$ ohm cm.

Bridgman (1952)	
Pressure kg/cm^2	R/R_0 (At Room Temperature) (Taking the Resistance at Atmospheric Pressure as R_0)
0	1.000
10000	0.891
20000	0.810
30000	0.746
40000	0.694
50000	0.650
60000	0.610
70000	0.578
80000	0.548
90000	0.520
100000	0.493

Swenson (1955)	
Temp. °K	$R/R_{273.2\,°K}$
4.2	0.0010
20.0	0.0200
40.0	0.0820
60.0	0.1520
77.7	0.2189
117.6	0.3607
143.0	0.4549
160.5	0.5214
180.7	0.6023
194.7	0.6576
210.8	0.7224
227.0	0.7929
242.0	0.8603
257.3	0.9286
272.2	0.9942

Olsen (1958)		
Temp. °K	$\rho \times 10^9$ ohm cm	ρ/ρ_{273}*
1.45	.277	3.39×10^{-5}
1.6	.277	3.39×10^{-5}
2.0	.295	3.61×10^{-5}
2.5	.321	3.93×10^{-5}
3.0	.356	4.36×10^{-5}
3.5	.435	5.32×10^{-5}
4.0	.567	6.94×10^{-5}
4.2	.620	7.59×10^{-5}

* $\rho_{273} = 8.17 \times 10^{-6}$ ohm cm was calculated using Olsen's $\rho_{293} = 8.79 \times 10^{-6}$ ohm cm and the Aleksandrov and D'Yakov ratio ρ_{273}/ρ_{293}.

Aleksandrov (1962)			
Temp. °K	Type of Crystal	R/R_{293}	R/R_{273}
4.2	Polycrystal	0.000073	0.000079
3.4	Polycrystal	0.000048	0.000052
4.2	Single crystal	0.000065	0.000070

Aleksandrov and D'Yakov (1962)		
Temp. °K	R/R^*_{293}	R/R^*_{273}
3.4	4.8×10^{-5}	5.2×10^{-5}
3.7	5.4×10^{-5}	5.8×10^{-5}
4.22	7.3×10^{-5}	7.8×10^{-5}
4.46	8.6×10^{-5}	9.2×10^{-5}
14.0	6.7×10^{-3}	7.2×10^{-3}
20.4	0.018	0.019
58.0	0.128	0.138
77.4	0.193	0.207
90.31	0.232	0.249
111.6	0.309	0.332
273.0	0.93	1.000

* $\rho_{293} = 9 \times 10^{-6}$ ohm cm and $\rho_{273} = 8.37 \times 10^{-6}$ ohm cm.

Powell, et al. (1962)			
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
-200	73.15	1.65	0.206
-150	123.15	3.08	0.385
-100	173.15	4.60	0.575
- 50	223.15	6.22	0.778
0	273.15	8.00	1.000
50	323.15	10.00	1.250
100	373.15	12.15	1.519
120	393.15	13.00	1.625

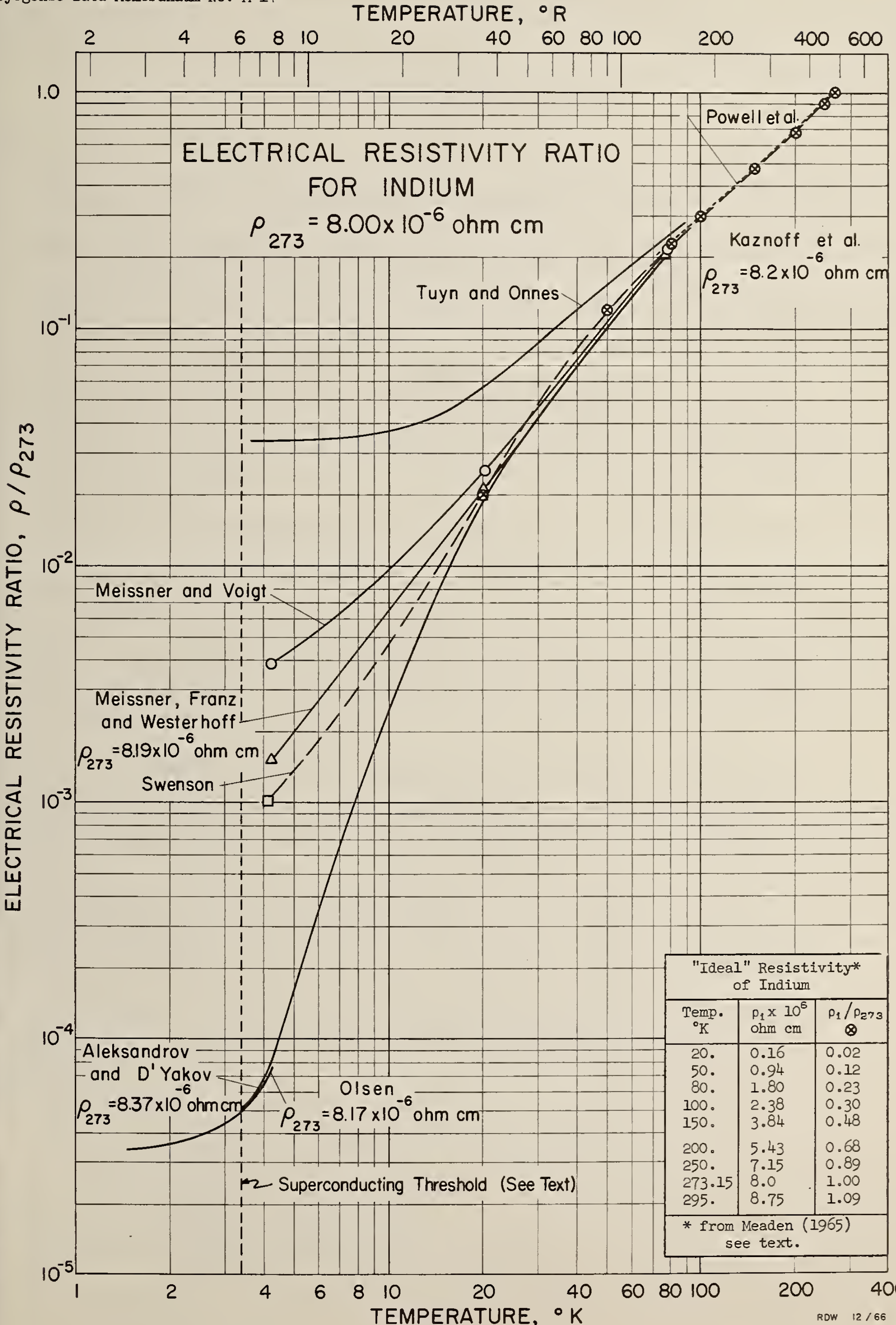
Protopopescu, et al. (1962)					
Sample Number	Purity %	$\rho_{293} \times 10^6$ ohm cm	$\rho_{80} \times 10^6$ ohm cm	ρ_{80}/ρ_{293}*	ρ_{80}/ρ_{273}*
5 (electrically refined)	99.99	8.16	1.62	0.199	0.216
6 (zone refined)	99.988	8.28	1.69	0.204	0.221
7 (zone refined)	99.996	7.92	1.33	0.168	0.182
8 (zone refined)	99.998	7.49	1.23	0.164	0.178

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

Orlova, et al. (1963)		
Thermometer Number	Resistance Ratios*	
	$R_{20.4}/R_{273}$	$R_{4.2}/R_{273}$
1	0.02123	0.0004216
2	0.02103	0.0004066
3	0.02105	0.0002968
4	0.02103	0.0002792
6	0.02101	0.0002704
8	0.01289	0.0002887

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

Kaznoff et al. (1967)					
Temp. °K	$\rho \times 10^6$ ohm cm	ρ/ρ_{273}	Temp. °K	$\rho \times 10^6$ ohm cm	ρ/ρ_{273}
80	1.826	0.222	180	4.869	0.593
100	2.431	0.296	200	5.499	0.670
120	3.038	0.370	220	6.155	0.750
140	3.647	0.444	240	6.894	0.840
160	4.257	0.518	260	7.694	0.937
			273	8.211	1.000



"Ideal" Resistivity* of Indium		
Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.16	0.02
50.	0.94	0.12
80.	1.80	0.23
100.	2.38	0.30
150.	3.84	0.48
200.	5.43	0.68
250.	7.15	0.89
273.15	8.0	1.00
295.	8.75	1.09

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-15

ELECTRICAL RESISTIVITY OF IRON, Fe
(Atomic Number 26)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc. 124-35 (1929).

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Comments:

The data for this graph were taken from the references cited above under "Sources of Data". The values listed in the Landolt-Börnstein tables are those reported by Meissner; and Cleaves and Hiegel; while those values appearing in the International Critical Tables are from Holborn. These primary sources are cited above under "Other References." The original authors are used in labeling the curves on the graph.

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.

The data in the Landolt-Börnstein tables and the International Critical Tables, tabulated here, are listed as ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. When the actual values of ρ_{273} for the samples used by the several investigators are not available, a datum value reported by Backlund (1961) ($\rho_{273} = 8.7 \times 10^{-6}$ ohm cm) is suggested for calculating values of electrical resistivity from these ratios. The value $\rho_{273} = 8.7 \times 10^{-6}$ ohm cm will be used for all data sets, except those investigations which measured ρ_{273}.

The Landolt-Börnstein tables list the sample used by Cleaves and Hiegel as an annealed polycrystalline specimen with less than 0.01% impurities. Their value for resistivity at 293°K was 9.71×10^{-6} ohm cm. The sample used by Meissner is reported as an annealed polycrystalline specimen with a very small amount of impurities present.

The Holborn (1919) sample contained 0.009% impurity and was heated to 500°C for several minutes, then annealed at 380°C for 3 hours.

Grüneisen and Goens (1927) report the following information about their iron samples: Iron 1 - double electrolytically refined, first hammered, then tempered; Iron 2 - electrolytically separated many crystals, technically "pure", not tempered; Iron 3 - electrolytic, hammered many times, tempered for one hour at 500°C.

Meissner and Voigt (1930) presented the same data as Meissner (1928).

Kannuluik (1931) used a 99.88% pure iron wire.

The samples used by Broom (1952) were 99.993% pure and were annealed at 600°C for two hours before measurements were made. The tabular values below are for resistivity measurements before deformation. Broom's graphs show the effect of deformation on resistivity.

Kemp, et al. (1956) made resistivity measurements on 2 mm diameter rods (99.99% purity) which were annealed at 750°C for four hours in vacuo. White and Woods (1959) presented a table of smoothed values based on the Kemp, et al. (1956) work and the subsequent work of White and Woods (1959).

The iron wires used by Kondorsky (1958) were made from chemically pure material. The specimens were heated in a vacuum at 900°C for one hour and then cooled slowly within the furnace. The residual resistivity was 1.458×10^{-6} ohm cm.

Kemp, et al. (1959) used iron specimens, believed to be from the same material as that of Grüneisen and Goens which was described as follows: "Doubly refined electrolytic iron, not melted in vacuo but cut out of a precipitated plate, annealed at 950°C to remove H_2 then compressed to destroy the precipitation structure and reannealed in vacuo at 950°C". However, the residual resistivity found by Kemp, et al. indicates that the samples were not as pure as the ones used by Grüneisen and Goens. The Kemp samples were cut into the shape of bars and measurements were made without any further treatment. The values listed in the table below are for Kemp's second sample, a slightly modified bar with projections of the same iron as the sample on which the potential and thermometer connections were made.

Backlund (1961) used very pure iron bars (cross section of about 15 mm^2 and length of 100 mm) which were annealed at about 500°C for 10 hours to remove the cold-work effects.

The iron specimen used by Semenenko and Sudovtsov (1962) was grown by distillation in vacuum in the form of a needle, having a grain size approximately equal to the specimen diameter. The purity of the sample was greater than 99.99% and compensation was made for the earth's magnetic field during the measurements. They give two equations to represent their data in the temperature ranges of their investigations:

1) for 1.23 to 4.2°K, $R/R_{0°C} = 3.9606 \times 10^{-3} + 3.1 \times 10^{-6}T + 1.10 \times 10^{-6}T^2$; and

2) for 14 to 20 °K, $R/R_{0°C} = 3.9606 \times 10^{-3} + 1.64 \times 10^{-6}T^2 + 4.02 \times 10^{-11}T^5$.

The values in the table below have been read from their graph.

Semenenko, et al.(1962) found "the residual resistance of the iron was $R(0°K)/R(0°C) = 3.9606 \times 10^{-3}$ in a compensated earth's field, for a measuring current of 150 mA; $R(0°K) = 1.2595 \times 10^{-3}\,\Omega$. The temperature was determined accurate to 10^{-2} °K from the helium vapor pressure". No information is given about the sample. They found the equation $R = 3.9606 \times 10^{-3} + 3.1 \times 10^{-6}T + 1.1 \times 10^{-6}T^2$ to represent their data.

The iron rectangular plate sample used by Soffer et al. (1965) was made from an ingot of zone-refined iron with a purity of 99.999815%. The sample was cold rolled and annealed to minimize strains. The sample size was 10 cm x 1 cm x 1 mm.

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.

<u>Tables of Values of Electrical Resistivity</u>

ρ = Resistivity, (ohm cm)

ρ_{273} = Resistivity at 273°K, (ohm cm)

Holborn (1919)			
Temp., °C	$100R/R_{273}$	Temp., °C	$100R/R_{273}$
- 78.1	57.86	-192.7	8.48
- 80 *	55.9	-200 *	6.2
-100 *	47.3	-220 *	2.7
-120 *	38.1	-240 *	1.4
-140 *	29.2	-253	1.13
-160 *	20.7		
* Values from interpolation			

Grüneisen and Goens (1927)					
Sample Number	$\rho_{273.2} \times 10^6$ ohm cm	$\rho_{83.2} \times 10^6$ ohm cm	$\rho_{21.2} \times 10^6$ ohm cm	$\rho_{83.2}/\rho_{273.2}$	$\rho_{21.2}/\rho_{273.2}$
1	8.71	0.77_8	0.068_1	0.0893	0.00782
2	9.11	0.92_9	0.143_7	0.1020	0.01120
3	9.95	1.91_7	1.060	0.1927	0.01937

Meissner and Voigt (1930) Meissner (1928)	
Temp. °K*	ρ/ρ_{273}**
1.98†	0.00618
4.21	0.00620
20.40	0.00761
78.24	0.0741
273.16†	1.000

* The second decimal place is in doubt.

** The fifth decimal place is in doubt.

† $\rho_{273} = 9.11 \times 10^{-6}$ ohm cm
$\rho_{1.98} = 0.0563 \times 10^{-6}$ ohm cm

Kannuluik (1931)			
Temp. °C	Temp. °K	Specific Resistance $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
-183	90.15	1.531	0.160
- 78.5	194.65	5.74	0.600
0	273.15	9.57	1.00

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

Broom (1952)			
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
-183.0	90.15	1.09	0.120
- 78.5	194.65	5.78	0.638
0.0	273.15	9.06	1.000
100.0	373.15	14.73	1.648

Kemp, Klemens, and White (1956) (read from graph)			
Temp. °K	"Ideal resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ where $\rho_0 = 2.48 \times 10^{-7}$ ohm cm	ρ/ρ_{273}
16	0.010	0.258	0.0289
23	0.014	0.262	0.0293
30	0.028	0.276	0.0309
35	0.041	0.289	0.0323
40	0.050	0.298	0.0333
58	0.19	0.438	0.0490
80	0.45	0.698	0.0781
100	0.98	1.228	0.137
130	2.0	2.248	0.251
200	5.0	5.248	0.587
273	9.0	9.248	1.000
293	10.0	10.248	1.146

Kondorsky, Galkina, and Tchernikova (1958) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
2	1.46	0.168
20	1.5	0.172
40	1.6	0.184
60	1.9	0.218
73	2.3	0.264

Kemp, Klemens, and Tainsh (1959)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
4.2	0.092	0.0103
15.2	0.097	0.0109
20.8	0.100	0.0112
26.1	0.106	0.0119
32.5	0.120	0.0134
54.4	0.269	0.0301
61.2	0.368	0.0412
74.2	0.631	0.0706
79.1	0.744	0.0832
90.2	1.06	0.119
273.0*	9.27*	1.000
293.0	10.3	1.152

* Interpolated value.

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ where $\rho_0 = 0.095 \times 10^{-6}$ ohm cm	ρ/ρ_{273}
10	0.001_5	0.0965	0.0110
15	0.003_4	0.0984	0.0112
20	0.00_7	0.102	0.0116
25	0.012_5	0.1075	0.0122
30	0.02_2	0.117	0.0133
40	0.06_0	0.155	0.0176
50	0.13_5	0.230	0.0262
60	0.25	0.345	0.0392
70	0.42	0.515	0.0586
80	0.64	0.735	0.0836
90	0.92	1.015	0.115
100	1.2_4	1.335	0.152
120	1.9_5	2.045	0.233
140	2.7_3	2.825	0.321
160	3.5_5	3.645	0.414
180	4.4_0	4.495	0.511
200	5.3	5.395	0.613
220	6.2	6.295	0.716
250	7.5_5	7.645	0.869
273	8.7	8.795	1.000
295	9.8	9.895	1.125

Backlund (1961) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
90	1.1	0.123
195	5.1	0.570
273	8.7	1.000
293	9.8	1.096

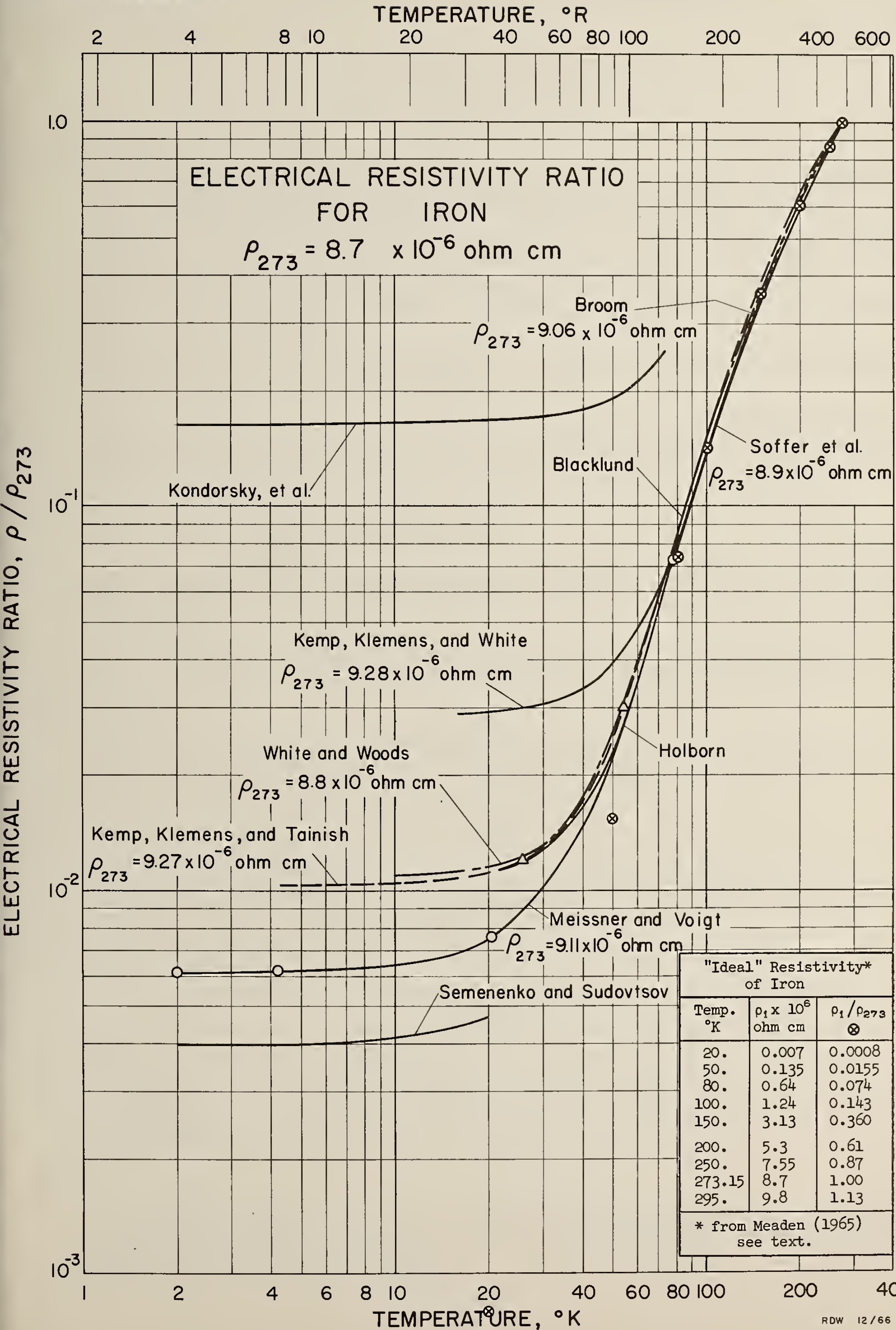
Semenenko and Sudovtsov (1962) (read from graph)	
Temp. °K	Resistance Ratio $R/R_{0°C}$
2.0	0.00397
4.0	0.00399
9.2	0.00410
12.0	0.00421
13.8	0.00430
16.0	0.00442
17.0	0.00450
20.0	0.00474

Semenenko, Sudovtsov and Shvets (1962) (read from graph)		
Temp. °K	Resistance $R \times 10^6$ ohm	R/R_{273} *
0.38	1261.35	0.00396
1.	1263.9	0.00397
2.	1270.7	0.00399
3.	1279.6	0.00402
4.	1291.1	0.00406
273.0	318000.	1.000

* These values are almost identical to the Semenenko and Sudovtsov (1962) values and are therefore not plotted on the Electrical Resistivity of Iron graph.

Soffer, Dreesen, and Pugh (1965) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
77	0.6	0.067
112	1.8	0.20
169	4.0	0.45
231	6.9	0.77
273	8.94	1.00
300	10.7	1.20

* These values are not plotted on the Electrical Resistivity of Iron graph because these points coincide with others previously plotted.



"Ideal" Resistivity* of Iron

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i / ρ_{273} ⊗
20.	0.007	0.0008
50.	0.135	0.0155
80.	0.64	0.074
100.	1.24	0.143
150.	3.13	0.360
200.	5.3	0.61
250.	7.55	0.87
273.15	8.7	1.00
295.	9.8	1.13

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-16

ELECTRICAL RESISTIVITY OF LEAD, Pb
(Atomic Number 82)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Aleksandrov, B. N., "Size Effect in Electrical Resistivity of High-Purity Metals," Soviet Phys. JETP 16, No. 2, 286-94 (1963), Transl. of Zh. Eksperim. i Teor. Fiz. 43, 399-410 (1962).

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 (1963), Transl. of Zh. Eksperim. i Teor. Fiz. 43, 852-59 (1962).

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, 165-251 (1952).

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Onnes, H. K., and Clay, J., "On the Change of the Resistance of the Metals at Very Low Temperatures and the Influence Exerted on It by Small Amounts of Admixtures," Communs. Phys. Lab. Univ. Leiden No. 99c (1907).

Van der Leeden, P., "Geleiding van warmte en electriciteit door metalen," (Conduction of heat by metals), Gedrukt Bij Drukherig Waltman, Koornmarkt 62, Te Delft 11-76 (July 1940).

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Bridgman, P. W., "Miscellaneous Measurements of the Effect of Pressure on Electrical Resistance," Proc. Am. Acad. Arts Sci. 82, No. 2, 83-100 (1953).

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Meissner, W., Ann. Physik (5) 13, 641 (1932).

Meissner, W., and Franz, H., Z. Physik 65, 30 (1930).

Onnes, H. K., and Tuyn, W., Communs. Kamerlingh Onnes Lab. Univ. Leiden Suppl. No. 58 (1926).

Onnes, H. K., and Tuyn, W., Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 160b (1922).

Van den Berg, G. J., "The Electric Resistance of Potassium, Tungsten, Copper, Tin, and Lead at Low Temperatures," Physica 14, 111-38 (Apr 1948), also Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 274a (1948).

Comments:

The data for this graph were taken from the references cited above under "Sources of Data". The data listed in the Landolt-Börnstein tables are those reported by Meissner and Franz; Meissner; Onnes and Tuyn; and Van den Berg; listed above under "Other References". The original authors are used in labeling the curves on the graph.

The curves on the graph should not be extrapolated to lower temperatures as lead becomes a superconductor at 7.22°K. It will be noted, however, that the data of Van den Berg; Aleksandrov and D'Yakov; and Meissner extend into the superconducting region. These data below the transition temperature were based on observations of the electrical resistance with the lead subjected to a super-critical magnetic field to maintain electrical resistance.

The data tabulated here are ratios of electrical resistivity with respect to the resistivity at a datum temperature of 273°K. When the actual values of ρ_{273} are not available for the samples used by the original investigators, a datum value reported by Aleksandrov and D'Yakov (ρ_{273} = 19.2 x 10^{-6} ohm cm) is suggested for calculating 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.

The Landolt-Börnstein tables report the samples used by all of the investigators in their compilation as polycrystalline with a very small amount of impurities present.

Yaeger and Diesselhorst (1900) report the sample used in determining ρ_{273} as polycrystalline with less than 0.05% impurities. Their value at 273°K was 19.2 x 10^{-6} ohm cm.

The purity of the lead strip used by Onnes and Clay (1907) was 99.985%. No other information is given about the preparation of the sample. The values listed in the table below are resistances compared with the resistance at 0°C.

Meissner (1915) reported ρ_{273} = 19.2_6 x 10^{-6} ohm cm.

Van der Leeden (1940) used a polycrystalline lead wire (0.025 cm diameter) in his electrical resistivity measurements. The purity of the sample was not stated.

The purity of Bridgman's (1952) sample was 99.9999%. His measurements show the effect of pressure on electrical resistivity at room temperature.

Buckel and Hilsch (1954) prepared metal layers for their measurement by low temperature condensation (4°K). They report only one measurement at 273°K of 19.9 x 10^{-6} ohm cm.

Aleksandrov (1962) used polycrystalline samples of 99.99964% purity. The samples were in the form of 0.5 to 2.5 mm diameter rods. He estimated the error to be $\ll$ 1%. Measurements were made in a magnetic field of H = 640 Oe in addition to H = 0 at 4.2°K. He used ρ_{273} = 19.3 x 10^{-6} ohm cm.

Aleksandrov and D'Yakov (1962) used the same lead samples as Aleksandrov (1962). However, they did not reduce the diameters so much so that the resistance would be affected. The measurements for temperatures below 7.22°K were made in the presence of a magnetic field. Using a quadratic dependence of ρ on H, they obtained values of ρ for H = 0. Their $\rho_0 \cong 4$ x 10^{-10} 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.

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).

Onnes and Clay (1907)		
Temp. °K	Temp. °C	Resistance ratio R/R_{273}
14.39	-258.70	0.01311
18.02	-255.07	0.02314
20.31	-252.78	0.03032
56.48	-216.61	0.17129
68.57	-204.52	0.21742
77.94	-195.15	0.25257
89.44	-183.65	0.29439
169.46	-103.63	0.59548
273.09	- 0.0	1.000
289.42	16.33	1.0652

Meissner (1915)	
Temp. °K	ρ/ρ_{273} **
21.8	0.035_0
91.7	0.303
273.1*	1.000

* $\rho_{273} = 19.2_8 \times 10^{-6}$ ohm cm.
** These values are not plotted on the Electrical Resistivity of Lead graph.

Onnes and Tuyn (1926)		Meissner and Voigt (1930) Meissner and Franz (1930)		Meissner (1932)	
Temp* °K	R/R_{273}	Temp* °K	R/R_{273}	Temp. °K	R/R_{273}
7.26	0.0010	7.26	0.0007	1.3	1.55×10^{-4}**
14.32	0.0113	14.02	0.0104	4.2	1.75×10^{-4}**
20.52	0.0301	20.32	0.0292		
73.11	0.2321	273.16	1.0000		
88.56	0.2895				

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

** These measurements were made with the aid of a supercritical magnetic field at temperatures at which lead is normally a superconductor.

Van der Leeden (1940)			
Temp. °K	$100R/R_0$*	Temp. °K	$100R/R_0$*
90.33	29.65	20.40	3.015
82.06	26.51	19.35	2.639
73.16	23.19	18.21	2.272
67.09	20.92	17.29	1.988
55.33	16.51	16.00	1.620
		15.03	1.356
		14.10	1.118

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

Van den Berg (1948)		Bridgman (1952)			
Temp.* °K	R/R_{273}**	(Resistance compared with the resistance at room temperature and one atmosphere pressure.)			
		Pressure kg/cm²	R/R_0	Pressure kg/cm²	R/R_0
2.30	0.00013 †	0	1.000	60000	0.570
3.22	0.00015 †	10000	0.873	70000	0.543
4.24	0.00019 †	20000	0.779	80000	0.521
7.22	0.00083	30000	0.704	90000	0.502
9.38	0.0025	40000	0.647	100000	0.487
20.32	0.0301	50000	0.603		

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

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

† These measurements were made with the aid of a supercritical magnetic field at temperatures at which lead is normally a superconductor.

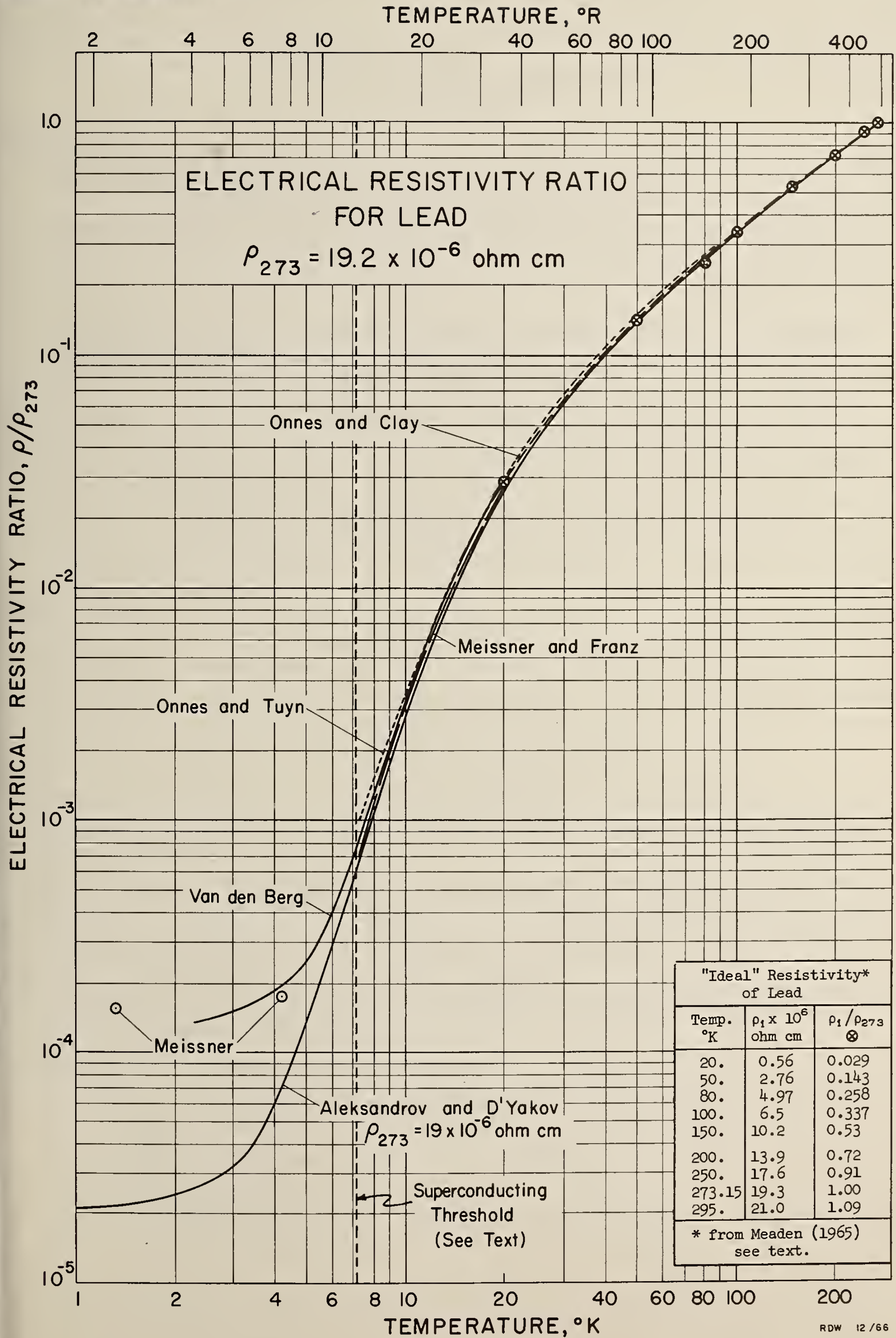
Aleksandrov (1962)				
Sample		Temp. °K	R/R_{293} †	R/R_{273} †
Polycrystal	H = 640 Oe	4.2	0.00007	0.00008
Polycrystal	H = 0	4.2	0.000063	0.000068
Polycrystal		20.4	0.00268	0.00290

† $\rho_{293} = 20.9 \times 10^{-6}$ ohm cm and $\rho_{273} = 19.3 \times 10^{-6}$ ohm cm.

Aleksandrov and D'Yakov (1962)					
Temp. °K	R/R_{293}*	R/R_{273}*	Temp. °K	R/R_{293}*	R/R_{273}*
0.0	1.9×10^{-5} †	2.1×10^{-5}	7.2	6.3×10^{-4} †	6.8×10^{-4}
1.9	2.15×10^{-5} †	2.33×10^{-5}	14.0	9.5×10^{-3}	10.3×10^{-3}
3.6	3.8×10^{-5} †	4.1×10^{-5}	20.4	0.027	0.029
3.8	4.52×10^{-5} †	4.90×10^{-5}	58.0	0.166	0.180
4.0	5.3×10^{-5} †	5.7×10^{-5}	77.4	0.230	0.249
4.22	6.28×10^{-5} †	6.80×10^{-5}	90.31	0.272	0.295
4.46	7.8×10^{-5} †	8.4×10^{-5}	273.0	0.917	1.00

* Using $\rho_{293} = 20.9 \times 10^{-6}$ ohm cm and $\rho_{273} = 19.2 \times 10^{-6}$ ohm cm from Aleksandrov (1962).

† Measurements below 7.22°K were made in the presence of a magnetic field.



"Ideal" Resistivity* of Lead

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.56	0.029
50.	2.76	0.143
80.	4.97	0.258
100.	6.5	0.337
150.	10.2	0.53
200.	13.9	0.72
250.	17.6	0.91
273.15	19.3	1.00
295.	21.0	1.09

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-17

ELECTRICAL RESISTIVITY OF MAGNESIUM, Mg (Atomic Number 12)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc., 124-35 (1929).

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, 165-251 (1952).

Goens, E., and Schmid, E., "Elastische Konstanten, electrischer Widerstand und thermische Ausdehnung des Magnesiumkristalls," (Elastic Constants, Electrical Resistance and Thermal Expansion of Magnesium Crystals), Physik. Z. 37, 385-91 (1936).

Grüneisen, E., "Elektrische Leitfahigkeit der Metalle bei tiefen Temperaturen," (Electrical Conductivity in Metals at Low Temperatures), Ergebn. exakt. Naturw. 21, 50-116 (1945).

Hein, R. A., and Falge, R. L., "Resistance Minimum of Magnesium: Electrical Resistivity Below 1°K," Phys. Rev. 105, 1433-34 (1957).

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

Spohr, D. A., and Webber, R. T., "Resistance Minimum of Magnesium: Electrical and Thermal Resistivities," Phys. Rev. 105, 1427-33 (1957).

Other References:

Bridgman, P. W., "Electrical Resistance Under Pressure, Including Certain Liquid Metals," Proc. Am. Acad. Arts Sci. 56, 61-154 (1921).

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Dewar, J., and Fleming, J. A., Phil. Mag. (5) 36, 271 (1893).

Kan, L. S., and Lazarev, B. G., "On the Resistance Minimum of Magnesium at Low Temperatures," Akad. Nauk. SSSR Doklady 81, 1027-29 (1951).

MacDonald, D. K. C., and Mendelssohn, K., Proc. Roy. Soc. (London) A202, 523-33 (1950).

Meissner, W., and Voigt, B., "Messungen mit Hilfe von flüssigem Helium. XI. Widerstand der reinen Metalle in tiefen Temperaturen," (Measurements with the Help of Liquid Helium. XI. Resistance of Pure Metals at Low Temperatures), Ann. Physik (5) 7, 761-97 (1930).

Niccolai, G., "Über den elektrischen Widerstand der Metalle zwischen sehr höhen und sehr tiefen Temperaturen," (Concerning the electrical resistance of metals between very high and very low temperatures), Physik. Z. 9, 367 (1908).

Nichols, J. L., J. Appl. Phys. 26, 470 (1955).

Rorschach, H. E., and Herlin, M. A., "The Resistance Minimum in Magnesium at Low Low Temperatures," Phys. Rev. 87, 193 (Jul 1952).

Rosenberg, H. M., "The Thermal and Electrical Conductivity of Magnesium at Low Temperatures," Phil. Mag. 45, 73-9 (1954).

Stager, R. A., and Drickamer, G. H., "Effect of Temperature and Pressure on the Electrical Resistance of Four Alkaline Earth Metals," Phys. Rev. 131, No. 6, 2524-27 (1963).

Yntema, G. B., "Magnetoresistance of Mg, Cu, Sb, and Al at Liquid Helium Temperatures," Phys. Rev. 91, 1388-94 (Sept 1953).

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 a datum temperature of 273°K. Since magnesium is an anisotropic metal, we list suggested values of ρ_{273} for Mg$\|$, Mg$\perp$, and polycrystalline magnesium to be used in calculating electrical resistivity from these ratios. These values are: $\rho_{(\|)_{273}} = 3.48 \times 10^{-6}$ ohm cm, $\rho_{(\perp)_{273}} = 4.18 \times 10^{-6}$ ohm cm, and $\rho_{(poly)_{273}} = 3.94 \times 10^{-6}$ ohm cm.

These values are from Grüneisen (1945).

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.

The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; Niccolai: Rosenberg; and Yntema; while those values listed in the International Critical Tables are from Dewar and Fleming. Those primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph.

The sample used by Meissner and Voigt is reported by Landolt-Börnstein as polycrystalline and annealed in a vacuum at 250°C for 2.5 hours. The sample used by Yntema was of a polycrystalline nature with less than 0.02% impurities present. The Yntema sample was also annealed but no mention is made of conditions. The sample used by Niccolai was reported as polycrystalline with very few impurities present. Rosenberg's sample was a 1.5 mm diameter rod (99.95% pure) which was annealed in vacuo at 500°C for six hours.

The Goens and Schmid (1936) measurements were made with cylindrical shaped single crystals which were grown from the melt of 99.95% pure starting material. Only two resistivity values are given for a temperature of 18.0°C:

$$\rho_{\|} = 3.77_5 \times 10^{-6} \text{ ohm cm and}$$
$$\rho_{\perp} = 4.53_0 \times 10^{-6} \text{ ohm cm.}$$

Grüneisen (1945) uses Goens and Schmid's data to determine the resistivity values at 0°C:

$$\rho_{\|} = 3.48 \times 10^{-6} \text{ ohm cm and}$$
$$\rho_{\perp} = 4.18 \times 10^{-6} \text{ ohm cm}$$

and by averaging the two using Voigt's equation, he calculates for the quasiisotrope:

$$\rho_{273} = 3.94 \times 10^{-6} \text{ ohm cm.}$$

Bridgman (1952) measured the effect of pressure on electrical resistivity. His sample was from "old single crystal stock" rolled to a thickness of 0.002 inch with widths varying from 0.013 to 0.039 inch.

Spohr and Webber (1957) measured the resistivity of two specimens in the shape of rods about 9 cm long and 3 mm in diameter. The first specimen Mg(Fe) was 99.98+ % pure with iron as the major contaminant and the second Mg(Mn) was 99.95+ % pure with manganese as the only significant contaminant. Prior to measurements Mg(Fe) was cold-worked and Mg(Mn) was annealed for 24 hours at 300°C and rapidly quenched in water at 40°C. The data in the table below have been read from their graph.

Hein and Falge (1957) extended the measurements of Spohr and Webber to temperatures below 1°K. They used the same specimens, Mg(Fe) and Mg(Mn). The values in the table below were taken from their graph.

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)

Dewar and Fleming (1893)		Meissner and Voigt (1930)		Yntema (1953)	
Temp. °C	$100\,\rho/\rho_{273}$	Temp.** °K	R/R_{273}	Temp. °K	R/R_{273}
- 78.3*	68.2*	1.27 †	0.0329	1.30	0.00537
- 80	67.4	3.16	0.0326	4.21	0.00516
-100	59.0	4.20	0.0323		
-120	50.5	20.46	0.0344_5		
-140	41.9	77.61	0.1576		
-160	33.2	88.19	0.2006		
-180	24.4	273.16 †	1.0000		
-182.9*	23.0*				

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

** The second decimal place is in doubt.

† $\rho_{273} = 5.00 \times 10^{-6}$ ohm cm; $\rho_{1.27} = 0.164 \times 10^{-6}$ ohm cm.

Goens and Schmid (1936)			
Temp. °C	Temp. °K	Resistance Ratio, R/R_0*	
		Mg ∥	Mg ⊥
+100	373.15	1.429	1.421
0	273.15	1.000	1.000
-183.1	90.05	0.182_9	0.179_8
-195.2_5	77.90	0.131_3	0.127_9
-252.8	20.35	0.001_0	0.001_6

* R_0 is the resistance at 0°C.

Rosenberg (1954)	
Temp. °K	ρ/ρ_{273}
2.5	0.00630*
5	0.00623*
10	0.00632*
15	0.0068
25	0.0096

* The fifth decimal place is in doubt.

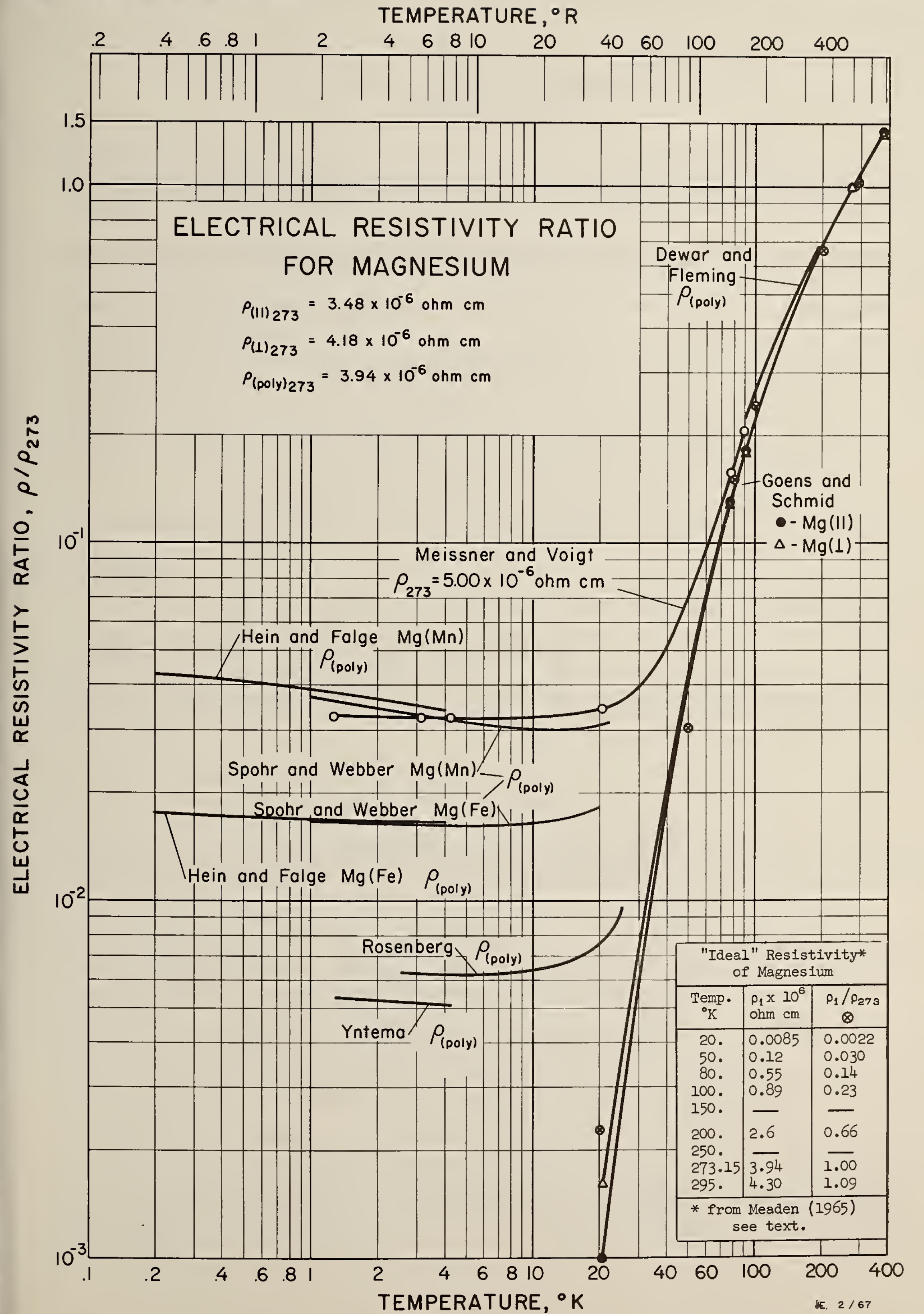
Bridgman (1952) (Resistance compared to resistance at room temperature and one atmosphere pressure.)			
Pressure kg/cm²	R/R_o	Pressure kg/cm²	R/R_o
0	1.000	60000	0.817
10000	0.953	70000	0.800
20000	0.916	80000	0.786
30000	0.886	90000	0.776
40000	0.859	100000	0.767
50000	0.837		

Spohr and Webber (1957) *				
Temp.	Resistivity, $\rho \times 10^8$ ohm cm		ρ/ρ_{273}	
°K	Mg(Fe)	Mg(Mn)	Mg(Fe)	Mg(Mn)
1	6.624	14.79	0.0168	0.0375
3	6.50	13.21	0.0165	0.0335
5	6.46	12.70	0.0164	0.0322
7	6.47	12.24	0.0164	0.0311
10	6.53	12.00	0.0166	0.0305
12	6.61	11.90	0.0168	0.0302
15	6.78	11.87	0.0172	0.0301
17	6.95	11.95	0.0176	0.0303
20	7.25	12.20	0.0184	0.0310
22		12.40		0.0315

* read from graph.

Hein and Falge (1957) *				
Temp.	Resistivity, $\rho \times 10^8$ ohm cm		ρ/ρ_{273}	
°K	Mg(Fe)	Mg(Mn)	Mg(Fe)	Mg(Mn)
0.2	6.92	16.90	0.0176	0.0429
0.4	6.86	16.40	0.0174	0.0416
0.8	6.75	15.66	0.0171	0.0397
1.2	6.70	15.18	0.0170	0.0385
1.6	6.66	14.78	0.0169	0.0375
2.0	6.60	14.48	0.0168	0.0368
2.4	6.60	14.20	0.0168	0.0360
2.8	6.59	13.96	0.0167	0.0354
3.2	6.59	13.72	0.0167	0.0348
3.6	6.58	13.60	0.0167	0.0345
4.0	6.58	13.48	0.0167	0.0342

* read from graph.



"Ideal" Resistivity* of Magnesium

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.0085	0.0022
50.	0.12	0.030
80.	0.55	0.14
100.	0.89	0.23
150.	—	—
200.	2.6	0.66
250.	—	—
273.15	3.94	1.00
295.	4.30	1.09

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-18

ELECTRICAL RESISTIVITY OF MOLYBDENUM, Mo (Atomic Number 42)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Holmwood, R. A., and Glang, R., "Resistivity and Temperature Coefficient of Pure Molybdenum," J. Chem. Eng. Data 10, 162-3 (1965).

Kannuluik, W. G., "The Thermal and Electrical Conductivities of Several Metals Between -183°C and 100°C," Proc. Roy. Soc. (London) A141, 159-68 (1931).

McLennan, J. C., Howlett, L. E., and Wilhelm, J. O., "On the Electrical Conductivity of Certain Metals at Low Temperatures," Trans. Roy. Soc. (Canada) 23, 287-306 (1929).

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

White, G. K., and Woods, S. B., "Electrical and Thermal Resistivity of the Transition Elements at Low Temperatures," Phil. Trans. Roy. Soc. (London) A251, 273-302 (1959).

Other References:

Blom, E. C., "Temperature Coefficient of Resistance of Molybdenum," Phys. Rev. 13, 308 (1919).

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).

Goree, W. S., "Electrical Conductivity of Metals at High Pressures and Low Temperatures," Univ. of Florida, Gainesville, Ph.D. Thesis (1964), (Avail. from Univ. Microfilms, Ann Arbor, Mich., Order No. 65-5985).

Holborn, L., Ann. Physik 59, 145 (1919).

Meissner, W., Physik. Z. 29, 897-904 (1928).

Meissner, W., and Voigt, B., "Messungen mit Hilfe von flüssigem Helium. XI. Widerstand der reinen Metalle in tiefen Temperaturen," (Measurements with the Help of Liquid Helium. XI. Resistance of Pure Metals at Low Temperatures), Ann. Physik 7, 892-936 (1930).

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Taylor, R. E., and Finch, R. A., "The Specific Heats and Resistivities of Molybdenum, Tantalum, and Rhenium from Low to Very High Temperatures," North Am. Aviation Inc., Atomics Intern. Div., Canoga Park, Calif., NAA-SR-6034 (1961) Contr. AT(11-1)-Gen-8, 32 pp.

Taylor, R. E., and Finch, R. A., "The Specific Heats and Resistivities of Molybdenum, Tantalum, and Rhenium," J. Less Common Metals 6, No. 4, 283-94 (Apr 1964).

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).

Volkenshtein, N. V., Romanov, E. P., Starostina, L. S., et al., "Temperature Dependence of Electric Resistance of Molybdenum Single Crystals," Fiz. Metal. i Metalloved 17, No. 4, 627-9 (1964).

Volkenshteyn, N. V., Starostina, L. S., Startsev, V. Ye., and Romanov, Ye. P., "Temperature Dependence of the Low-Temperature Electrical Conductivity of Molybdenum and Tungsten Single Crystals," Phys. Metals Metallog. 18, 85-90 (1964), Transl. of Fiz. Metal. i Metalloved. 18, No. 6, 888-94 (1964).

Worthing, A. G., "Physical Properties of Well Seasoned Molybdenum and Tantalum as a Function of Temperature," Phys. Rev. 28, 190-201 (1920).

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 a datum temperature of 273°K. When the actual values of ρ_{273} for the samples used by the several investigators are not available, a datum value reported by Holmwood and Glang (ρ_{273} = 5.0 x 10^{-6} ohm cm) is suggested for calculating 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.

The values listed in the Landolt-Börnstein tables are those reported by Meissner and Voigt; and Blom; while the values listed by the International Critical Tables are from Holborn. The samples used by both authors are listed as polycrystalline with no mention made of impurities present. No reference is made as to the nature of the sample used by Holborn, and no information is available on mechanical strain or heat treatment for any of the samples from any of the above sources of data. Meissner & Voigt gave ρ_{273} = 5.22 x 10^{-6} ohm cm. Blom gave ρ_{273} = 4.4 x 10^{-6} ohm cm.

The McLennan et al. (1929) wire sample was "baked in vacuo at a high temperature for a number of hours" prior to measurement. They do not list the purity of the sample.

Kannuluik (1931) used a 99.83% pure wire sample.

The three samples used by White and Woods (1959) were 99.9% pure wires. One sample was vacuum annealed at 1350°C prior to measurement, but the other two were not given any further treatment. The tabular data are smoothed values obtained from large-scale graphs.

Holmwood and Glang (1965) measured the resistivity of a 99.999% molybdenum bar, zone purified in vacuum and nearly single crystalline.

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)

Holborn (1919)	
Temp. °C	$100R/R_{273}$
- 78.2	66.60
- 80*	65.9
-100*	57.4
-120*	48.9
-140*	40.5
-160*	32.2
-180*	24.2
-192.5	19.11
* Values from interpolation	

Mc Lennan, Howlett, and Wilhelm (1929)	
Temp. °K	Resistance Ratio $R/R_{0°C}$
2.3	0.079
4.2	0.079
20.6	0.079
84.1	0.206
273.1	1.00
298.6	1.12

Meissner and Voigt (1930)	
Temp. °K	ρ/ρ_{273}*
1.5	0.0462*
4.2	0.0455
20.4	0.0448
77.8	0.1370
86.9	0.1701
273.16	1.0000

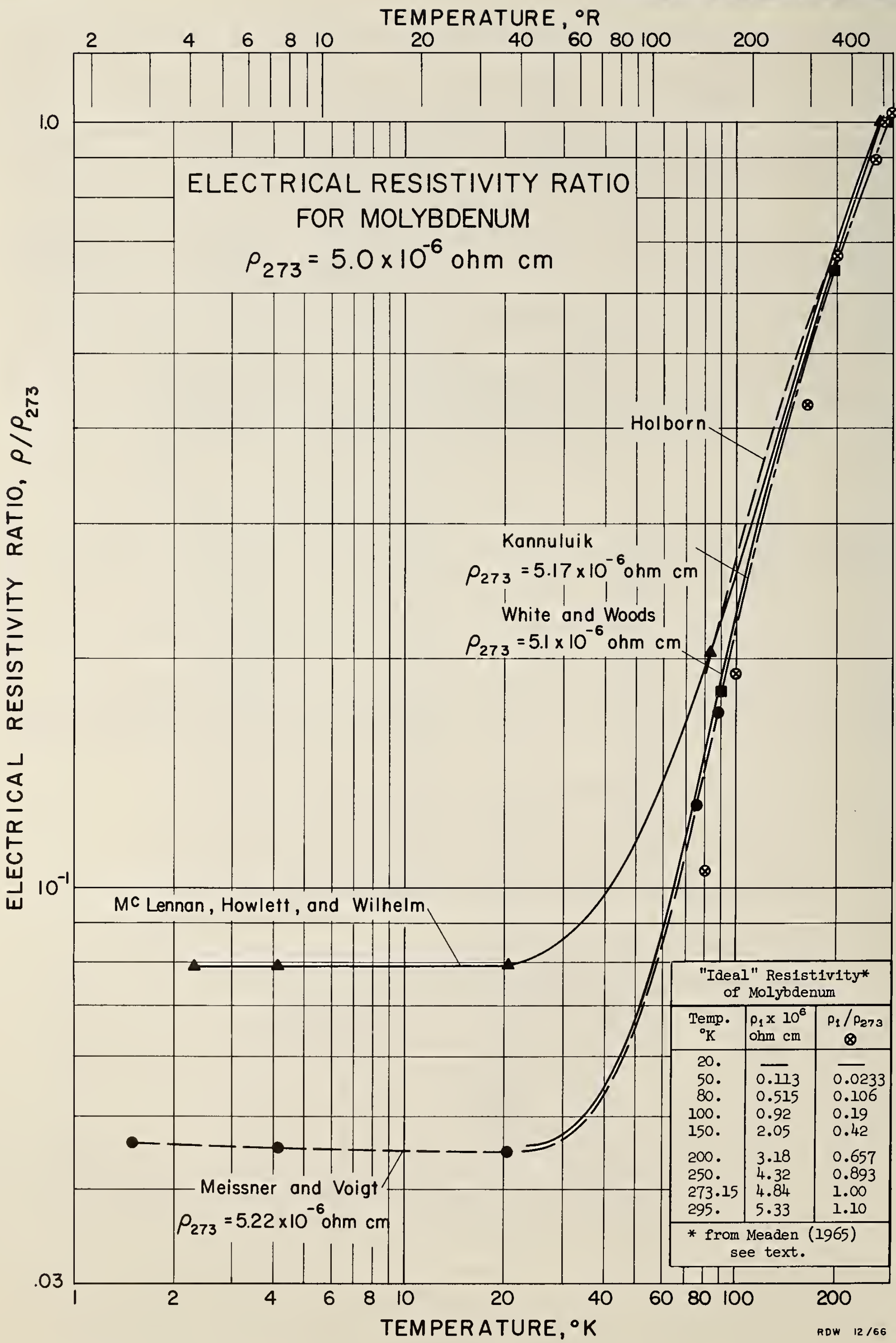
* ρ_{273} = 5.22 x 10^{-6} ohm cm;
$\rho_{1.5}$ = 0.241 x 10^{-6} ohm cm.

Kannuluik (1931)				
Sample	Temp. °C	Temp. °K	Specific Resistance ρ x 10^6 ohm cm	ρ/ρ_{273}
Mo 1	-183.0	90.15	0.952	0.181
	- 78.5	194.65	3.39	0.646
	0.	273.15	5.25	1.00
	100.	373.15	7.67	1.46
Mo 2	-183.0	90.15	0.882	0.171
	78.5	194.65	3.33	0.644
	0.	273.15	5.17	1.00
	100.	373.15	7.56	1.46

White and Woods (1959)			
Temp. °K	"Ideal resistivity" ρ_i x 10^6 ohm cm	Resistivity, ρ x 10^6 ohm cm $\rho = \rho_i + \rho_o$ where ρ_o = 0.227 x 10^{-6} ohm cm	ρ/ρ_{273}
25	0.004_6	0.232	0.0458
30	0.01_2	0.239	0.0472
40	0.04_7	0.274	0.0541
50	0.11_3	0.340	0.0671
60	0.21_6	0.443	0.0874
70	0.35_4	0.581	0.1147
80	0.51_5	0.742	0.1464
90	0.71_4	0.941	0.1857
100	0.92	1.147	0.2264
120	1.36	1.587	0.3132
140	1.8_2	2.047	0.4040
160	2.2_7	2.497	0.4928
180	2.7_3	2.957	0.5836
200	3.1_8	3.407	0.6724
220	3.6_4	3.867	0.7632
250	4.3_2	4.547	0.8974
273	4.8_4	5.067	1.0000
295	5.3_3	5.557	1.0967

Holmwood and Glang (1965)		
Temp. °C	Temp. °K	Resistivity* ρ x 10^6, ohm cm
-196	77.15	0.486
0	273.15	5.00
25	298.15	5.57
50	323.15	6.17
75	348.15	6.78
100	373.15	7.40

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



"Ideal" Resistivity* of Molybdenum

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	——	——
50.	0.113	0.0233
80.	0.515	0.106
100.	0.92	0.19
150.	2.05	0.42
200.	3.18	0.657
250.	4.32	0.893
273.15	4.84	1.00
295.	5.33	1.10

* from Meaden (1965) see text.

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CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-19

ELECTRICAL RESISTIVITY OF NICKEL, Ni
(Atomic Number 28)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Broom, T., "The Effect of Temperature of Deformation on the Electrical Resistivity of Cold-Worked Metals and Alloys," Proc. Phys. Soc. (London) B65, 871-81 (1952).

Greig, D., and Harrison, J. P., "The Low Temperature Electrical Transport Properties of Nickel and Dilute Nickel-Copper Alloys," Phil. Mag. 12, No. 115, 71-79 (1965).

Kemp, W. R. G., 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 (1956).

Kondorsky, E., Galkina, O. S., and Tchernikova, L. A., "Nature of Electrical Resistivity of the Ferromagnetic Metals at Low Temperatures," J. Appl. Phys. 29, No. 3, 243-6 (1958), also Zh. Eksperim. i Teor. Fiz. 34, No. 5, 1070-6 (1958).

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 with the Help of Liquid Helium, XI. Resistance of Pure Metals at Low Temperatures), Ann. Physik (5) 7, 892 (1930).

Sudovtsov, A. I., and Semenenko, E. E., "Peculiarities of the Temperature Dependence of the Electrical Resistance of Ferromagnetic Metals at Low Temperatures," Zh. Eksptl. i Teor. Fiz. 31, 525 (1956), Soviet Phys. JETP 4, 592 (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, 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).

Dewar, J., Proc. Roy. Soc. (London) 73, 244 (1904).

Fleming, J. A., Proc. Roy. Soc. (London) 66, 50 (1900).

Grüneisen, E., "Elektrische Leitfahigkeit der Metalle bei tiefen Temperaturen," (Electrical Conductivity of Metals at Low Temperatures), Ergebn. exakt. Naturw. 21, 50-116 (1945).

Meissner, W., Physik. Z. 27, 725 (1926).

Mott, N. F., "Resistance and Thermoelectric Properties of Transition Metals," Proc. Roy. Soc. (London) A156, 368-82 (1936).

Schwerer, F.C., and Silcox, J., "Electrical Resistivity of Nickel at Low Temperatures," Phys. Rev. Letters 20, No. 3, 101-3 (Jan 1968).

Volvick, G., "Influence de la pression d'un gaz neutre sur la resistance d'un fil de nickel," (Effect of the Pressure of a Neutral Gas on the Resistance of Nickel Wire), Compt. Rend. 252, 1285-87 (1961).

Wise, E. M., Proc. Inst. Radio Engrs. 25, 714 (1937).

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 a datum temperature of 273°K. When the actual values of ρ_{273} for the samples used by the several investigators are not available, a datum value reported by White and Woods (1959) (ρ_{273} = 6.23 x 10^{-6} ohm cm) is suggested for calculating 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.

The values listed in the Landolt-Bornstein tables are those reported by Meissner and Wise; while those values appearing in the International Critical Tables are from Dewar and Fleming. These primary references are cited above under "Other References". The original authors are used in labeling both curves on the graph.

The Landolt-Bornstein tables list the sample used by Wise as polycrystalline with 0.01% impurities of unknown composition. A value of 6.14×10^{-6} ohm cm was reported by Wise for 273°K. The sample used by Meissner is reported as polycrystalline and was annealed in a hydrogen atmosphere.

Meissner and Voigt (1930) report the same data as Meissner (1926).

Broom's sample (1952) was 99.8% pure nickel wire and was annealed for two hours at 600°C before measurements were made. The values in the table below were before deformation.

The purity of the nickel sample used by Kemp, et al. (1956) was greater than 99.99%. The sample was in the form of a 2 mm diameter rod which was annealed four hours in vacuo at 750°C prior to measurement.

The Sudovtsov and Semenenko (1957) paper available to us was the Russian version and therefore I could not find out anything about the sample.

The nickel wires used by Kondorsky et al. (1958) were made from chemically pure material. The specimens were heated in a vacuum at 900°C for one hour and then cooled slowly within the furnace. The residual resistivity was 0.20×10^{-6} ohm cm.

White and Woods (1959) used 99.997% pure nickel rods which were annealed in vacuo at 800°C prior to measurement. These smoothed tabular values were read from a large-scale graph.

Greig and Harrison (1965) used 99.998% pure nickel rod with 2 mm diameter which had been annealed for 12 hours at 850°C. The values in the table below were read from their graph.

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)

Dewar and Fleming (1904, 1900)					
Temp. °C	Temp. °K	100 ρ/ρ_{273}	Temp. °C	Temp. °K	100 ρ/ρ_{273}
- 78.3	194.85	61.3	-180 †	93.15	21.7
- 80 †	193.15	60.5	-182.9	91.25	20.8
-100 †	173.15	51.8	-200 †	73.15	15.6-
-120 †	153.15	43.7	-220 †	53.15	11.2
-140 †	133.15	36.1	-240 †	33.15	8.9
-160 †	113.15	28.7	-252.7	20.45	8.5
† Values are from interpolation					

Meissner and Voigt (1930) Meissner (1926)	
Temp.* °K	R/R_{273}**
1.34†	0.00503
4.21	0.00508
20.40	0.00662
78.8	0.0919
87.4	0.1179
273.16†	1.0000

* The second decimal place is in doubt.
** The fifth decimal place is in doubt.
† $\rho_{1.34} = 0.035 \times 10^{-6}$ ohm cm.
$\rho_{273} = 7.07 \times 10^{-6}$ ohm cm.

Broom (1952)			
Temp. °C	Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
-183.0	90.15	1.77	0.24
- 78.5	194.65	4.59	0.62
0.0	273.15	7.37	1.00
100.0	373.15	11.56	1.57

Kemp, Klemens, and White (1956) (read from graph)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ (where $\rho_0 = 0.0347 \times 10^{-6}$ ohm cm)	ρ/ρ_{273}
12	0.0043	0.0390	0.0063
15	0.0055	0.0402	0.0065
17	0.0075	0.0422	0.0068
27	0.024	0.0587	0.0095
38	0.066	0.101	0.0163
57	0.20	0.235	0.0379
78	0.45	0.485	0.0782
110	1.3	1.33	0.215
160	2.5	2.53	0.408
293	7.2	7.22*	1.166

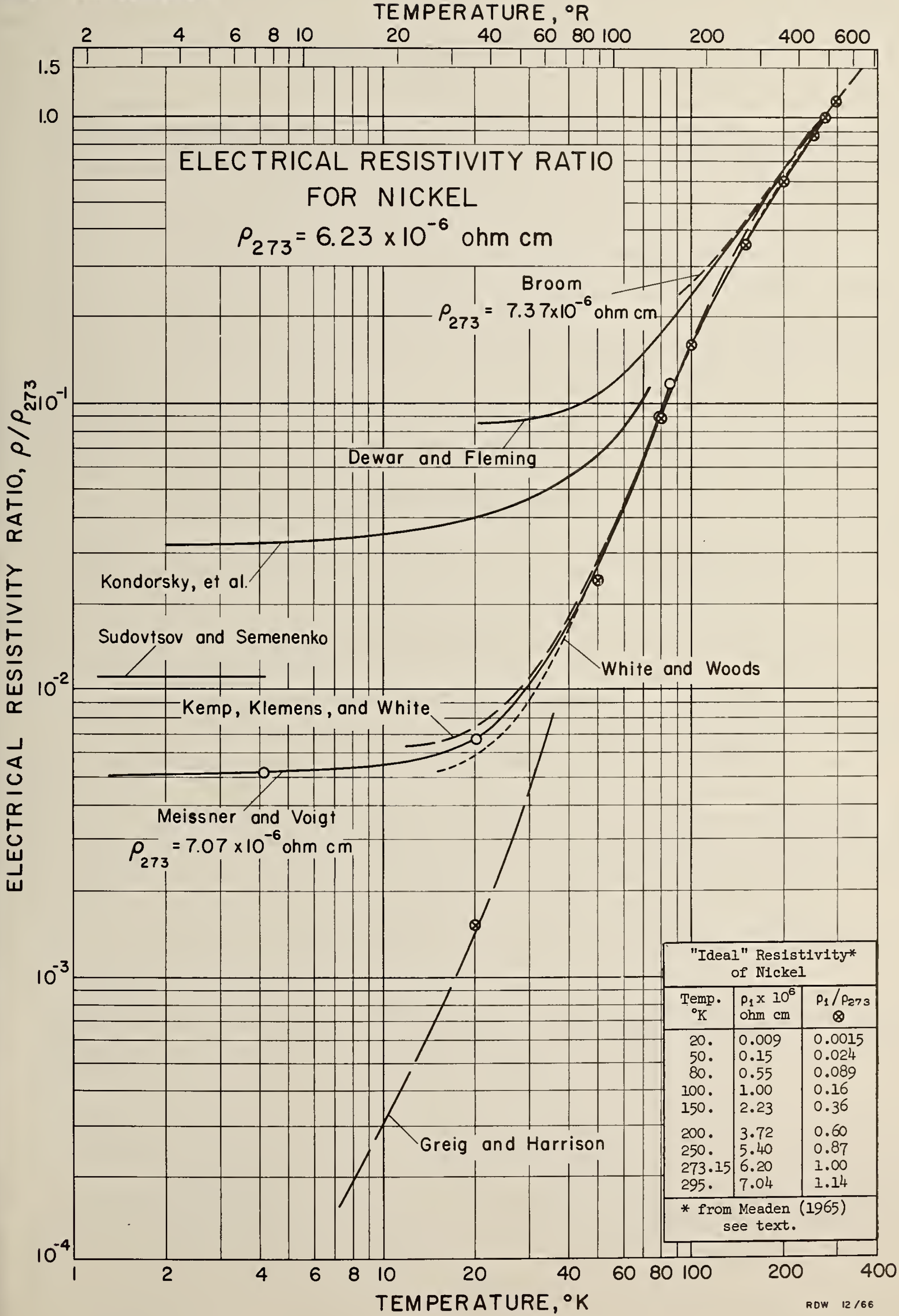
* Reported in text.

Sudovtsov and Semenenko (1957) (read from graph)	
Temp. °K	R/R_{273}
1.2	0.010105
1.6	0.010108
2.0	0.010112
2.6	0.010120
3.0	0.010125
3.6	0.010136
4.0	0.010144
4.2	0.010148

Kondorsky, Galkina and Tchernikova (1958) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
2	0.20	0.032
20	0.25	0.040
40	0.35	0.056
60	0.50	0.081
73	0.71	0.11

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 0.0280 \times 10^{-6}$ ohm cm)	ρ/ρ_{273}
15	0.004_5	0.0325	0.0052
20	0.009	0.037	0.0059
25	0.017	0.045	0.0072
30	0.03_0	0.058	0.0093
40	0.07_3	0.101	0.0162
50	0.15	0.178	0.0286
60	0.24_5	0.273	0.0438
70	0.38	0.408	0.0655
80	0.55	0.578	0.0928
90	0.75	0.778	0.125
100	1.0_0	1.028	0.165
120	1.4_6	1.488	0.239
140	1.9_7	1.998	0.321
160	2.5_2	2.548	0.409
180	3.1_0	3.128	0.502
200	3.7_2	3.748	0.602
220	4.3_6	4.388	0.705
250	5.4_0	5.428	0.872
273	6.2_0	6.228	1.00
295	7.0_4	7.068	1.13

Greig and Harrison (1965) (read from graph)		
Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}
7.5	0.001	0.00016
10.05	0.002	0.00032
15.05	0.005	0.00081
21.0	0.01	0.0016
26.0	0.02	0.0032
35.0	0.05	0.0081



"Ideal" Resistivity* of Nickel

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.009	0.0015
50.	0.15	0.024
80.	0.55	0.089
100.	1.00	0.16
150.	2.23	0.36
200.	3.72	0.60
250.	5.40	0.87
273.15	6.20	1.00
295.	7.04	1.14

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-20

ELECTRICAL RESISTIVITY OF NIOBIUM, Nb
(Atomic Number 41)

Sources of Data:

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

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, 165-251 (1952).

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

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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).

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Reimann, A. L., and Grant, K., Phil. Mag. (7) 22, 34 (1936).

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 (1961).

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 the resistivity at a datum temperature of 273°K. The value of the electrical resistivity at 273°K (ρ_{273}) for niobium to be used in calculating values of electrical resistivity (ρ) is 13.96 x 10^{-6} ohm cm from White and Woods (1959). These data should not be extrapolated to lower temperatures as niobium becomes a superconductor at about 9.3°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.

The values listed in the Landolt-Börnstein tables are those reported by Meissner, Franz and Westerhoff; and Reimann and Grant, cited above under "Other References". The Landolt-Börnstein tables list the samples used by Meissner, et al. as polycrystalline with 0.08% O_2 and 0.02% Ta impurities present. No other pertinent information is given about either of the samples. Reimann and Grant reported a value of ρ_{273} = 16.1 x 10^{-6} ohm cm.

Bridgman (1952) measured the effect of pressure on electrical resistivity of metal sheets of 0.0012 inch thickness. The purity of the sample was not given. His reported values are ratios of resistance at the given pressure to resistance at room temperature and one atmosphere pressure.

The niobium samples used by White and Woods (1957) were 99.7 and 99.9% pure and were in the form of rods and wires. Their table of values "may be regarded as somewhat tentative below 30°K, Mattheissen's rule not being strictly valid". They found that niobium becomes superconducting at 9.25°K.

White and Woods (1959) cite their 1957 work as the basis for their tabular values. These values differ from the earlier ones in the lower temperature region. They note that there is appreciable uncertainty in the value of ρ_0.

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)

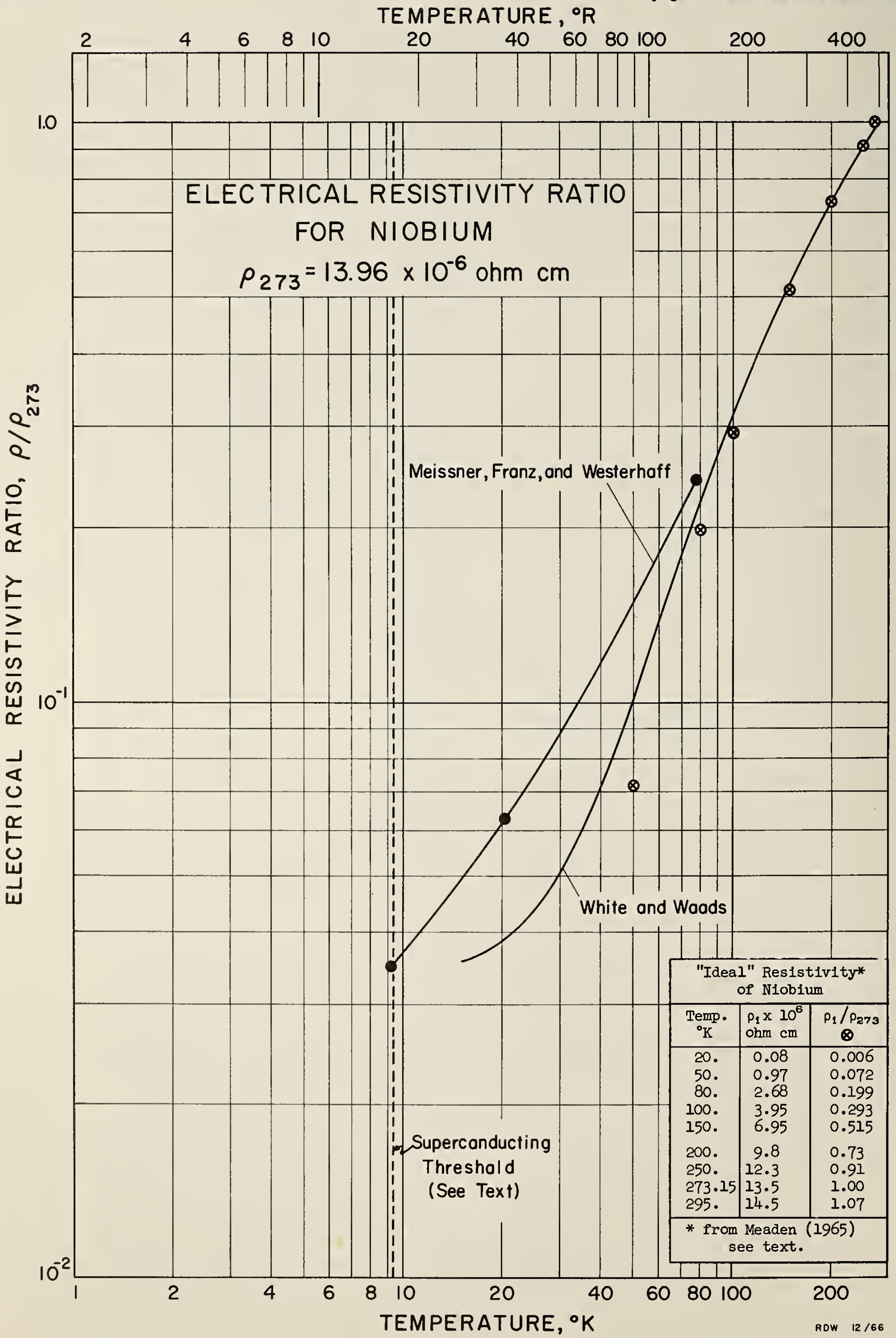
ρ_{273} = Resistivity at 273°K, (ohm cm)

Meissner, Franz and Westerhoff (1933)	
Temp. °K	R/R_{273}
9.33	0.035
20.4	0.0617
78	0.2416
273.16	1.0000

Bridgman (1952)	
Pressure kg/cm^2	R/R_0 (Resistance compared with the resistance at room temperature and 1 atmosphere)
0	1.000
10000	0.986
20000	0.973
30000	0.961
40000	0.950
50000	0.938
60000	0.928
70000	0.918
80000	0.909
90000	0.901
100000	0.894

White and Woods (1957)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ (where $\rho_0 = 0.46 \times 10^6$ ohm cm)	ρ/ρ_{273}
15	0.03_8	0.498	0.0357
20	0.08_4	0.544	0.0390
30	0.2_5	0.71	0.0508
40	0.5_6	1.02	0.0730
50	0.9_7	1.43	0.102
75	2.3_6	2.82	0.202
100	3.9_0	4.36	0.312
150	7.0	7.46	0.534
200	9.8	10.26	0.735
250	12.3	12.76	0.914
273	13.5	13.96	1.00
295	14.5	14.96	1.07

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_o$ (where $\rho_o = 0.46 \times 10^{6}$ ohm cm)	ρ/ρ_{273}
15	0.03_5	0.495	0.0354
20	0.08	0.54	0.0387
25	0.1_5	0.61	0.0437
30	0.25	0.71	0.0508
40	0.5_6	1.02	0.0730
50	0.9_7	1.43	0.102
60	1.5	1.96	0.140
70	2.0_7	2.53	0.181
80	2.6_8	3.14	0.225
90	3.3_0	3.76	0.269
100	3.9_5	4.41	0.316
120	5.2	5.66	0.405
140	6.4	6.86	0.491
160	7.5_5	8.01	0.574
180	8.7	9.16	0.656
200	9.8	10.26	0.735
220	10.8	11.26	0.806
250	12.3	12.76	0.914
273	13.5	13.96	1.00
295	14.5	14.96	1.07



"Ideal" Resistivity* of Niobium

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.08	0.006
50.	0.97	0.072
80.	2.68	0.199
100.	3.95	0.293
150.	6.95	0.515
200.	9.8	0.73
250.	12.3	0.91
273.15	13.5	1.00
295.	14.5	1.07

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-21

ELECTRICAL RESISTIVITY OF PLATINUM, Pt
(Atomic Number 78)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Cath, P. G., Onnes, H. K., and Burgers, J. M., "On the Measurement of Very Low Temperatures. XXVIII. Comparison of the Platinum and the Gold Resistance Thermometers with the Helium Thermometer," Communs. Phys. Lab. Univ. Leiden No. 152c (1917).

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Hoge, H. J., and Brickwedde, F. G., "Establishment of a Temperature Scale for the Calibration of Thermometers between 14° and 83°K," J. Res. Natl. Bur. Std. 22, 351-73 (1939).

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Meissner, W., and Voigt, B., "Messungen mit Hilfe von flüssigem Helium. XI. Widerstand der reinen Metalle in tiefen Temperaturen," (Measurements with the Help of Liquid Helium. XI. Resistance of Pure Metals at Low Temperatures), Ann. Physik (5) 7, 892 (1930).

Powell, R. W., Tye, R. P., and Woodman, M. J., "Thermal Conductivities and Electrical Resistivities of the Platinum Metals," Platinum Metals Rev. 6, No. 4, 138-43 (1962).

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Other References:

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Bridgman, P. W., "The Electric Resistance to 30,000 kg/cm² of Twenty Nine Metals and Intermetallic Compounds," Proc. Am. Acad. Arts Sci. 149-79 (1951).

Grüneisen, E., "Electrische Leitfahigkeit der Metalle bei tiefen Temperaturen", (Electrical Conductivity of Metals at Low Temperatures), Ergebn. exakt. Naturw. 21, 50-116 (1945).

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Holborn, L., Ann. Physik 59, 145 (1919).

Kos, J. F., and Lamarche, J. L. G., "The Electrical Resistivity of Thermometrically Pure Platinum below 11°K," Can. J. Phys. 45, No. 2, Part 1, 339-54 (1967).

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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 a datum temperature of 273°K. The value of electrical resistivity at 273°K (ρ_{273}) for platinum to be used in calculating values of electrical resistivity (ρ) is 9.60×10^{-6} ohm cm. This value is taken from White and Woods (1959).

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.

The values listed in the Landolt-Börnstein tables are those reported by Holborn; Meissner; and Meissner and Grassmann; while those values appearing in the International Critical Tables are from Henning; Onnes and Tuyn; and Van der Horst, Tuyn and Onnes. These primary sources are listed above under "Other References". The original authors are used in labeling the several curves on the graph. The sample used by Holborn is reported in the Landolt-Börnstein tables as cast polycrystalline with a very small amount of impurities present. The Meissner sample from the 1915 reference is reported to have been annealed. Meissner found $\rho_{273} = 9.81 \times 10^{-6}$ ohm cm. The sample used by Meissner and Grassmann is reported as an annealed polycrystalline sample with less than 0.001% of Cu and Pb impurities present.

The Cath et al. (1917) measurements were made with "extremely pure" platinum wires with 1/10 mm diameter. The wires are designated Pt-21 and Pt-26.

Meissner and Voigt (1930) report the same data as that found in the earlier Meissner paper (1928). The calculated value of ρ_{273} from the (1930) paper is 9.53×10^{-6} ohm cm.

The samples used by de Haas and de Boer (1933-1934) were 99.999% pure wires (6mm diameter) which had been previously tempered for 20 minutes at 750°C.

Hoge and Brickwedde (1939) measured the resistance of several platinum resistance thermometers in an effort to establish a method for measuring temperature below 83°K by a means other than the gas thermometer. The data for thermometer L6 was used to construct a table of smoothed values. The purity of the platinum was not stated.

Van der Leeden's (1940) measurements were made with 0.15 mm diameter wire which had been vacuum annealed at 840°C for 2 hours. The purity of the sample was not stated.

White and Woods (1957) used 99.99% pure rods which had been annealed at 1050°C prior to measurement. White and Woods (1959) used their 1957 measurements plus some additional measurements to obtain their table of smoothed values.

Powell et al. (1962) used 99.9997% pure platinum polycrystalline rods which were annealed at $\sim$ 1000°C prior to measurement. They report one value at 273°K, $\rho_{273} = 9.85 \times 10^{-6}$ 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.

Powell et al.(1967) measured the resistivity of polycrystalline rods which were annealed at 1273°K prior to measurement. The purity of the sample was ~99.999995%.

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 (1915)	
Temp. °K	ρ/ρ_{273}
20.7	0.00631
91.4	0.250
273.1	1.000
* $\rho_{273} = 9.81 \times 10^{-6}$ ohm cm	

Cath, Onnes, and Burgers (1917)			
Pt-21		Pt-26	
Temp. °K	R/R_0*	Temp. °K	R/R_0*
273.09	1.00000	273.09	1.00000
250.08	0.90890	250.08	0.90867
230.07	0.82907	230.07	0.82839
211.79	0.75545	211.79	0.75453
170.07	0.58615	170.07	0.58468
160.37	0.54627	160.37	0.54469
152.26	0.51277	152.26	0.51111
142.72	0.47313	142.72	0.47132
129.44	0.41762	129.44	0.41570
89.14	0.24605	89.14	0.24375
85.98	0.23249	85.98	0.23014
77.21	0.19475	77.21	0.19233
67.78	0.15459	67.78	0.15210
64.91	0.14261	64.91	0.14011
61.04	0.12667	61.04	0.12419
56.83	0.10959	56.83	0.10704
50.31	0.084278		
44.38	0.063510		
43.83	0.061757		
43.78	0.061566		
43.09	0.059297		
41.39	0.054016		
39.48	0.048324		
36.29	0.039554		
36.25	0.039425	36.28	0.037087
32.83	0.031219	32.83	0.028743
31.32	0.027921	31.31	0.025470
29.88	0.025195	29.88	0.022698
29.42	0.024253		
28.40	0.022524		
27.30	0.020618	27.30	0.018208
20.62	0.012535	20.58	0.010172
20.52	0.012415	20.52	0.010103
20.50	0.012412	20.52	0.010098
19.04	0.011235	20.50	0.010093
18.08	0.010559	20.31	0.010015
16.94	0.0098758	20.25	0.0098924
15.36	0.0090808	18.08	0.0083504
14.20	0.0085984	14.18	0.0065589

* These values are almost identical with the values of Van der Horst et al. and therefore were not plotted on the Electrical Resistivity of Platinum graph.

Holborn (1919)		Meissner and Voigt (1930) Meissner (1926)		Meissner and Grassmann (1933)	
Temp. °K	R/R_{273}	Temp.* °K	R/R_{273}**	Temp.* °K	ρ/ρ_{273}**
20	0.0060	1.35 †	0.00165	1.35	0.00031
81	0.2060	4.21	0.00168	4.2	0.00031
195	0.6860	20.4	0.00607	20.4	0.00425
		91.4	0.250		
		273.16 †	1.000		

* The second decimal place is in doubt.
** The fifth decimal place is in doubt.

† $\rho_{1.35} = 0.016 \times 10^{-6}$ ohm cm,
$\rho_{273} = 9.53 \times 10^{-6}$ ohm cm.

	Onnes and Tuyn (1926)	Van der Horst et al. (1929)	Henning (1926)
Temp., °C	$100R/R_{273}$	$100R/R_{273}$	$100\rho/\rho_{273}$
- 80	68.158	68.017	67.782
- 90	64.113	63.955	63.688
-100	60.053	59.874	59.576
-120	51.863	51.650	51.295
-140	43.595	43.337	42.928
-160	35.213	34.904	34.463
-180	26.709	26.356	25.885
-200	18.176	17.750	17.268
-210	14.009	13.563	--
-220	--	9.587	--
-230	--	6.030	--
-240	--	3.252	--
-250	--	1.571	--
-255	1.5885	1.1263	0.5706
-260	1.335	0.894	--
-265	1.239	0.810	--
-270	1.225	0.7863	--

de Haas and de Boer (1933 - 1934)			
Temp. °K	$R/R_{0°C}$	Temp. °K	$R/R_{0°C}$
0.00	0.0003621	9.07	0.0005770
1.07	0.0003638	9.96	0.0006500
1.68	0.0003664	11.01	0.0007641
2.49	0.0003712	13.14	0.0011129
3.36	0.0003791	14.09	0.0013335
4.25	0.0003902	15.31	0.0017107
5.28	0.0004098	16.47	0.0021656
6.75	0.0004535	17.45	0.0026332
7.41	0.0004797	18.51	0.0031913
8.51	0.0005387	19.60	0.0038916
8.82	0.0005598	20.44	0.0045148

Hoge and Brickwedde (1939) (smoothed values based on thermometer L6)	
Temp. °K	$R/R_{0°C}$
10	0.002789
13	0.003298
15	0.003868
20	0.006513
25	0.011539
30	0.019454
35	0.030348
40	0.043967
50	0.077525
60	0.116550
70	0.158396
80	0.201338
90	0.244716

Van der Leeden (1940)					
Temp. °K	$100R/R_0$	Temp. °K	$100R/R_0$	Temp. °K	$100R/R_0$
4.24	0.068474	20.43	0.4664	17.37	0.2731
3.72	0.067781	19.42	0.3918	16.32	0.2265
3.15	0.067178	18.26	0.3204	15.18	0.1839
2.70	0.066786	18.23	0.3215	14.13	0.1535
0.00	0.065760	17.38	0.2742		

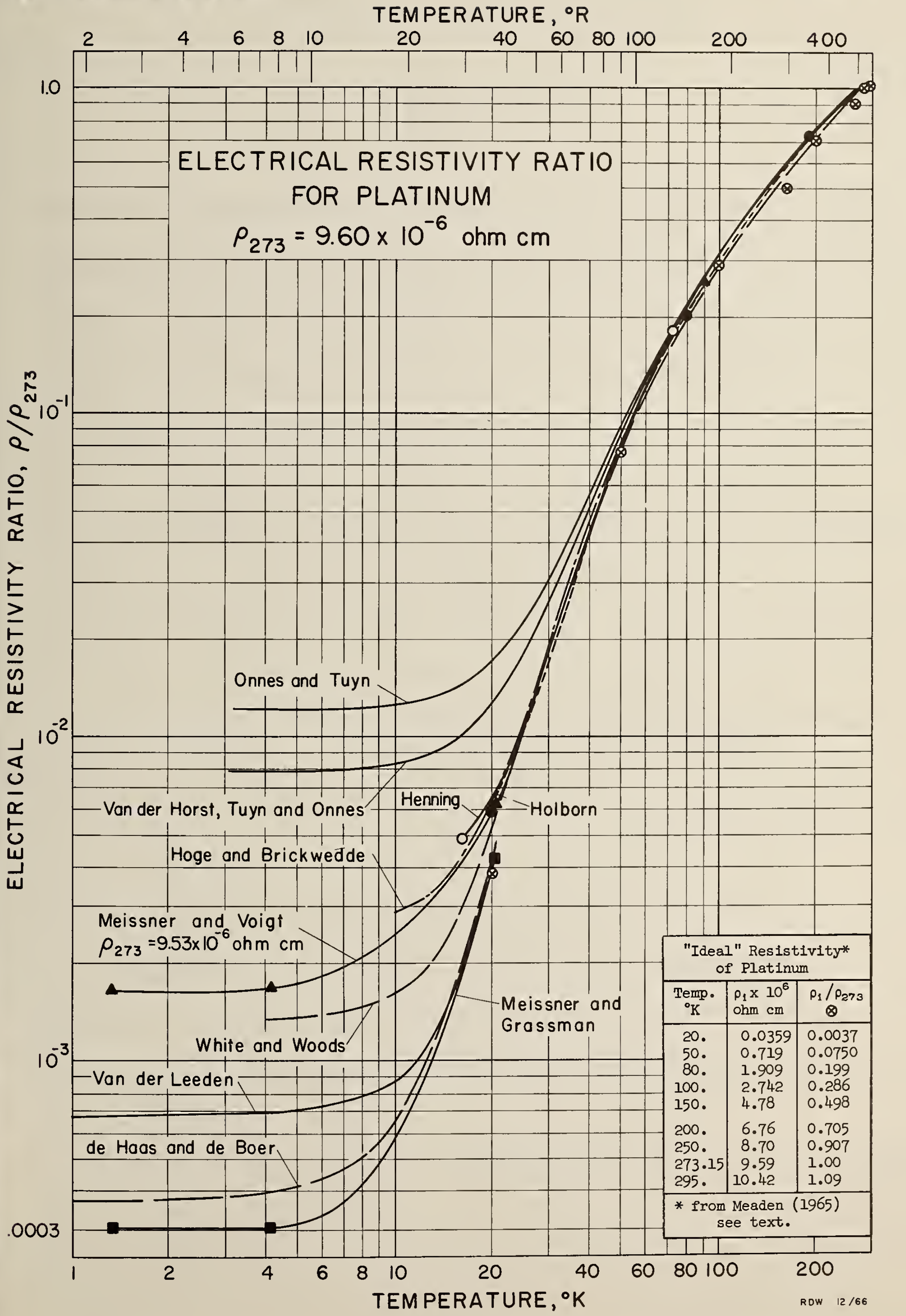
White and Woods (1957)			
Temp. °K	"Ideal Resistivity" ρ_i x 10^6 ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ (where $\rho_0 = 0.0125 \times 10^{-6}$ ohm cm)	ρ/ρ_{273}*
6	0.0006	0.0131	0.00134
10	0.0031	0.0156	0.00159
15	0.0155	0.0280	0.00286
20	0.044	0.057	0.0058
30	0.180	0.193	0.0197
40	0.45	0.46	0.047
50	0.76	0.77	0.079
75	1.7_2	1.73	0.176
100	2.8_0	2.81	0.287
150	4.8_0	4.81	0.491
200	6.8_0	6.81	0.695
273	9.8_0	9.81	1.00
295	10.65	10.66	1.09

* These values were not shown on the Electrical Resistivity Ratio for Platinum graph which is found on the last page of this Data Memorandum No. M-21.

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ (where $\rho_0 = 0.0125 \times 10^{-6}$ ohm cm)	ρ/ρ_{273}
4	0.0002_4	0.01274	0.001325
6	0.0006_5	0.01315	0.001368
8	0.001_4	0.0139	0.001446
10	0.0029	0.0154	0.00160
15	0.0116	0.0241	0.00251
20	0.0359	0.0484	0.00503
25	0.0837	0.0962	0.01000
30	0.160	0.173	0.0180
40	0.396	0.409	0.0425
50	0.719	0.732	0.0761
60	1.094	1.107	0.115
70	1.49_7	1.510	0.157
80	1.90_9	1.922	0.200
90	2.32_6	2.339	0.243
100	2.74_2	2.755	0.287
120	3.56_5	3.578	0.372
140	4.37_5	4.387	0.456
160	5.18	5.19	0.540
180	5.97	5.98	0.622
200	6.76	6.77	0.704
220	7.54	7.55	0.785
250	8.70	8.71	0.906
273	9.59	9.60	1.00
295	10.42	10.43	1.08

Powell, Tye, and Woodman (1967)	
Temp. °K	Resistivity* $\rho \times 10^6$ ohm cm
100	2.8
200	6.9
300	10.92
400	14.72
500	18.4

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



"Ideal" Resistivity* of Platinum

Temp. °K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20.	0.0359	0.0037
50.	0.719	0.0750
80.	1.909	0.199
100.	2.742	0.286
150.	4.78	0.498
200.	6.76	0.705
250.	8.70	0.907
273.15	9.59	1.00
295.	10.42	1.09

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-22

ELECTRICAL RESISTIVITY OF SILVER, Ag
(Atomic Number 47)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co., Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

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, 165-251 (1952).

Gerritsen, A. N., and Linde, J. O., "Thermal Conductivity of Some Dilute Silver Alloys," Communs. Kamerlingh Onnes Lab. Univ. Leiden No. 305b (1956).

Kannuluik, W. G., "The Thermal and Electrical Conductivities of Several Metals Between -183°C and 100°C," Proc. Roy. Soc. (London) A141, 159-68 (1931).

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

Meissner, W., and Voigt, B., "Messungen mit Hilfe von flüssigem Helium. XI. Widerstand der reinen Metalle in tiefen Temperaturen," (Measurements with the Help of Liquid Helium. XI. Resistivity of Pure Metals at Low Temperatures), Ann. Physik (5) 7, 761-97 (1930).

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Onnes, H. K., and Clay, J., Proc. Acad. Sci. Amsterdam 10, 207 (1908) and Communs. Phys. Lab. Univ. Leiden No. 99c (1907).

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 a datum temperature of 273°K. When the actual values of ρ_{273} are not available for the samples used by the several investigators, a datum value reported by White and Woods (1959) (ρ_{273} = 1.476 x 10^{-6} ohm cm) is suggested for calculating 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.

The values listed in the Landolt-Börnstein tables are those reported by Dewar and Fleming; Holborn; de Haas and Van den Berg; and Meissner; while those values appearing in the International Critical Tables are from Onnes and Clay. These primary sources are listed above under "Other References". The original authors are used in labeling the curves on the graph. The samples used by the investigators appearing in Landolt-Börnstein are all reported as polycrystalline with a small amount of impurities present. The samples used by Holborn, and de Haas and Van den Berg were annealed. The sample used by Meissner was aged. The Onnes and Clay sample was 99.82% pure silver wire. Dewar and Fleming reported one value ρ_{273} = 1.47 x 10^{-6} ohm cm.

Meissner and Voigt (1930) present the same data as Meissner (1926).

The purity of the Kannuluik (1931) sample was not given.

The samples used by Van der Leeden (1940) were 0.2 cm and 0.6 cm diameter wires designated Ag 1 and Ag 2, respectively. They were annealed at 500°C for 2 hours prior to measurement.

The purity of the Bridgman (1952) sample is not stated nor is there any mention of heat treatment made. The samples were in the form of thin sheets, 0.001 inch thick.

The samples Ag 2t and Ag 4t used by Gerritsen and Linde (1956) were annealed in "the gas" (assume air) for 4 hours at 740°K and 750°K, respectively. They were in the form of rectangular rods. No chemical analysis was available.

White and Woods (1959) rod specimens were 99.999% pure and were annealed in vacuum at 650° and 530°C. The smoothed values in the table below were taken from large-scale graphs.

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.

The sample used by Pawlek and Rogalla (1966) was 99.9964% pure silver wire. The wire was annealed one hour in argon at 500°C and cooled at less than 50°C/hr.

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 cm).

Onnes and Clay (1908)					
Temp. °C	$100R/R_{273}$	Temp. °C	$100R/R_{273}$	Temp. °C	$100R/R_{273}$
- 80 †	67.8	-140 †	43.2	-204.67	15.528
-100 †	59.6	-160 †	34.8	-220 †	9.2
-103.81	58.087	-180 †	26.3	-240 †	2.6
-120	51.4	-183.57	24.679	-252.92	0.8913
-139.87†	43.282	-195.17	19.703	-259.22	0.6942
		-200 †	17.6		

† Values from interpolation.

Holborn (1919)		Meissner & Voigt (1930) Meissner (1926)		de Haas and Van den Berg (1936)	
Temp. °K	ρ/ρ_{273}	Temp.* °K	ρ/ρ_{273}**	Temp. °K	ρ/ρ_{273}
20	0.0054	1.34 †	0.00679	4.2	0.00266
81	0.2071	4.21	0.00682	6.0	0.00268
195	0.6841	20.40	0.01000	8.4	0.00274
		78.85	0.1974	10.8	0.00288
		87.42	0.2349	20.4	0.00543
		273.16†	1.0000		

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

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

† $\rho_{273} = 1.48 \times 10^{-6}$ ohm cm; $\rho_{1.34} = 0.010 \times 10^{-6}$ ohm cm.

Kannuluik (1931)				
Sample	Temp. °C	Temp. °K	Specific Resistance $\rho \times 10^{6}$ ohm cm	ρ/ρ_{273}**
Ag	-183.0	90.15	0.377	0.250
	- 78.5	194.65	1.036	0.687
	0.	273.15	1.509	1.00
	100.	373.15	2.121	1.41
Ag*	-183.0	90.15	0.341	0.226
	- 78.5	194.65	1.035	0.685
	0.	273.15	1.510	1.00
	100.	373.15	2.123	1.41

* Measurements were repeated after the silver wire had received a prolonged annealing at 500°C.

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

Van der Leeden (1940)		
Temp. °K	Ag 1 100 R/R_0*	Ag 2 100 R/R_0
20.45	0.337	1.180
19.41	0.2815	1.124
18.23	0.232	1.058
17.28	0.199	1.0215
15.80	0.1605	0.959
14.01	0.130	0.929
0.00	0.079	0.830

* Only the Ag 1 values were plotted on the Electrical Resistivity of Silver graph.

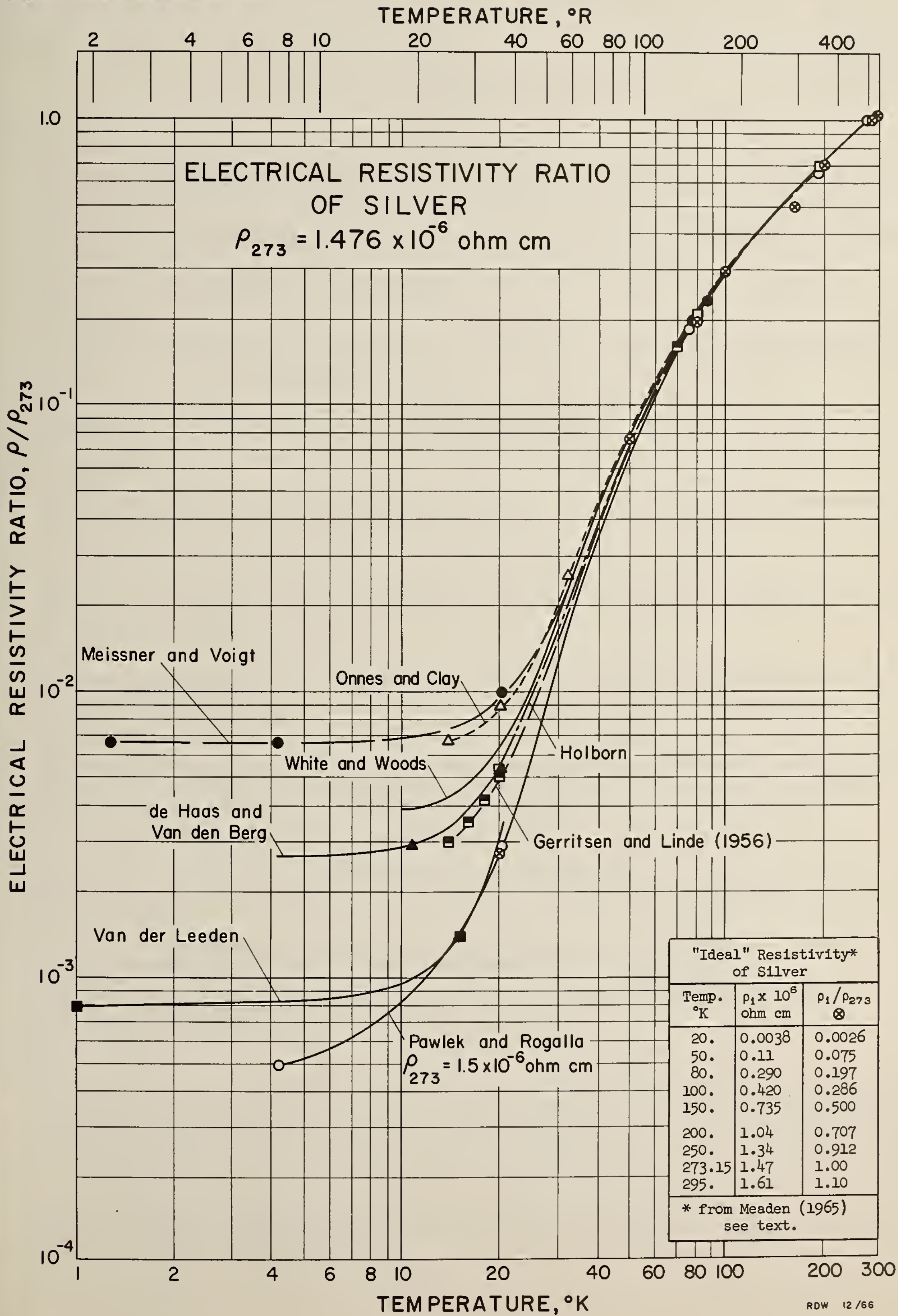
Gerritsen and Linde (1956)				
Temp. °K	Resistivity $\rho \times 10^{6}$ ohm cm		ρ/ρ_{273}	
	Ag 2t	Ag 4t	Ag 2t*	Ag 4t
14	0.00447	0.00694	0.00304	0.00469
16	0.00519	0.00758	0.00353	0.00512
18	0.00619	0.00852	0.00421	0.00576
20	0.00743	0.00983	0.00505	0.00664
70	0.238	0.235	0.162	0.159
80	0.297	0.299	0.202	0.202
90	0.359	0.363	0.244	0.245
273	1.47	1.48	1.00	1.00

* Ag 2t values were plotted.

Bridgman (1952)			
(Resistance is compared with resistance at room temperature and one atmosphere pressure)			
Pressure kg/cm^2	R/R_o	Pressure kg/cm^2	R/R_o
0	1.000	50000	0.683
10000	0.910	60000	0.647
20000	0.837	70000	0.618
30000	0.775	80000	0.592
40000	0.724	90000	0.569
		100000	0.548

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_o + \rho_i$ (where $\rho_o = 5.63 \times 10^{-9}$ ohm cm)	ρ/ρ_{273}
10	0.0002	0.0058	0.0039
15	0.0011	0.0067	0.0045
20	0.0038	0.0094	0.0064
25	0.010	0.0156	0.0106
30	0.020	0.0256	0.0173
40	0.058	0.0636	0.0431
50	0.11	0.1156	0.0783
60	0.17	0.1756	0.1190
70	0.23_0	0.2356	0.1597
80	0.29_0	0.2956	0.2003
90	0.35_5	0.3606	0.2444
100	0.42_0	0.4256	0.2884
120	0.54_5	0.5506	0.3731
140	0.67_5	0.6806	0.4612
160	0.79_5	0.8006	0.5426
180	0.92	0.9256	0.6273
200	1.04	1.0456	0.7086
220	1.16	1.1656	0.7899
250	1.34	1.3456	0.9119
273	1.47	1.4756	1.0000
295	1.61	1.6156	1.0949

Pawlek and Rogalla (1966)		
Temp. °K	Resistivity $\rho \times 10^9$ ohm cm	ρ/ρ_{273}
4.2	0.739	0.000493
20.4	4.33	0.00289
77.0	276.0	0.184
195.0	991.0	0.661
273.0	1500.0	1.000



"Ideal" Resistivity* of Silver

Temp. °K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20.	0.0038	0.0026
50.	0.11	0.075
80.	0.290	0.197
100.	0.420	0.286
150.	0.735	0.500
200.	1.04	0.707
250.	1.34	0.912
273.15	1.47	1.00
295.	1.61	1.10

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

ELECTRICAL RESISTIVITY OF TANTALUM, Ta
(Atomic Number 73)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

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, 165-251 (1952).

Cox, M., "Thermal and Electrical Conductivities of Tungsten and Tantalum," Phys. Rev. 64, 241-47 (1943).

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

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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).

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Holborn, L., Ann. Physik 59, 145 (1919).

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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 a datum temperature of 273°K. When actual values of ρ_{273} are not available for the samples used by the investigators, a datum value reported by White and Woods (1959) (ρ_{273} = 12.3 x 10^{-6} ohm cm) is suggested for calculating values of electrical resistivity from these ratios. The curves on this graph should not be extrapolated to lower temperatures as tantalum becomes a superconductor at 4.2°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.

The values listed in the Landolt-Börnstein tables are those reported by Burgers and Basart; McLennan, Howlett and Wilhelm; and Meissner and Voigt; while those values appearing in the International Critical Tables are from Holborn. These primary sources are cited above under "Other References". The names of the original authors are used in labeling the curves on the graph. The samples used by the investigators appearing in Landolt-Börnstein are reported as polycrystalline with no mention made of impurities. Burgers and Basart reported $\rho_{273} = 12.4 \times 10^{-6}$ ohm cm.

The wire sample used by Cox (1943) was 99.9% pure tantalum. No mention is made of any heat treatment prior to measurements.

Bridgman (1952) measured the effect of pressure on the resistivity of thin sheets (0.003 inch thick). No additional information is given about the sample.

White and Woods (1959) used 99.9% pure tantalum rods which were annealed in vacuo at 2500°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).

Holborn (1919)			
Temp. °C	$100R/R_{273}$	Temp. °C	$100R/R_{273}$
- 78.2	72.98	-140 †	49.6
- 80 †	72.4	-160 †	41.9
-100 †	64.9	-180 †	34.3
-120 †	57.3	-192.6	29.55

† Values from interpolation.

McLennan, Howlett and Wilhelm (1929)	
Temp. °K	R/R_{273}
4.3	0.029
20.6	0.033
80.0	0.230
273.1	1.00

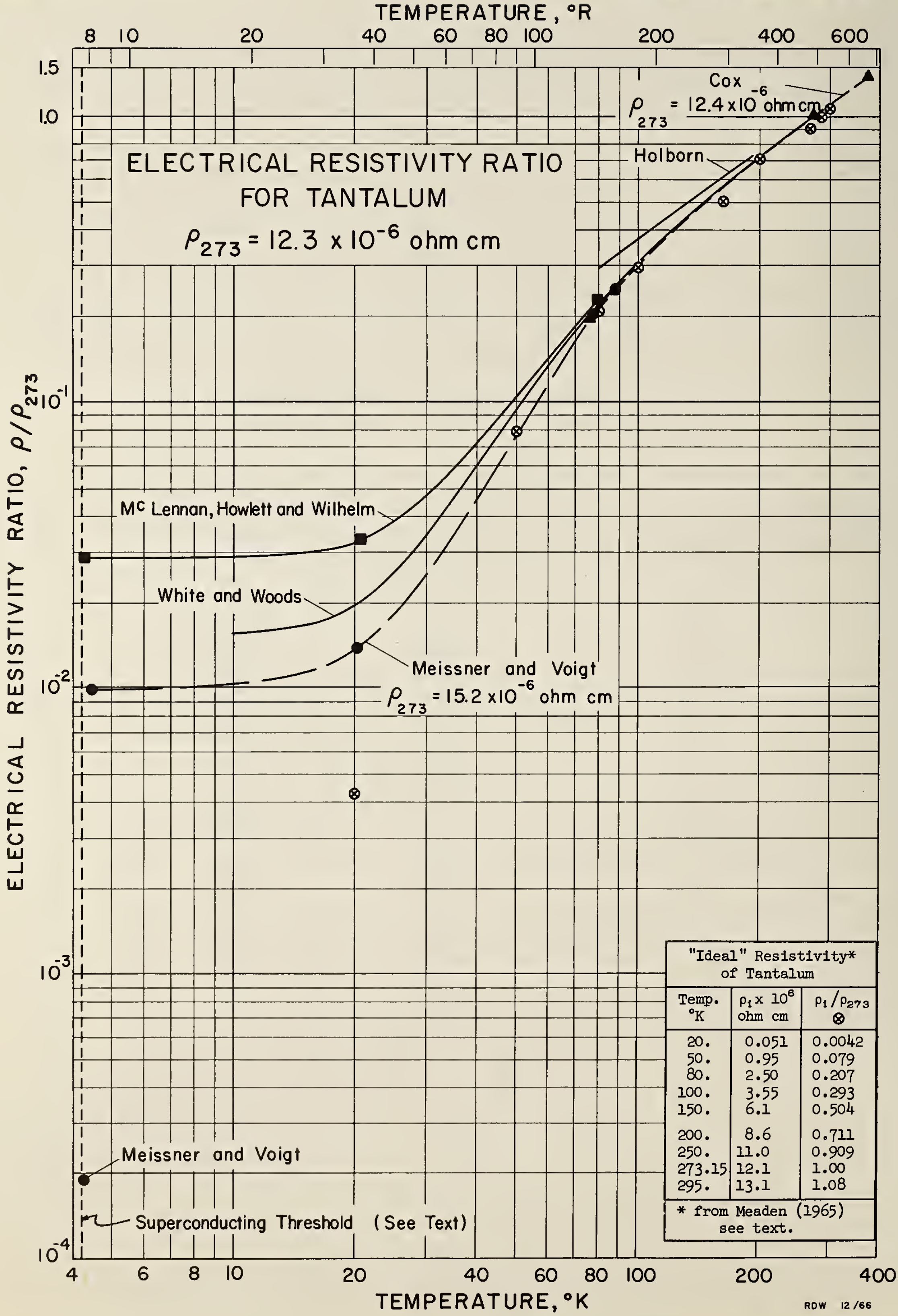
Meissner and Voigt (1930)	
Temp.* °K	R/R_{273}
4.29**	0.00019
4.49	0.0099
20.44	0.0140
77.61	0.2037
88.30	0.2511
273.16**	1.0000

* The second decimal place of the temperature values is somewhat in doubt.
** $\rho_{273} = 15.2 \times 10^{-6}$ ohm cm
$\rho_{4.29} = 0.0029 \times 10^{-6}$ ohm cm

Cox (1943)		
Temp. °K	Resistivity $\rho \times 10^{6}$ ohm cm	ρ/ρ_{273}
77.33	2.46	0.1982
273.2	12.41	1.000
373.4	17.18	1.384

Bridgman (1952)			
(Resistance compared with resistance at room temperature and 1 atmosphere pressure)			
Pressure kg/cm^2	R/R_0	Pressure kg/cm^2	R/R_0
0	1.000	60000	0.918
10000	0.984	70000	0.908
20000	0.968	80000	0.898
30000	0.954	90000	0.890
40000	0.941	100000	0.882
50000	0.929		

White and Woods (1959)			
Temp. °K	"Ideal Resistivity" $\rho_i \times 10^6$ ohm cm	Resistivity, $\rho \times 10^6$ ohm cm $\rho = \rho_i + \rho_0$ (where $\rho_0 = 0.1881 \times 10^6$ ohm cm)	ρ/ρ_{273}
10	0.003_2	0.1913	0.01557
15	0.01_7	0.2051	0.01669
20	0.05_1	0.2391	0.01946
25	0.1_2	0.3081	0.02507
30	0.2_3	0.4181	0.03402
40	0.5_4	0.7281	0.05925
50	0.9_5	1.138	0.09262
60	1.4_3	1.618	0.1317
70	1.9_6	2.148	0.1748
80	2.5_0	2.688	0.2187
90	3.0_3	3.218	0.2619
100	3.5_5	3.738	0.3042
120	4.6	4.788	0.3896
140	5.6	5.788	0.4710
160	6.6_5	6.838	0.5565
180	7.6_5	7.838	0.6379
200	8.6	8.788	0.7152
220	9.6	9.788	0.7965
250	11.0	11.188	0.9105
273	12.1	12.288	1.000
295	13.1	13.288	1.081



"Ideal" Resistivity* of Tantalum

Temp. °K	$\rho_i \times 10^6$ ohm cm	ρ_i/ρ_{273} ⊗
20.	0.051	0.0042
50.	0.95	0.079
80.	2.50	0.207
100.	3.55	0.293
150.	6.1	0.504
200.	8.6	0.711
250.	11.0	0.909
273.15	12.1	1.00
295.	13.1	1.08

* from Meaden (1965) see text.

CRYOGENIC DATA MEMORANDUM

PROJECT NO. 3150123 **FILE NO.** M-24

ELECTRICAL RESISTIVITY OF TIN, Sn
(Atomic Number 50)

Sources of Data:

International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, VI, 1st Edition, Published for the National Research Council by the McGraw-Hill Book Co. Inc., 124-35 (1929).

Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, sechste Auflage, II Band, 6 Teil, Springer-Verlag, Berlin, 1-46 (1959).

Aleksandrov, B. N., "Size Effect in Electrical Resistivity of High-Purity Metals," Soviet Phys. JETP 16, No. 2, 286-94 (1963).

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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).

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Kunzler, J. E., and Renton, C. A., "Size Effect in Electrical Resistivity Measurements on Single Crystals of High-Purity Tin at Liquid Helium Temperatures," Phys. Rev. 108, No. 6, 1397 (1957).

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

Van der Leeden, P., "Geleiding van warmte en electriciteit door metalen," (Conduction of heat by metals), Gedrukt Bij Drukherig Waltman, Koornmarkt 62, Te Delft 11-76 (July 1940).

Other References:

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).

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Goree, W. S., "Electrical Conductivity of Metals at High Pressures and Low Temperatures," Univ. of Florida, Gainesville, Ph.D. Thesis (1964), 166 p., Univ. Microfilms Order No. 65-5985.

Goree, W. S., and Scott, T. A., "Pressure Dependence of Electrical Conductivity of Metals at Low Temperatures," J. Phys. Chem. Solids 27, 835-48 (1966).

Grüneisen, E., Ergbn. exakt. Naturw. 21, 50 (1945).

Jaeger, W., and Diesselhorst, H., Wiss. Abhandl. physik. tech. Reichsanstalt 3, 269 (1900).

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Zernov, V. B., and Sharvin, Y. V., Soviet Phys. JETP 9, 737 (1959), Transl. of Zh. Eksperim. i Teor. Fiz. 36, 1038 (1959).

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 a datum temperature of 273°K. Since tin is an anisotropic metal, we list suggested values of ρ_{273} for Sn$\parallel$, Sn$\perp$, and polycrystalline tin to be used in calculating electrical resistivity from these ratios. These values are: $\rho_{(\parallel)_{273}} = 13.084 \times 10^{-6}$ ohm cm, $\rho_{(\perp)_{273}} = 9.01275 \times 10^{-6}$ ohm cm, and $\rho_{(poly)_{273}} = 10.05 \times 10^{-6}$ ohm cm.

The first and second values are from Aleksandrov and D'Yakov (1963) and the third value was calculated from their data using Voigt's equation: $\dfrac{1}{\rho_{(poly)}} = \dfrac{1}{3}\left[\dfrac{1}{\rho_{\parallel}} + \dfrac{2}{\rho_{\perp}}\right]$.

The curves on the graph should not be extrapolated to lower temperatures as tin becomes a superconductor at 3.74°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.

The values listed in the Landolt-Börnstein tables are those reported by Jaeger and Diesselhorst; and Meissner; while those values appearing in the International Critical Tables are from Onnes and Tuyn. These primary sources are listed above under "Other References". The Landolt-Börnstein tables list the samples of Meissner as polycrystalline with no mention of impurities present. The sample used by Onnes and Tuyn is reported as polycrystalline with less than 0.01% impurities of unknown composition. Jaeger and Diesselhorst reported less than 0.03% Pb impurity in the polycrystalline sample used in the determination of ρ_{273}. Their value was $\rho_{273} = 11.15 \times 10^{-6}$ ohm cm. No information was given on the mechanical or heat treatment of any of the above samples.

The Bridgman (1933) measurements were made with a 1 mm diameter single crystal rod at four crystal orientations; 82°, 17°, 90°, and 0° angles between axis and length of rod. The rod was formed in pyrex tubing by slowly lowering from a furnace.

Van der Leeden (1940) measured the resistivity of a 0.2 mm diameter wire. The wire was presumably polycrystalline with purity not stated.

Bridgman (1952) measured the effect of pressure on the resistivity of thin sheets of 0.001 inch thickness.

Kunzler and Renton (1957) made measurements on single crystals of high purity. The values in the table are for the specimen before it was reduced in cross section; the initial thickness was 4 mm.

Aleksandrov (1963) used 99.99985% pure tin in the form of rods of 2.7 mm diameter. Aleksandrov and D'Yakov (1963), using the same samples as Aleksandrov, obtained values for resistivity of tin from 3.7 to 273°K, using wire diameters which do not affect the resistivity values. Their samples were single crystals with the principal axis parallel to the sample axis (Sn$\parallel$), and with the principal axis at right angles to the sample axis (Sn$\perp$). They state that the error of a single measurement of R/R_{293} at T = 4.2°K amounted to 2 - 2.5% for tin. The ρ_0(Sn$\parallel$) $\simeq 10^{-10}$ ohm cm and ρ_0(Sn$\perp$) $\simeq 7 \times 10^{-11}$ 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.

Tables of Values of Electrical Resistivity

ρ = Resistivity, (ohm cm)

ρ_{273} = Resistivity at 273°K, (ohm cm)

R = Resistance, (ohm)

R_0 = Resistance at 0°C, (ohm)

Onnes and Tuyn (1923)

Temp. °C	Temp. °K	$100\rho/\rho_{273}$	Temp. °C	Temp. °K	$100\rho/\rho_{273}$
-102.13	171.02	57.36	-209.98	63.17	14.67
-115.14	158.01	52.16	-218.30	54.85	11.45
-127.50	145.65	47.25	-252.65	20.50	1.162
-141.06	132.09	41.90	-254.95	18.30	0.836
-158.74	114.41	34.91	-256.61	16.54	0.637
-182.80	90.35	25.44	-258.89	14.26	0.409
-194.07	79.08	20.98	-269.33	3.82	0.099
-202.07	71.08	17.79			

Meissner (1925)

Temp. °K	ρ/ρ_{273}
4.2	0.00078
20.4	0.0120
88.2	0.2457

Van der Leeden (1940)

Temp. °K	$100R/R_0$
14.29	0.443
16.31	0.672
17.48	0.813
19.46	1.107
20.40	1.266
69.05	17.52
77.50	20.93
78.15	21.40
84.15	23.66
90.30	26.08

Bridgman (1952)

Pressure kg/cm^2	R/R_0*	Pressure kg/cm^2	R/R_0*
0	1.000	60000	0.647
10000	0.910	70000	0.618
20000	0.837	80000	0.592
30000	0.775	90000	0.569
40000	0.724	100000	0.548
50000	0.683		

* Resistance compared with resistance at room temperature and one atmosphere pressure.

Bridgman (1933)

Temp. °K	Angle between axis and length: 90°	0°	90°	0°
	Resistivity $\rho \times 10^6$ ohm cm		ρ/ρ_{273}*	
90.35	3.255	2.404	0.2489	0.2646
194.85	8.736	6.147	0.6678	0.6764
273.15	13.08	9.088	1.000	1.000

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

Kunzler and Renton (1957)

Temp. °K	Resistivity $\rho \times 10^6$ ohm cm	ρ/ρ_{273}*
4.2	0.000525	0.000035
273.0	15.0	1.0

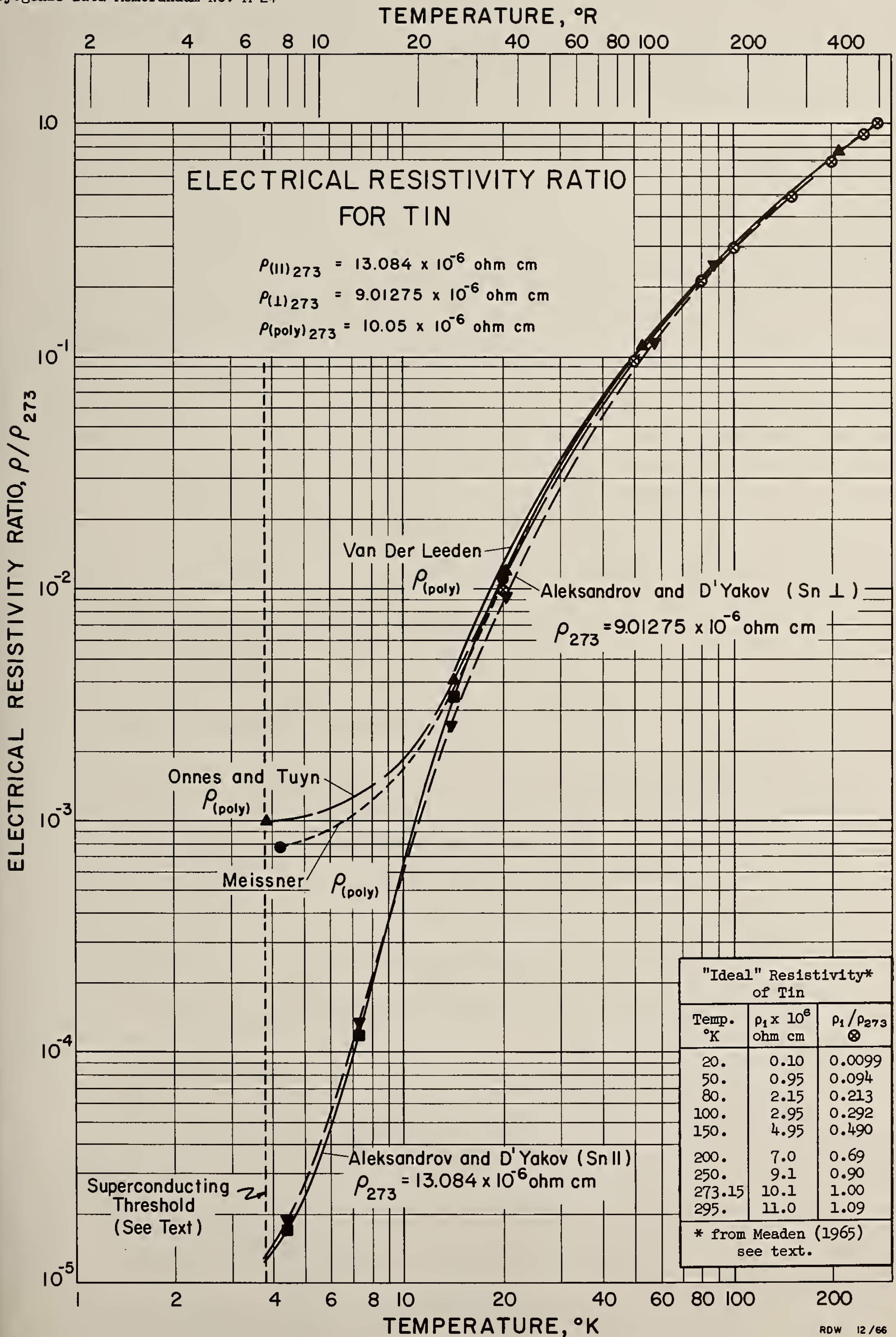
*These values were not plotted on the Electrical Resistivity of Tin graph.

Aleksandrov (1963)		
Temp. °K	Resistance Ratio R/R_{293}^*	
	Sn ∥	Sn ⊥
4.2	1.45	1.55

* For Sn ∥ , ρ_{293} = 14.3 x 10^{-6} ohm cm.
For Sn ⊥, ρ_{293} = 9.85 x 10^{-6} ohm cm.

Aleksandrov and D'Yakov (1963)				
Temp. °K	Resistance Ratio R/R_{293}^*		Resistance Ratio R/R_{273}^*	
	Sn ∥	Sn ⊥	Sn ∥	Sn ⊥
3.7	1.13 x 10^{-5}	1.17 x 10^{-5}	1.23 x 10^{-5}	1.28 x 10^{-5}
4.22	1.45 x 10^{-5}	1.55 x 10^{-5}	1.58 x 10^{-5}	1.70 x 10^{-5}
4.46	1.64 x 10^{-5}	1.81 x 10^{-5}	1.79 x 10^{-5}	1.99 x 10^{-5}
7.2	1.05 x 10^{-4}	1.23 x 10^{-4}	1.15 x 10^{-4}	1.35 x 10^{-4}
14.0	3.2 x 10^{-3}	2.54 x 10^{-3}	3.5 x 10^{-3}	2.79 x 10^{-3}
20.4	0.0111	8.68 x 10^{-3}	0.0121	9.52 x 10^{-3}
58.0	0.119	0.109	0.130	0.120
63.5	0.140	0.128	0.153	0.140
77.4	0.199	0.182	0.217	0.200
90.31	0.244	0.23	0.267	0.252
111.6	0.331	0.316	0.362	0.347
273.0	0.915	0.915	1.000	1.000

* For Sn∥ ; ρ_{293} = 14.3 x 10^{-6} ohm cm, ρ_{273} = 13.084 x 10^{-6} ohm cm.
For Sn⊥ ; ρ_{293} = 9.85 x 10^{-6} ohm cm, ρ_{273} = 9.01275 x 10^{-6} ohm cm.



"Ideal" Resistivity* of Tin

Temp. °K	ρ_i x 10^6 ohm cm	ρ_i/ρ_{273} ⊗
20.	0.10	0.0099
50.	0.95	0.094
80.	2.15	0.213
100.	2.95	0.292
150.	4.95	0.490
200.	7.0	0.69
250.	9.1	0.90
273.15	10.1	1.00
295.	11.0	1.09

* from Meaden (1965) see text.

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