

# Electrical Resistivity of Ten Selected Binary Alloy Systems

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This work compiles, reviews, and discusses the available data and information on the electrical resistivity of ten selected binary alloy systems and presents the recommended values resulting from critical evaluation, correlation, analysis, and synthesis of the available data and information. The ten binary alloy systems selected are the systems of aluminum-copper, aluminum-magnesium, copper-gold, copper-nickel, copper-palladium, copper-zinc, gold-palladium, gold-silver, iron-nickel, and silver-palladium. The recommended values for each of the ten binary alloy systems except three (aluminum-copper, aluminum-magnesium, and copper-zinc) are given for 27 compositions: 0 (pure element), 0.5, 1, 3, 5, 10(5)95, 97, 99, 99.5, and 100% (pure element). For aluminum-copper, aluminum-magnesium, and copper-zinc alloy systems, the recommended values are given for 26, 12, and 11 compositions, respectively. For most of the alloy systems the recommended values cover the temperature range from 1 K to the solidus temperature of the alloys or to about 1200 K. For most of the nine elements constituting the alloy systems, the recommended values cover the temperature range from 1 K to above the melting point into the molten state. The estimated uncertainties in most of the recommended values are about  $\pm 3\%$  to  $\pm 5\%$ .

Key words: alloy systems; alloys; conductivity; critically evaluated data; data analysis; data compilation; data synthesis; electrical conductivity; electrical resistivity; metals; recommended values; resistivity.

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### Nomenclature

$a, b$	Constants in Eq. (17).
$A, B$	Constants in Eq. (20)

$c$	Impurity concentration; mole fraction; composition	$\kappa$	Constant
$\delta_c$	Composition error	$\mu$	$\mu = \rho_{0d}/\rho_{0s}$
$C$	Constant in Eqs. (3)–(6)	$\nu$	$\nu = \rho_{id}/\rho_{is}$
$e$	Electron charge; base of natural logarithm	$\rho$	Electrical resistivity
$\hbar$	Planck constant divided by $2\pi$	$\rho_0$	Residual electrical resistivity
$k$	Boltzmann constant	$\rho_{0b}, \rho_{ib}$	Residual and intrinsic electrical resistivities of the belly electrons (those associated with the spherical portions of the Fermi surface)
$\delta\ell$	Dimensional error	$\rho_{0d}$	Residual electrical resistivity of the $d$ -bands
$L$	Length of specimen at $T$	$\rho_{0n}, \rho_{in}$	Residual and intrinsic electrical resistivities of the neck electrons (those associated with the portions of the Fermi surface which approach or make constant with the zone boundary)
$L_0$	Length of specimen at $T_0$	$\rho_{0s}$	Residual electrical resistivity of the $s$ -bands
$\Delta L$	$\Delta L = L - L_0$	$\delta\rho_0$	Increase of residual electrical resistivity
$m$	Electron mass	$\rho_e$	Electrical resistivity due to electron–electron scattering
$M$	Atomic weight; net magnetization	$\rho_i(T)$	Intrinsic electrical resistivity of a pure metal
$N$	Electron density	$\rho_i(c, T)$	Temperature-dependent part of electrical resistivity of an alloy or impure metal
$p$	Number of positive holes per atom	$\rho_{id}$	Intrinsic electrical resistivity of the $d$ -bands
$T$	Temperature	$\rho_{is}$	Intrinsic electrical resistivity of the $s$ -bands
$T_0$	Reference temperature	$\rho_{sd}$	Electrical resistivity due to $s$ – $d$ transitions
$T_t$	Test temperature	$\rho_{ss}$	Electrical resistivity due to $s$ – $s$ scattering
$U$	Quantity defined by Eq. (15)	$\delta\rho_{vac}$	Increase in electrical resistivity due to vacancies
$v$	Electron velocity	$\delta\rho_{int}$	Increase in electrical resistivity due to interstitials
$V_\alpha, V_\beta$	Volume fractions of $\alpha$ and $\beta$ phases	$\phi$	Potential energy
$z$	$z = \hbar\omega/kT$	$\delta\phi$	Potential energy perturbation
$\delta Z$	Difference in valence	$\psi$	Wave function
$\alpha, \beta, \gamma$	Positive quantities in Eq. (10)	$\omega$	Phonon angular frequency
$\Delta$	Deviation from the Matthiessen's rule; deviation of $\rho_i(c, T)$ of an alloy from its interpolated value $\bar{\rho}_i(c, T)$		
$\delta\Delta$	Change in $\Delta$		
$\epsilon_F$	Fermi energy		
$\theta_D$	Debye temperature		
$\theta_R$	Characteristic temperature for intrinsic electrical resistivity		

## 1. Introduction

The principal objective of this study was to critically evaluate, correlate, analyze, and synthesize all the available data and information on the electrical resistivity of ten selected binary alloy systems and to generate recommended values over the widest practicable ranges of temperature and alloy composition for each of the alloy systems. This study is a continuation of a similar work on the thermal conductivity of the same ten binary alloy systems.<sup>1</sup>

The ten binary alloy systems selected are the systems of aluminum–copper, aluminum–magnesium, copper–gold, copper–nickel, copper–palladium, copper–zinc, gold–palladium, gold–silver, iron–nickel, and silver–palladium. These systems include all of the three different kinds of binary alloy systems: nontransition-metal and nontransition-metal systems (aluminum–copper, aluminum–magnesium, copper–gold, copper–zinc, and gold–silver), nontransition-metal and transition-metal systems (copper–nickel, copper–palladium, gold–palladium, and silver–palladium), and a transition-metal and transition-metal system (iron–nickel). Most of these alloy systems are among those for which the largest amounts of experimental data are available. However, it will become evident later that even for these alloy systems serious gaps still exist in the electrical resistivity data, as concerns dependence on both composition and temperature, and that some of the available experimental data sets show large uncertainties or wide divergences.

The resulting electrical resistivity values presented in this work are designated as recommended or provisional values depending upon the level of confidence placed on the values and, hence, upon the uncertainty in the value assigned. The uncertainty in the recommended electrical resistivity values is less than or equal to  $\pm 5\%$  and that in the provisional values is greater than  $\pm 5\%$ . It will be noted that most of the resulting values are designated as recommended values and the uncertainty in the values is generally of the order of  $\pm 3\%$  to  $\pm 5\%$ .

The recommended electrical resistivity values are based on the room-temperature dimensions of the alloys, as thermal expansion corrections have not been made. This is due to the fact that the available experimental data on the electrical resistivity of the alloys, upon which the recommendations are based, are not corrected for thermal expansion, and that thermal expansion values for the respective alloys are not available for such corrections to be made. If the values of thermal expansion  $\Delta L(T)/L_0$  for the alloys are available, the electrical resistivity values corrected for thermal expansion  $\rho_{corrected}$  can easily be calculated from the given values uncorrected for thermal expansion,  $\rho_{uncorrected}$ , by the following relation:

$$\rho_{corrected}(T) = \left(1 + \frac{\Delta L(T)}{L_0}\right) \rho_{uncorrected}(T),$$

where  $\Delta L = L - L_0$ , and  $L$  and  $L_0$  are the lengths of the specimens at any temperature  $T$  and at a reference tempera-

ture  $T_0$ , respectively. The thermal expansion correction amounts roughly to about  $-0.2\%$  to  $-0.7\%$  at very low temperatures, zero at room temperature, about  $0.3\%$  to  $0.7\%$  at 500 K, and about  $2\%$  near the melting point of the alloy.

The recommended (or provisional) values generated are for alloys that are not ordered and have not been cold-worked severely; the values would be lower for ordered alloys and higher for cold-worked alloys at low temperatures.

The general background information on this work is given in Sec. 2, which includes a brief summary of the theory of the electrical resistivity of metals and alloys, a short description of the procedure and method used for the evaluation, correlation, analysis, and synthesis and the generation of recommended values, and a detailed explanation of the specifics and conventions used in the presentation of the data and information.

The experimental data and information and the recommended (or provisional) values for the electrical resistivity of the ten binary alloy systems are presented in Sec. 3. In the discussion of the electrical resistivity of each alloy system, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties in the recommended values are stated. For each of the alloy systems except three (aluminum-copper, aluminum-magnesium, and copper-zinc), the recommended values are given for 27 compositions: 0 (pure element), 0.5, 1, 3, 5, 10(5)95, 97, 99, 99.5, and 100% (pure element). For aluminum-copper alloy system, recommended values are presented for 26 compositions, without that containing 80% copper. For aluminum-magnesium alloy system, recommended values are generated only for 12 compositions, lacking those containing 15% to 85% magnesium. Recommended values are given for only 11 compositions of the copper-zinc alloy system, and no values are for those with 35% to 99.5% zinc. For most of the compositions the recommended values cover the temperature range from 1 K to near the solidus temperature (melting starting point). The recommended values have been smoothed simultaneously over both temperature and composition dependences.

The last three sections are for acknowledgments, appendices, and references. There are three appendices given. The first appendix presents, as an example, a detailed account of analysis and synthesis of the electrical resistivity of gold-silver alloy system. A logical organization of the methods for the measurement of electrical resistivity is given in the second appendix. The third appendix presents conversion factors for the units of electrical resistivity, which may be used to convert easily the electrical resistivity values in the SI units given in this work to values in any of the several other units listed.

## 2. General Background

### 2.1. Theoretical Background

#### a. Matthiessen's Rule

It was found experimentally by Matthiessen<sup>2,3</sup> that the increase in the electrical resistivity of a metal due to the pres-

ence of a small amount of another metal in solid solution is independent of the temperature. According to this Matthiessen's rule, the total electrical resistivity of an impure metal may therefore be separated into two additive contributions and written in the form

$$\rho(c, T) = \rho_0(c) + \rho_i(T), \quad (1)$$

where  $\rho_0$  is the residual resistivity caused by the scattering of electrons by impurity atoms and lattice defects and is temperature-independent but dependent on the impurity concentration  $c$ , and  $\rho_i$  is the temperature-dependent intrinsic resistivity arising from the scattering of electrons by lattice waves, or phonons.

The validity of the Matthiessen's rule has been assessed by Sondheimer,<sup>4</sup> who concluded that the maximum deviation should not exceed 1% of  $\rho_0$  in the idealized case in which the impurities do not affect the phonon and electron spectra. However, significant deviations from Matthiessen's rule do occur, which will be discussed in Sec. 2.1.e. Thus, in general the electrical resistivity of an impure metal is given by

$$\rho(c, T) = \rho_0(c) = \rho_i(T) + \Delta(c, T), \quad (2)$$

where  $\Delta$  is the deviation from the Matthiessen's rule.

In separating the electrical resistivity into its components, the temperature-dependent part sometimes includes the electrical resistivity due to electron-electron scattering,  $\rho_e$ ; indeed, this is thought to be the dominant temperature-dependent term in transition metals at low temperatures.

In what follows, we will first discuss  $\rho_i$ ,  $\rho_e$ ,  $\rho_0$ , and  $\Delta$ , then consider the electrical resistivity of nontransition-metal alloys, and finally comment on aspects of the electrical resistivity of transition metals and their alloys. The theory of electrical resistivity of metals and alloys has been the subject of a number of reviews and has constituted a large portion of the material in several books.<sup>5-21</sup>

#### b. Intrinsic Electrical Resistivity

The intrinsic electrical resistivity which is due to scattering of electrons by phonons may be approximated by the Bloch-Grüneisen formula<sup>22-24</sup>:

$$\rho_i = \frac{C}{M\theta_R} \left( \frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{z^5 e^z dz}{(e^z - 1)^2}, \quad (3)$$

where  $C$  is a constant characteristic of the metal and proportional to the square of the electron-phonon interaction constant,  $M$  is the atomic weight, and  $\theta_R$  is a characteristic temperature of the metal which characterizes its intrinsic electrical resistivity in the same way as the Debye temperature,  $\theta_D$ , characterizes its lattice specific heat. The dimensionless variable of integration  $z = \hbar\omega/kT$ , where  $\hbar$  is the Planck constant divided by  $2\pi$ ,  $\omega$  is the phonon angular frequency, and  $k$  is the Boltzmann constant. The derivation of Eq. (3) is based on the simplifying assumptions that the Fermi surface is spherical, that the conduction electrons can be treated as free in the first approximation, that the spectrum of lattice vibrations is that of the Debye model, that the phonon distribution is essentially undisturbed by the scattering processes, and that electron-phonon Umklapp processes can be ignored. Consequently, it is perhaps most reasonable

to expect the Bloch–Grüneisen formula to agree with experiment in the case of monovalent metals. Nevertheless, the intrinsic resistivity of many metals can be well represented by Eq. (3) over a wide temperature range by a suitable choice of  $\theta_R$  and  $C$ , though no single value of  $\theta_R$  can fit the data at all temperatures.

At low temperatures ( $T < \theta_R/20$ ), Eq. (3) reduces to

$$\rho_i = \frac{124.4C}{M\theta_R} \left( \frac{T}{\theta_R} \right)^5, \quad (4)$$

while at high temperatures ( $T > \theta_R$ ), to a good approximation, it reduces to

$$\rho_i \approx \frac{C}{4M\theta_R} \left( \frac{T}{\theta_R} \right). \quad (5)$$

Thus it agrees with the experimental facts that at very low temperatures the intrinsic electrical resistivity (after subtracting  $\rho_0$  from  $\rho$ ) of most metallic elements is proportional to  $T^5$ , and at high temperatures the resistivity of most metals increases approximately linearly with temperature.

The intrinsic resistivity of a metal at the characteristic temperature,  $T = \theta_R$  in Eq. (3), is

$$\rho_i(\theta_R) = \frac{C}{M\theta_R} \int_0^1 \frac{z^5 e^z dz}{(e^z - 1)^2} = \frac{0.2366C}{M\theta_R}. \quad (6)$$

Combining Eqs. (3) and (6) yields the reduced intrinsic resistivity equation

$$\frac{\rho_i(T)}{\rho_i(\theta_R)} = 4.226 \left( \frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{z^5 e^z dz}{(e^z - 1)^2}, \quad (7)$$

which gives a single curve for all metals. The values of the reduced intrinsic resistivity from Eq. (7) as a function of the reduced temperature,  $T/\theta_R$ , have been compared favorably with the experimental data for a number of metals.<sup>25,26</sup>

### c. Electrical Resistivity due to Electron–Electron Scattering

As in the case of the scattering of electrons by phonons, electron–electron collisions are of two types: normal processes, in which the total wave vector is conserved, and Umklapp processes in which the total wave vectors before and after the collision differ by a reciprocal lattice vector. On the other hand, unlike electron–phonon Umklapp processes which are frozen out at low temperatures if the Fermi surface is everywhere clear of the zone boundary, electron–electron Umklapp processes are not frozen out at low temperatures.

Normal processes, involving the collision between two  $s$ -band conduction electrons, do not contribute directly to the electrical resistivity because they do not change the total momentum and thus have no effect on the current. Normal processes involving the scattering of an  $s$ -band conduction electron by a nonconducting  $d$ -band electron do contribute to the electrical resistivity, and are thought to be the dominant temperature-dependent resistive processes in transition elements and their alloys at very low temperatures, since their resistivities show the  $T^2$  temperature dependence expected for electron–electron scattering rather than the  $T^3$  temperature dependence expected for the intrinsic resistivity. This temperature dependence of the electrical resistivity due to electron–electron scattering:

$$\rho_e \propto T^2 \quad (8)$$

comes about through the double application of the exclusion principle in the scattering processes; it applies to both the initial states and final states. For simplicity assume all the states with energies less than the Fermi energy,  $\epsilon_F$ , to be occupied and consider the scattering of electron 1, in an excited state of energy greater than  $\epsilon_F$  by  $\epsilon_1$ , colliding with electron 2 having energy less than  $\epsilon_F$  by  $\epsilon_2$ . Then conservation of energy requires that  $\epsilon_1$  be greater than  $\epsilon_2$ , since the final states must be empty and, therefore, must have energies greater than  $\epsilon_F$ . Thus, the orbital of electron 2 must lie within a shell of thickness  $\epsilon_1$  within the Fermi surface so that only a fraction,  $\epsilon_1/\epsilon_F$ , of the electrons can scatter electron 1. Further, the final states must also lie within a shell of thickness less than  $\epsilon_1$  outside the Fermi surface so that only a fraction,  $\epsilon_1/\epsilon_F$ , of the final states compatible with conservation of energy and momentum are allowed by the exclusion principle. The average energy of an occupied excited state measured from  $\epsilon_F$  is approximately  $kT$  so that  $\epsilon_1/\epsilon_F \approx kT/\epsilon_F$  and the effect of the double application of the exclusion principle is to reduce the collision cross section for electron–electron scattering by a factor  $(kT/\epsilon_F)^2$  below its value for a screened Coulomb interaction.

Umklapp processes between two conduction electrons do contribute to the electrical resistivity. Because these processes involve a reciprocal lattice vector, the wave functions of the electrons involved cannot be regarded as simple plane waves, but must be treated as true Bloch functions having the periodicity of the lattice. The result of this is to introduce into the expression for the resistivity the square of an interference factor. Apparently this factor is quite small, as the low temperature electrical resistivity of most ordinary metals does not show the  $T^2$  temperature dependence expected for such a resistance mechanism; however, a contribution proportional to  $T^2$  has been observed in the liquid-helium-temperature resistivity of indium and aluminum.

### d. Residual Electrical Resistivity

The electrical resistivity of a metal or an alloy approaches a constant value, the residual electrical resistivity, as the temperature decreases toward absolute zero. Exceptions to this rule are the phenomena of superconductivity, which are not considered here. The residual resistivity is due to the scattering of electrons by foreign atoms and lattice defects such as vacancies, interstitials, dislocations, and stacking faults.

The most important contribution to the residual resistivity is the scattering of electrons by foreign atoms, which will be discussed in Sec. 2.1.f in connection with the electrical resistivity of alloys.

Electrical resistivities due to vacancies and interstitials have been estimated theoretically, and studied experimentally by using neutron-irradiated samples. The increase in the resistivity due to vacancies  $\delta\rho_{vac}$  and that due to interstitials  $\delta\rho_{int}$  have been given for copper by Blatt<sup>20</sup> as follows:

$$\delta\rho_{vac} = (1.0 \text{ to } 1.5) \times 10^{-8} \Omega\text{m/at.}\%$$

$$\delta\rho_{int} = (0.5 \text{ to } 1.0) \times 10^{-8} \Omega\text{m/at.}\%$$

Dislocations scatter electrons weakly; however, it is

sometimes energetically favorable for a dislocation to dissociate into two partial dislocations separated by a ribbon of stacking faults which, particularly if it is wide, may be effective in scattering electrons. Thus, the resistivity due to dislocations is often significantly larger than predicted by theoretical calculations, which may be caused by the substantial contributions of stacking faults and of the core of the dislocation line to the resistivity of plastically deformed metals.

Calculation of the resistivity due to stacking faults is difficult and requires a knowledge of the Fermi surface. However, Howie<sup>27</sup> was able to account for the resistivity of a deformed copper specimen in terms of a reasonable density of stacking faults.

#### e. Deviations from Matthiessen's Rule

For Matthiessen's rule to be exact, the scattering of electrons by imperfections and by phonons would have to be independent of each other, and this is only approximately true. Other causes for deviations from Matthiessen's rule are as follows:

1. Alloying may alter the band structure of the metal.
2. Alloying may change the phonon spectrum or perturb the phonon distribution in the steady state.
3. There may be parallel conduction by two groups of electrons.

The first two effects are to be expected in concentrated alloys, but two-band effects can cause significant deviations in multivalent elements and in very dilute alloys of monovalent elements.

The two-band effect was first discussed by Sondheimer and Wilson,<sup>28</sup> who considered the case in which the *s*- and *d*-bands of electrons of a transition element conduct in parallel. They found that if  $\rho_0$  depends only on  $\rho_{0s}$  and  $\rho_{0d}$  of the *s*- and *d*-bands, respectively, and  $\rho_i$  depends only on  $\rho_{is}$  and  $\rho_{id}$ , then the deviation from Matthiessen's rule is given by

$$\Delta = \rho - \rho_0 - \rho_i = \frac{\rho_{0s}\rho_{is}(\mu - \nu)^2}{(1 + \mu)(1 + \nu)[\rho_{0s}(1 + \mu) + \rho_{is}(1 + \nu)]} \quad (9)$$

where  $\mu = \rho_{0d}/\rho_{0s}$  and  $\nu = \rho_{id}/\rho_{is}$ . Thus, there is a positive deviation unless these ratios are equal. At low temperatures  $\rho_{is}$  is smaller than  $\rho_{0s}$  so that  $\Delta$  is approximately proportional to  $\rho_{is}$  and thus to  $\rho_i$ , while at high temperatures  $\rho_{is}$  is larger than  $\rho_{0s}$  so that  $\Delta$  is approximately proportional to  $\rho_{0s}$  and thus to  $\rho_0$ . It follows that  $\Delta$  increases from zero at zero temperature to a constant value proportional to  $\rho_0$  at high temperatures. When  $\rho_0$  and  $\rho_i$  are of the same order of magnitude, the deviation can be approximated by

$$\Delta \approx \frac{\alpha\rho_0\rho_i}{\beta\rho_0 + \gamma\rho_i} \quad (10)$$

where  $\alpha$ ,  $\beta$ , and  $\gamma$  are positive quantities of the order of unity (Ref. 6, p. 312). Taking  $\alpha$ ,  $\beta$ , and  $\gamma$  equal to unity it follows that the largest relative deviation,  $\Delta/(\rho_0 + \rho_i)$ , occurs when  $\rho_0$  and  $\rho_i$  are equal.

Dugdale and Basinski<sup>29</sup> explained the deviations from Matthiessen's rule observed in dilute copper alloys and silver alloys on the basis of an argument by Ziman<sup>30</sup> concerning the different anisotropies of relaxation times for phonon and impurity scattering. While their expression for  $\Delta$  is equivalent

to that obtained by Sondheimer and Wilson, the interpretation and temperature dependence are quite different.

Ziman divided electrons into two groups: (1) the belly electrons associated with the spherical portions of the Fermi surface and (2) the neck electrons associated with the portions of the Fermi surface which approach or make contact with the zone boundary. The electron-phonon interactions responsible for  $\rho_i$  are of two types: normal processes in which the sum of the wave vectors remain unchanged, and Umklapp processes in which the sum of the wave vector changes by a reciprocal lattice vector. In the case of belly electrons, Umklapp processes can take place only with phonons having a minimum wave vector and minimum energy determined by the differences between the belly electron wave vector and the nearest wave vector in the next Brillouin zone. At low temperatures such phonons disappear and the Umklapp processes involving belly electrons are frozen out. On the other hand, the neck electrons have wave vectors arbitrarily near to the zone boundary and Umklapp processes can occur at both low and high temperatures. Thus, while the strength of the electron-phonon interactions may be about the same for the two groups at room temperature and above, at low temperatures they are much stronger on the neck than on the belly so that the ratio  $\rho_{ib}/\rho_{in}$  increases from a small value at low temperatures to a constant value at room temperature and above. Ziman considered impurity scattering in the cases of silver in gold and of copper in gold. In the first case the atomic volumes are very nearly equal and the effect of silver atoms on the conduction electrons is due only to differences in the effective potential in the ion core, consequently the belly electrons, which have wave functions that are large in the region of the core, will be strongly scattered, while the neck electrons, which have wave functions that are large only in the region between the cores, will be weakly scattered. In the second case the atomic volumes are very different, and the effect of the copper atoms on the conduction electrons is much like that of a charged impurity, a change in the potential extending out into the region between the ion cores, so that the neck electrons are also scattered strongly.

It follows from the above that on this model if the ratio  $\rho_{ib}/\rho_{in}$  is always smaller than the ratio  $\rho_{0b}/\rho_{0n}$ , then  $\Delta$  rises from zero at zero temperature, goes through a maximum, and takes on a constant value at high temperatures; this is the behavior observed in the dilute Cu + Au and Ag + Au alloys investigated by Dugdale and Basinski.

The deviations from Matthiessen's rule in iron alloys<sup>31</sup> and nickel alloys<sup>32</sup> have been explained in terms of parallel conduction by the spin-up and spin-down electrons. At low temperatures there are few interactions between the electrons of opposite spin, so that an electron with its spin in a given direction emerging from an impurity collision will reach the next impurity with its spin unchanged; thus an impurity resistivity can be defined for each group. If the impurity relaxation time is considerably longer for one group of electrons than for the other, the scattering of electrons of that group will contribute relatively little to the residual resistivity. At high temperatures, on the other hand, there may exist (presumably as a result of electron-electron collisions) a process of spin mixing in which the electrons change their



spin directions a number of times between impurity collisions. There will then be no group of electrons that experiences relatively small impurity scattering, and the high-temperature impurity resistivity will become considerably greater than the low-temperature residual resistivity.

Deviations from Matthiessen's rule have been comprehensively reviewed by Bass<sup>33</sup> and by Cimberle *et al.*<sup>34</sup>

#### f. Electrical Resistivity of Alloys

Alloying affects the electrical resistivity of the host metal drastically, since it causes lattice perturbations, modifies the lattice-vibrational spectrum and electronic band structure, changes the Fermi energy and electron density of states, etc.

For the residual electrical resistivity of binary solid-solution alloys containing  $c$  mole fraction of element A and  $(1 - c)$  mole fraction of element B, Nordheim's rule<sup>35</sup> is

$$\rho_0 \propto c(1 - c). \quad (11)$$

This rule is applicable only to homogeneous random (not ordered) solid solutions of two metals which are not transition elements. It is apparent from Eq. (11) that  $\rho_0$  is directly proportional to  $c$  if  $c \ll 1$ .

Nordheim's rule can be made plausible by the following argument. The average cellular potential for a binary alloy with mole fraction  $c$  of element A in element B is given by

$$\phi = c\phi_A + (1 - c)\phi_B, \quad (12)$$

and the perturbations of this potential at the sites of the A and B atoms are

$$\delta\phi_A = \phi_A - \phi = (1 - c)(\phi_A - \phi_B) = (1 - c)\phi_{AB}, \quad (13)$$

$$\delta\phi_B = \phi_B - \phi = c(\phi_B - \phi_A) = -c\phi_{AB}. \quad (14)$$

In the Born approximation, the scattering cross section per scattering center is proportional to the square of the matrix element of the perturbation. The probability per unit time that an electron will be scattered from state  $\Psi_k$  into state  $\Psi_{k'}$  by a single A atom is  $(1 - c)^2 U^2$ , where

$$U = \int \Psi_{k'} \phi_{AB} \Psi_k d^3r, \quad (15)$$

and  $\Psi_k$  and  $\Psi_{k'}$  are the initial and final wave functions. The probability per unit time that an electron will be scattered by a single B atom is  $c^2 U^2$ . Since the fractions of A atoms and B atoms are  $c$  and  $(1 - c)$ , the total scattering probability per unit time, and therefore the residual resistivity, is of the form

$$\rho_0 \propto [c(1 - c)^2 + (1 - c)c^2]U^2 = c(1 - c)U^2. \quad (16)$$

This rule is obeyed quite well by many binary alloy systems, but not by those in which either constituent is a transition element.

In dilute solid-solution alloys, Norbury<sup>36</sup> found that the increase of residual resistivity per at. % solute  $\delta\rho_0$ , increases with the valence difference  $\delta Z$ , between the solute and the solvent atoms. By analyzing thoroughly the data on this effect, Linde<sup>37-39</sup> concluded that  $\delta\rho_0$  is proportional to the square of  $\delta Z$ , i.e.,

$$\delta\rho_0 = a + b(\delta Z)^2, \quad (17)$$

where  $a$  and  $b$  are constants for a given solvent metal and a given row of the periodic table to which the solvent elements

belong. This is the Norbury-Linde's rule.

A rough theoretical justification for Norbury-Linde's rule was given by Mott,<sup>40</sup> who calculated  $\delta\rho_0$  on the assumption that the electrons behave as if they were free and used a screened Coulomb potential to describe the perturbation, and used the Born approximation to calculate the scattering cross section. For a solute in the same row of the periodic table, in which case  $a$  is zero, he obtained

$$\delta\rho_0 = \frac{2\pi(\delta Z)^2 e^2}{100 m v^2} \left[ \ln \left( 1 + \frac{4m^2 v^2}{q^2 \hbar^2} \right) - \left( 1 + \frac{q^2 \hbar^2}{4m^2 v^2} \right)^{-1} \right]. \quad (18)$$

Here  $e$ ,  $m$ , and  $v$  are the electronic charge, mass, and velocity,  $q$  is the screening parameter, and  $\hbar$  is the reduced Planck constant. The  $(\delta Z)^2$  dependence is obtained because in the Born approximation the scattering is proportional to the square of the matrix element of the perturbation. The Born approximation overestimates the scattering for this type of potential so that Eq. (18) is only an approximation; however, fair agreement with experiment can be obtained by taking the screening parameter to be somewhat greater than the usual estimate. Better estimates of  $\delta\rho_0$  can be obtained by the more refined phase-shift calculations, but these do not yield the simple  $(\delta Z)^2$  dependence.

Norbury-Linde's rule is not obeyed when the alloying involves transition elements or polyvalent elements such as aluminum and magnesium.

Another factor influencing the residual resistivity of alloys is short range order which may either decrease it, as in the case of  $\alpha$  brass,<sup>41</sup> or increase it as in the case of copper-gold alloys.<sup>42,43</sup> Short range order is increased by annealing and destroyed by mechanical deformation and by heating and quenching.

In the case of binary alloy systems whose alloys are two-phase ( $\alpha + \beta$ ) mixtures, the electrical resistivity of the alloys is equal to the sum of the product of the electrical resistivity of each phase and its volume fraction, i.e.,

$$\rho = \rho_\alpha V_\alpha + \rho_\beta V_\beta, \quad (19)$$

where  $\rho_\alpha$  and  $\rho_\beta$  are the electrical resistivities and  $V_\alpha$  and  $V_\beta$  are the volume fractions of  $\alpha$  and  $\beta$  phases, respectively. Equation (19) is derived by considering the alloy as a rod which consists of a bundle of numerous small parallel fibers, with each fiber having a certain volume of  $\alpha$ -phase in series with a certain volume of  $\beta$ -phase.

#### g. Electrical Resistivity of Transition Elements and Their Alloys

In terms of electronic transport properties, the most important feature of transition elements, at least those having face-centered cubic crystal structure such as nickel and palladium, is the presence of a narrow  $d$ -band with a high density of states overlapping the conduction band at the Fermi energy level. As originally suggested by Mott,<sup>44</sup> the role of this  $d$ -band is to provide a large number of levels into which the  $s$ -electrons can be scattered and lost from the current, thus causing the high electrical resistivity of transition elements as compared with that of ordinary metals.

As palladium is added to silver, the resistivity first increases in the way observed for binary alloys of ordinary metals. At a certain composition, about 40 at. % palladium, the number of conduction electrons is no longer sufficient to

fill the  $d$ -band holes and the resistivity begins to increase rapidly, rising to an asymmetric peak. Mott<sup>44</sup> provided a semiquantitative explanation of the shape of the curve which may be summarized as follows. The resistivity was taken to be the sum of terms due to  $s$ - $s$  and  $s$ - $d$  scattering. The resistivity due to  $s$ - $s$  scattering was taken to have the composition dependence given by Nordheim's rule while that due to  $s$ - $d$  scattering was taken to be proportional to the density of vacant states in the  $d$ -band, which in turn was taken to vary in the same way as the paramagnetic susceptibility, that is, as  $(p - c)^2$  for  $c < p$ , and zero for  $c > p$  for atomic fraction  $c$  of silver in palladium, where  $p$  is the number of positive holes per atom in pure palladium. Also, while silver and palladium in the alloy were assumed to have a common  $s$ -band, the  $d$ -band was assumed to be split into two bands and the one associated with silver atoms was taken to be below that associated with palladium atoms and thus below the Fermi energy level. With these assumptions Mott obtained the following equation for the electrical resistivity of the alloys:

$$\rho = A(p - c)^2(1 - c)c^2 + B(1 - c)c, \quad (20)$$

where  $A$  and  $B$  are constants. If  $A$  and  $B$  are properly chosen, Eq. (20) will result in a resistivity-composition curve similar to that observed experimentally for this alloy system.

Coles and Taylor<sup>45</sup> used a similar model to explain the shape of this resistivity-composition curve but derived the density of states of the  $d$ -band from the electronic specific heat. Later, Dugdale and Guénault<sup>46</sup> modified Mott's model to make it consistent with the findings of Vuillemin and Priestley<sup>47</sup> concerning the Fermi surface of palladium. With this model they were able to explain not only the shape of the resistivity-composition curve but also the low-temperature thermoelectric power of these alloys.

The temperature dependence of the electrical resistivity of nickel and iron shows an anomaly caused by their being ferromagnetic: while above the Curie temperature the resistivity has the usual concave-downward curvature, below the Curie temperature it is concave upward. This behavior can be explained on the basis of a band model for the  $d$ -electrons in terms of  $s$ - $d$  scattering, and on the basis of a model in which the  $d$ -electrons are localized on their atoms in terms of spin-disorder scattering. Mott and Stevens<sup>48</sup> argued that the former model applied to nickel and the latter to iron.

In the band model the narrow  $d$ -band overlaps the  $s$ -band. Above the Curie temperature, vacant  $d$ -states of both spin directions are present in equal numbers. Below the Curie temperature, there is a greater number of vacant states with spin up in a given domain and the number increases with decreasing temperature, while the number with spin down decreases until at zero temperature all of the spin down states are filled. If only states with spin up are vacant, then a spin-down electron cannot make a spin-conserving transition into the  $d$ -band, so that its mean free path is greater than in the unmagnetized state. Assuming that the energy is proportional to the square of the wave vector so that the density of  $d$ -states at the Fermi level  $N_d(\epsilon_F)$ , is proportional to the square root of the Fermi energy, noting that the Fermi wavenumber is proportional to the cube root of the electron density, one obtains

$$N_{d\pm}(\epsilon_F) \propto \left(1 \mp \frac{M}{M_0}\right)^{1/3}, \quad (21)$$

where  $M$  is the net magnetization, reaching the saturation value  $M_0$  at  $T = 0$  K, and  $\pm$  refers to spin up and spin down electrons. Since the reciprocal relaxation time, and thus the resistivity due to  $s$ - $d$  transitions, is proportional to  $N_d(\epsilon_F)$ , one obtains

$$\rho_{\pm} = \rho_{ss} + \rho_{sd} \left(1 \mp \frac{M}{M_0}\right)^{1/3}. \quad (22)$$

In an unmagnetized specimen there are many domains in which the magnetization of the  $d$ -spin is in different directions so that, instead of having parallel conduction by spin-up and spin-down electrons, both types of electrons see an average resistivity:

$$\rho = \rho_{ss} + \frac{\rho_{sd}}{2} \left[ \left(1 - \frac{M}{M_0}\right)^{1/3} + \left(1 + \frac{M}{M_0}\right)^{1/3} \right]. \quad (23)$$

For small  $M/M_0$  this reduces to

$$\rho \approx \rho_{ss} + \rho_{sd} \left[ 1 - \frac{1}{9} \left(\frac{M}{M_0}\right)^2 \right], \quad (24)$$

which is in qualitative agreement with the experimental data for nickel.

If the  $d$ -electrons are localized on their atoms, then instead of  $s$ - $d$  scattering, the theory proposes an  $s$ - $d$  exchange interaction with an energy depending on the relative orientation of the spin of a moving  $s$ -electron to that of the fixed  $d$ -electron near which it is passing. If the spins of the  $d$ -electrons in a domain are lined up parallel, then the electrons would not be scattered, but as the temperature is increased, the  $d$ -spins within the domain become disordered, and there is an extra contribution to the resistivity which increases rapidly as the Curie temperature is approached and takes a constant value above the Curie temperature.

Since  $s$ - $d$  scattering due to the electron-phonon interaction continues to increase with temperature above the Curie temperature, while the spin-disorder scattering takes on a constant value, the two mechanisms can be distinguished experimentally. Coles<sup>49</sup> predicts the former behavior for a Ni-Pd alloy and the latter behavior for an Fe-Rh alloy.

## 2.2. Data Evaluation and Generation of Recommended Values

The recommended electrical resistivity values were generated through critical evaluation, correlation, analysis, and synthesis of the available experimental data and information compiled from all sources. The procedure involved critical evaluation of the validity of available data and related information, judgment on the reliability and accuracy of the data, resolution, and reconciliation of disagreements in conflicting data, correlation of data in terms of various controlling parameters, curve fitting with theoretical or empirical equations, and synthesis of the often fragmentary data to generate a full range of coverage of internally consistent "best" values.

In the critical evaluation of the validity and reliability of a set of experimental electrical resistivity data, the temperature dependence of the data was examined, and any unusual

dependence or anomaly was carefully investigated. The experimental technique was reviewed to see whether the actual boundary conditions in the measurement agreed with those assumed in the theory, and the estimation of inaccuracies by the authors was checked to ensure that all the possible sources of error were considered. The sources of error might include the inaccuracy in the measurement of specimen dimensions and of the distance between potential probes, uncertainty due to the effect of thermal expansion, inaccuracy in temperature measurement, inaccuracy due to poor sensitivity of measuring devices or circuits, uncertainty at high temperature due to specimen instability or specimen and/or thermocouple contamination, etc. These and other possible sources of error were carefully considered in critical evaluation of experimental data.

The uncertainty of a set of experimental data is caused, however, not only by the experimental error in the measurement, but also by the inadequacy of characterization of the material for which the data are reported. Therefore, in data analysis it should be kept in mind that the total difference between two sets of experimental data is a combination of the difference due to experimental error and the real difference due to sample variance. It was found in this and other studies that the chemical composition of a specimen reported by the author was often unreliable. This might partly be due to the fact that in many cases the stated composition of a specimen was what the author obtained from the company who supplied the specimen and it could at best represent only the nominal composition; the actual composition varied from sample to sample. In other cases there was a strong tendency for only certain elements to be detected by a particular chemical analysis which could miss other important constituents. Furthermore, the chemical composition of a specimen might have changed when it was measured at high temperature.

In many cases research papers did not contain adequate information for performing a truly critical evaluation. In these cases, some other considerations were used for data evaluation. For instance, if several author's data agreed and, more importantly, these were obtained by using different experimental methods, these data were judged to be reliable. However, if the different sets of data were obtained by means of the same experimental method, even though they all agreed, the reliability of the data was still subject to questioning, because they might all suffer from a common, but unknown, source of error. Secondly, if the same apparatus had been used for measurements of other materials and the other results were reliable, the result for the new material was judged also to be reliable. If the information given by the author was entirely inadequate to make any value judgment, the data assessment was subjective. At times, judgments were based upon factors and considerations such as the central purpose of his research, the motivation for his measurement, general knowledge of the experimenter, his past performance, the reputation of his laboratory, etc.

In the process of critical evaluation of experimental data outlined above, unreliable and erroneous data were noted and set aside. The remaining data were used for data correlation and synthesis, and graphical smoothing was often used. In graphical smoothing of experimental data for a bi-

nary alloy system, cross-plotting from electrical resistivity data versus temperature to resistivity data versus composition and vice versa were made. Smooth curves were drawn which approximate the best fit to the resistivity data versus temperature, and points from the smoothed curves were used to construct resistivity-versus-composition curves for a convenient set of selected temperatures. In a resistivity-versus-composition graph, the family of isotherms was similar and any required smoothing of the data could be done more easily and with greater confidence than when working directly with the resistivity-versus-temperature curves. The points from the resulting smoothed curves were then used to construct resistivity-versus-temperature curves for selected compositions, and these curves were further smoothed. In the graphical smoothing process it was extremely important that the alloy phase diagrams be constantly consulted and the phase boundaries between solid solution and/or mechanical mixtures and the boundaries of magnetic transitions be kept in mind, so as to be aware of any possible discontinuity or sudden change of slope in the resistivity curves.

In graphical smoothing and synthesis of data for a binary alloy system, instead of cross-plotting the total electrical resistivity  $\rho(c, T)$ , it was often better to work with the temperature-dependent part  $\rho_i(c, T)$ , of the electrical resistivity, i.e.,

$$\rho_i(c, T) = \rho(c, T) - \rho_0(c). \quad (25)$$

This temperature-dependent part changes more slowly with the alloy composition,  $c$ , than does the total electrical resistivity, and its isotherms may form a family more convenient for cross-plotting. Furthermore, for a binary alloy system that forms a continuous series of solid solutions over the entire range of compositions, it has proved very useful to go further in this direction by working with the quantity

$$\Delta(c, T) = \rho_i(c, T) - \bar{\rho}_i(c, T), \quad (26)$$

where  $\bar{\rho}_i$  is the atomic-fraction-weighted average of the intrinsic resistivities,  $\rho_i^{(A)}$  and  $\rho_i^{(B)}$ , of the pure metals A and B:

$$\bar{\rho}_i(c, T) = c\rho_i^{(A)}(T) + (1 - c)\rho_i^{(B)}(T) \quad (27)$$

with  $c \equiv c_A$  of metal A.

Since the quantity  $\Delta$  is at most a few percent of  $\rho$ , irregularities and discrepancies in the values of  $\rho$  become very conspicuous in plots of  $\Delta$  or  $\Delta/T$ , and this increases the confidence with which one can reject some data as aberrant or unreliable. In the low-temperature region it is better to cross-plot  $\Delta$  versus  $T$  or  $c$ , while at high temperature cross-plotting  $\Delta/T$  versus  $T$  or  $c$  is preferred. Cross-plotting of  $\Delta$  is convenient up to 300 K and cross-plotting of  $\Delta/T$  down to 100 K; the range of overlap in  $T$  makes it useful to employ both types of plot in relating low-temperature data to high-temperature data. As an example to illustrate the application of this method and procedure, a detailed account of analysis and synthesis of the electrical resistivity data for the gold-silver alloy system is presented in Appendix 5.1.

Combining Eqs. (25) to (27) gives an expression for the electrical resistivity of a binary alloy:

$$\rho(c, T) = \rho_0(c) + c\rho_i^{(A)}(T) + (1 - c)\rho_i^{(B)}(T) + \Delta(c, T). \quad (28)$$

This expression reduces to Eq. (2) for an impure metal for which  $c$  approaches zero.

### 2.3. Presentation of Data and Information

In this work, the term "binary alloy system" refers to the full range of composition of two alloying elements and is signified by a hyphen between the two elements, such as aluminum-copper alloy system. The term "binary alloys" refers to a group of binary alloys in which the first alloying element is predominant and is signified by a plus between the two elements, such as aluminum + copper alloys. In specifying the composition of an alloy, weight percent is denoted by % and atomic percent by At.% or at.%.

In each of the subsections in Sec. 3, electrical resistivity data and information for each alloy system are presented in the following order:

1. A discussion text,
  2. A table of recommended values given as a function of both temperature and composition,
  3. Two figures presenting recommended values as a function of temperature,
  4. Two comparable figures presenting experimental data as a function of temperature,
  5. A figure presenting both recommended values and experimental data as a function of composition.
- In addition, the following supplementary tables which provide measurement information and tabular data for the experimental data sets shown in the figures are deposited in AIP's Physics Auxiliary Publication Service:
6. Two tables giving measurement information on the experimental data presented in the two figures of item 4.
  7. Two comparable tables tabulating experimental data of all the data sets presented in the two figures of item 4 and/or listed in the two tables of item 6.
  8. A table giving measurement information on the experimental data presented in the figure of item 5.
  9. A comparable table tabulating experimental data of all the data sets presented in the figure of item 5 and/or listed in the table of item 8.

Thus, there are normally five figures and seven tables for each alloy system, excepting that some additional figures presenting other useful information are also given for a few particular alloy systems.

In the discussion text on the electrical resistivity of each alloy system, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties of the recommended values are stated.

In the table of recommended values, those values that are provisional are indicated each by a double dagger (‡). The designation as recommended or provisional values depends upon the level of confidence placed on the values and, hence, upon the uncertainty in the values assigned. The uncertainty in the recommended electrical resistivity values is  $\pm 5\%$  or smaller and that in the provisional values is greater than  $\pm 5\%$ .

Values in a temperature range where no experimental

data are available are indicated each by an asterisk (\*). However, it is important to note that in many cases whether experimental data are available or not in a particular temperature range has no bearing on the accuracy or uncertainty in the recommended values generated for that temperature range. It is because in many cases the available experimental data in a particular temperature range are those already rejected as erroneous or unreliable and therefore not used at all in the generation of recommended values for that temperature range, and in many other cases the recommended values for a particular temperature range were generated from accurate values in other ranges and therefore are accurate even though no experimental data are available in that particular temperature range. In other words, recommended values with asterisks do not necessarily have larger uncertainty than those without, and in many cases the opposite is true.

The recommended (or provisional) values in some of the tables are given with more significant figures than warranted, which is merely for tabular smoothness or for the convenience of internal comparison. Hence, the number of significant figures given in the table has no bearing on the degree of accuracy or uncertainty in the values; the uncertainty in the values is always explicitly stated.

For each of the ten binary alloy systems except three (aluminum-copper, aluminum-magnesium, and copper-zinc), the recommended (or provisional) values are given for 27 compositions: 0 (pure element), 0.5, 1, 3, 5, 10(5)95, 97, 99, 99.5, and 100% (pure element). The alloy compositions in atomic percent corresponding to these in weight percent are also specified. For aluminum-copper alloy system, recommended values are presented for 26 compositions, without that containing 80% copper. For aluminum-magnesium alloy system, recommended values are generated only for 12 compositions, lacking those containing 15% to 85% magnesium. Recommended values are given for only 11 compositions of the copper-zinc alloy system, and no values are for those with 35% to 99.5% zinc. For most of the compositions the recommended values cover the temperature range from 1 K to near the solidus temperature (melting starting point). The recommended values have been smoothed simultaneously over both temperature and composition dependences.

The recommended values for the elements are for well-annealed high-purity specimens of the respective elements; however, those values for temperatures below about 100 K are applicable only to the particular specimens having residual electrical resistivities as given at 1 K in the tables. The recommended values generated for the alloys are for those which are not ordered and have not been severely cold-worked or quenched; the electrical resistivity values would be lower for ordered alloys and higher for cold-worked alloys at low temperatures. Furthermore, the values generated are based on the room-temperature dimensions of the alloys, as thermal expansion corrections have not been made. This is due to the fact that the available experimental data on the electrical resistivity of the alloys, upon which the recommendations are based, are not corrected for thermal expansion, and that thermal expansion values for the respective alloys are not available for such corrections to be made. If the values of thermal expansion,  $\Delta L(T)/L_0$ , for the alloys are avail-

able, the electrical resistivity values corrected for thermal expansion,  $\rho_{\text{corrected}}$ , can easily be calculated from the given values uncorrected for thermal expansion,  $\rho_{\text{uncorrected}}$ , by the following relation:

$$\rho_{\text{corrected}}(T) = \left(1 + \frac{\Delta L(T)}{L_0}\right) \rho_{\text{uncorrected}}(T), \quad (29)$$

where  $\Delta L = L - L_0$ , and  $L$  and  $L_0$  are the lengths of the specimen at any temperature  $T$  and at a reference temperature  $T_0$ , respectively. The thermal expansion correction amounts roughly to about  $-0.2\%$  to  $-0.7\%$  at very low temperatures, zero at room temperature, about  $0.3\%$  to  $0.7\%$  at 500 K, and about  $2\%$  near the melting point of the alloy.

In the figures presenting recommended (or provisional) electrical resistivity values as a function of temperature, continuous (solid) curves represent recommended values and long-dashed curves represent provisional values. The short-dashed portion of any of the above two types of curves represents values in that temperature range where no experimental data are available. In a particular temperature range experimental data are considered to be available for a particular alloy composition for which recommended values have been generated if the available experimental data are for a composition closer to that particular composition than to the next composition for which recommended values have also been generated. If the available experimental data are for a composition in the middle of two compositions for which recommended values have been generated, experimental data are considered available for both compositions.

In the figures presenting experimental data, a data set consisting of a single data point is denoted by a number enclosed by a square, and a curve that connects a set of two or more data points is denoted by a ringed number. These data set numbers correspond to those listed in the accompanying tables providing measurement information and tabulating numerical data for each of the data sets. When several sets of data are too close together to be distinguishable, some of the data sets, though listed and tabulated in the tables, are omitted from the figure for the sake of clarity. The data set numbers of those data sets omitted from the figure are asterisked in both tables providing the measurement information and tabulating the experimental data. If only part of the data points of a data set are omitted from the figure, only those data points omitted are asterisked in the table tabulating the experimental data.

The tables providing the measurement information, which are deposited in AIP's Physics Auxiliary Publication Service, contain for each set of experimental data the following information: data set number, reference number, author(s), year of publication, experimental method used for the measurement, temperature range covered by the data, alloy name and specimen designation, alloy composition, specimen specification and characterization, and information on measurement conditions, which are contained in the original paper. The experimental methods used for the measurement of the electrical resistivity of alloys are indicated in the tables by the following code letters:

- A Direct-current potentiometer method
- B Direct-current bridge method
- C Alternating-current potentiometer method
- E Eddy current decay method
- P Van der Pauw method
- R Rotating magnetic field method
- V Voltmeter and ammeter direct reading method

Details of these and other methods for the measurement of electrical resistivity may be found in the literature references given in Appendix 5.2, which presents a complete scheme for the classification and organization of the methods.

The last column of the table on measurement information with heading "Composition, Specification, and Remarks" should contain the following information on the specimen and its measurement if such information is provided in the original source document:

1. Chemical composition,
2. Type of crystal and crystalline axis orientation,
3. Microstructure and inhomogeneity,
4. Specimen shape and dimensions,
5. Method and procedure of fabrication,
6. Manufacturer, supplier, and stock number,
7. Prior heat history and cold-work history,
8. Heat treatment, cold working, irradiative and other treatments,
9. Test environment such as measured in vacuum, or in nitrogen under pressure.
10. Relevant physical properties such as density, transition temperature, Curie temperature, etc., and
11. Whether the data were corrected for the thermal expansion of the specimen.

It will be noted, however, that in the majority of cases the authors did not report in their research papers all the necessary pertinent information.

In the tables tabulating the experimental data, which are deposited in AIP's Physics Auxiliary Publication Service, all the original data reported in different units have been converted to have the same units:  $10^{-8} \Omega\text{m}$  (the SI units). The recommended values generated are also given in the same units. Conversion factors for the units of electrical resistivity, which may be used to convert the electrical resistivity values in the SI units given in this work to values in other units, are given in Appendix 5.3.

It should be noted that in this work the measurement information and experimental data are given in the above two kinds of tables only for the binary alloys, but not for the pure metals, even though the recommended values for the pure metals are given in the tables of recommended values. The experimental data and measurement information on the nine metallic elements which constitute the ten binary alloy systems together with details of their critical reviews, evaluation, and discussions are presented elsewhere.<sup>50-54</sup>

In the figures presenting both recommended values and experimental data as a function of composition, for the sake of clarity recommended or provisional values are presented only for a selected few temperatures and are all represented as continuous (solid) curves. In these figures the alloy compositions are given in atomic percent, with weight percent indicated at the top of the figures.

### 3. Electrical Resistivity of Binary Alloy Systems

#### 3.1. Aluminum-Copper Alloy System

The aluminum-copper alloy system does not form a continuous series of solid solutions. The maximum solid solubility of copper in aluminum is 5.7% (2.50 at.%) at 821 K and the solubility decreases to 0.1%–0.2% (0.48–0.08 at.%) at 523 K. The maximum solid solubility of aluminum in copper is 9.4% (19.6 at.%) in the range from about 650 to 838 K and the solubility decreases at higher and lower temperatures. Thus the region of solid solution is limited.

There are 154 sets of experimental electrical resistivity data available for this system. Eight of the 27 data sets for Al + Cu alloys listed in Table S-1, tabulated in Table S-2, and shown in Fig. 3 are merely single data points. Most of the data were measured between 250 and 700 K for alloys containing no more than 15% Cu. Only a single point is available at 4.2 K. Of the 106 data sets for Cu + Al alloys listed in Table S-3, tabulated in Table S-4, and shown in Fig. 4, 36 sets are single data points measured at 4.2 K or at room temperature. Most of the data were measured between room temperature and 1000 K. Three of the 21 resistivity-composition data sets listed in Table S-5, tabulated in Table S-6, and shown in Fig. 5 are for specimens in liquid state.

For the Al + Cu alloys, the resistivity-composition curve at 273 K was first determined in Fig. 5 following mainly the data of Smith<sup>55</sup> (Al-Cu data set 4). For ordinary alloys, it is usually reasonable to assume that the deviation of the electrical resistivity from the Matthiessen's rule due to alloying is small at low temperatures, say, below 50 K. The resistivity-composition curve at 4.2 K is then drawn parallel to the curve for 273 K. Starting from the values at these two temperatures, the recommended curves for the Al + Cu alloys were drawn according to the temperature dependence of the data of Griffiths and Schofield<sup>56</sup> (Al + Cu data sets 1–5).

For the Cu + Al alloys containing 10% Al or less, the recommended values for the resistivity at 293 K were obtained by drawing a best smooth isotherm so as to agree to within  $\pm 4\%$  with the data of Gaudig and Warlimont<sup>57</sup> (Cu + Al data sets 86, 87), Panin *et al.*<sup>58,59</sup> (Cu + Al data sets 88, 90, 92, 94), Hibbard<sup>60</sup> (Cu + Al data set 48), Wechsler and Kernohan<sup>61</sup> (Cu + Al data set 43), Gulyaev and Trusova<sup>62</sup> (Al-Cu data set 16), Linde<sup>63</sup> (Cu + Al data sets 44–46; Cu + Al data set 47 is 10% higher than the recommended value), and Smith and Palmer<sup>64</sup> (Cu + Al data sets 2, 3, 5, 6; Cu + Al data set 4 is 11% higher than the recommended values). For specimens containing more than 10% Al, the isotherm representing the recommended values for the resistivity at 293 K follows the trend of the room-temperature data of Pecijare and Jannsen<sup>65,66</sup> (Cu + Al data sets 33–42). Köster and Rothenbacher<sup>67</sup> (Cu + Al data sets 67–70), and Hishiyama<sup>68</sup> (Al-Cu data set 21). For these more concentrated alloys, it should be noted that some authors, notably Smith and Palmer<sup>64</sup> (Cu + Al data sets 8, 9), Sinha and Pra-

sad<sup>69</sup> (Cu + Al data sets 52, 53), and Griffiths and Schofield<sup>56</sup> (Cu + Al data set 1), have reported resistivities as much as 30% greater than the recommended values. The isothermal resistivities suggested by these authors increase more rapidly as a function of increasing aluminum content than do the recommended values. The discrepancy is largely unexplained due to lack of information, other than to suggest a probable difference in specimen impurities and crystalline structures, which points to a need for detailed specimen characterization in any future work on the resistivity of these alloys. For specimens containing from 15% to 25% Al, the data indicate a maximum in the isothermal resistivity as a function of composition. However, there is insufficient evidence to indicate where the maximum is, and not enough information is available in this region to warrant the recommendation of values for the resistivity of the 20% Al alloy at 293 K or other temperatures.

The recommended values for the residual resistivities of Cu + Al alloys were generated by drawing a best smooth isotherm through the data of Weinberg<sup>70</sup> (Cu + Al data sets 65, 66), Chu and Lipschultz<sup>71,72</sup> (Cu + Al data sets 28, 55), Charley and Salter<sup>73,74</sup> (Cu + Al data sets 10–17, 19; Al-Cu data set 19), Kusunoki and Suzuki<sup>75</sup> (Cu + Al data set 20), Wechsler and Kernohan<sup>61</sup> (Cu + Al data set 43), Lindenfeld and Pennebaker<sup>76</sup> (Cu + Al data set 18), Kapoor *et al.*<sup>77</sup> (Cu + Al data sets 103–105), and Mitchell *et al.*<sup>78</sup> (Cu + Al data sets 22, 24). The great majority of those data lie within  $\pm 0.5 \times 10^{-8} \Omega m$  of the recommended isotherm. For alloys containing more than 10% Al, no measurements were made below 250 K except a single point for a 46% Al alloy at 4.2 K. Consequently no recommendations are made below 250 K for the more dense alloys. The recommended values for the resistivities at temperatures above room temperature were based primarily on the data of Smith and Palmer<sup>64</sup> (Cu + Al data sets 2, 3, 5, 6), Gaudig and Warlimont<sup>57</sup> (Cu + Al data sets 86, 87), and Panin *et al.*<sup>59</sup> (Cu + Al data sets 92, 94) with some weight given to the data of Jannsen and Pecijare<sup>65,66</sup> (Cu + Al data sets 33–42) and Sinha and Prasad<sup>69</sup> (Cu + Al data sets 50–53).

The resulting recommended electrical resistivity values for Al, Cu, and for 24 Al-Cu binary alloys are presented in Table 1 and shown in Figs. 1, 2, and 5. No values were generated for Cu + 20% Al alloy. The recommended values for Al and for Cu are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Al and Cu having residual electrical resistivities as given at 1 K in Table 1. The alloys for which the recommended values are generated are not ordered and have not been quenched or cold-worked severely. For most of the alloys, the recommended values cover a full range of temperature from 1 K to the solidus temperature of the alloy where melting starts. These values are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 1. Some of the values in Table 1 are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

TABLE 1. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-COPPER ALLOY SYSTEM†  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Al: 100.00% (100.00 At.%) Cu: 0.00% ( 0.00 At.%)		Al: 99.50% (99.79 At.%) Cu: 0.50% ( 0.21 At.%)		Al: 99.00% (99.57 At.%) Cu: 1.00% ( 0.43 At.%)		Al: 97.00% (98.70 At.%) Cu: 3.00% ( 1.30 At.%)		Al: 95.00% (97.81 At.%) Cu: 5.00% ( 2.19 At.%)		Al: 90.00% (95.49 At.%) Cu: 10.00% ( 4.51 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.00100*	1	0.043*	1	0.089*	1	0.269*	1	0.453*	1	0.934*
4	0.00100	4	0.043*	4	0.089	4	0.269*	4	0.453*	4	0.934*
7	0.00100	7	0.043*	7	0.089*	7	0.269*	7	0.453*	7	0.934*
10	0.00103	10	0.043*	10	0.089*	10	0.269*	10	0.453*	10	0.934*
15	0.00117	15	0.043*	15	0.089	15	0.269*	15	0.453*	15	0.934*
20	0.00168	20	0.044*	20	0.090	20	0.270*	20	0.454*	20	0.935*
25	0.00296	25	0.046*	25	0.092	25	0.273*	25	0.456*	25	0.936*
30	0.00564	30	0.050*	30	0.095	30	0.276*	30	0.459*	30	0.940*
40	0.0188	40	0.063*	40	0.109	40	0.289*	40	0.473*	40	0.954*
50	0.0480	50	0.092*	50	0.138	50	0.318*	50	0.502*	50	0.983*
60	0.0960	60	0.139*	60	0.186	60	0.366*	60	0.550*	60	1.03*
70	0.163	70	0.206*	70	0.252*	70	0.452	70	0.616	70	1.10*
80	0.246	80	0.289*	80	0.335*	80	0.515	80	0.699	80	1.18*
90	0.340	90	0.383*	90	0.429*	90	0.609	90	0.793	90	1.27
100	0.443	100	0.485*	100	0.531*	100	0.711	100	0.895	100	1.38
150	1.010	150	1.05*	150	1.10*	150	1.28	150	1.46	150	1.94
200	1.593	200	1.63*	200	1.68*	200	1.86	200	2.04	200	2.51
250	2.167	250	2.21*	250	2.25*	250	2.44	250	2.62	250	3.09
273	2.429	273	2.48	273	2.51	273	2.70	273	2.88	273	3.36
293	2.653	293	2.69	293	2.74	293	2.92	293	3.10	293	3.59
300	2.731	300	2.72	300	2.82	300	3.00	300	3.18	300	3.67
350	3.292	350	2.43*	350	3.38*	350	3.56	350	3.75	350	4.25
400	3.854	400	3.24*	400	3.95*	400	4.14	400	4.33	400	4.86
500	4.992	500	5.15*	500	5.10*	500	5.32	500	5.54	500	6.14
600	6.155	600	6.32*	600	6.28*	600	6.55	600	6.81	600	7.48
700	7.353	700	7.41	700	7.50	700	7.82	700	8.12	700	8.89
800	8.622	800	8.72	800	8.79	800	9.12	800	9.46	800	10.4
900	10.019	900	10.1	900	10.2	875	10.1	835	9.73	821	10.7
933.52	10.516*	923	10.4	913	10.3						

† Uncertainties in the electrical resistivity values are as follows:

- 100.00 Al - 0.00 Cu:  $\pm 2\%$  below 80 K,  $\pm 1\%$  from 80 to 200 K,  $\pm 0.5\%$  above 200 K to 500 K, and  $\pm 2\%$  above 500 K.
- 99.50 Al - 0.50 Cu:  $\pm 5\%$  below 200 K,  $\pm 2\%$  from 200 to 600 K, and  $\pm 3\%$  above 600 K.
- 99.00 Al - 1.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 2\%$  from 200 to 600 K, and  $\pm 3\%$  above 600 K.
- 97.00 Al - 3.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 2\%$  from 200 to 600 K, and  $\pm 3\%$  above 600 K.
- 95.00 Al - 5.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 2\%$  from 200 to 600 K, and  $\pm 3\%$  above 600 K.
- 90.00 Al - 10.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 3\%$  above 600 K.

\* In temperature range where no experimental data are available.

TABLE 1. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-COPPER ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Al: 85.00% (93.03 At.%) Cu: 15.00% ( 6.97 At.%)		Al: 80.00% (90.40 At.%) Cu: 20.00% ( 9.60 At.%)		Al: 75.00% (87.60 At.%) Cu: 25.00% (12.40 At.%)		Al: 70.00% (84.60 At.%) Cu: 30.00% (15.40 At.%)		Al: 65.00% (61.39 At.%) Cu: 35.00% (18.61 At.%)		Al: 60.00% (77.94 At.%) Cu: 40.00% (22.06 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	1.44 <sup>‡</sup>	1	1.90 <sup>‡</sup>	1	2.28 <sup>‡</sup>	1	2.59 <sup>‡</sup>	1	2.82 <sup>‡</sup>	1	3.08 <sup>‡</sup>
4	1.44 <sup>‡</sup>	4	1.90 <sup>‡</sup>	4	2.28 <sup>‡</sup>	4	2.59 <sup>‡</sup>	4	2.82 <sup>‡</sup>	4	3.08 <sup>‡</sup>
7	1.44 <sup>‡</sup>	7	1.90 <sup>‡</sup>	7	2.28 <sup>‡</sup>	7	2.59 <sup>‡</sup>	7	2.82 <sup>‡</sup>	7	3.08 <sup>‡</sup>
10	1.44 <sup>‡</sup>	10	1.90 <sup>‡</sup>	10	2.28 <sup>‡</sup>	10	2.59 <sup>‡</sup>	10	2.82 <sup>‡</sup>	10	3.08 <sup>‡</sup>
15	1.44 <sup>‡</sup>	15	1.90 <sup>‡</sup>	15	2.28 <sup>‡</sup>	15	2.59 <sup>‡</sup>	15	2.82 <sup>‡</sup>	15	3.08 <sup>‡</sup>
20	1.44 <sup>‡</sup>	20	1.90 <sup>‡</sup>	20	2.28 <sup>‡</sup>	20	2.59 <sup>‡</sup>	20	2.82 <sup>‡</sup>	20	3.08 <sup>‡</sup>
25	1.44 <sup>‡</sup>	25	1.90 <sup>‡</sup>	25	2.28 <sup>‡</sup>	25	2.59 <sup>‡</sup>	25	2.82 <sup>‡</sup>	25	3.08 <sup>‡</sup>
30	1.45 <sup>‡</sup>	30	1.91 <sup>‡</sup>	30	2.29 <sup>‡</sup>	30	2.60 <sup>‡</sup>	30	2.83 <sup>‡</sup>	30	3.09 <sup>‡</sup>
40	1.46 <sup>‡</sup>	40	1.92 <sup>‡</sup>	40	2.30 <sup>‡</sup>	40	2.61 <sup>‡</sup>	40	2.84 <sup>‡</sup>	40	3.10 <sup>‡</sup>
50	1.49 <sup>‡</sup>	50	1.95 <sup>‡</sup>	50	2.33 <sup>‡</sup>	50	2.64 <sup>‡</sup>	50	2.87 <sup>‡</sup>	50	3.13 <sup>‡</sup>
60	1.54 <sup>‡</sup>	60	2.00 <sup>‡</sup>	60	2.38 <sup>‡</sup>	60	2.69 <sup>‡</sup>	60	2.92 <sup>‡</sup>	60	3.18 <sup>‡</sup>
70	1.60 <sup>‡</sup>	70	2.06 <sup>‡</sup>	70	2.45 <sup>‡</sup>	70	2.75 <sup>‡</sup>	70	2.99 <sup>‡</sup>	70	3.23 <sup>‡</sup>
80	1.69 <sup>‡</sup>	80	2.15 <sup>‡</sup>	80	2.53 <sup>‡</sup>	80	2.83 <sup>‡</sup>	80	3.06 <sup>‡</sup>	80	3.30 <sup>‡</sup>
90	1.78	90	2.24 <sup>‡</sup>	90	2.62 <sup>‡</sup>	90	2.92 <sup>‡</sup>	90	3.15 <sup>‡</sup>	90	3.39 <sup>‡</sup>
100	1.88	100	2.34 <sup>‡</sup>	100	2.72 <sup>‡</sup>	100	3.02 <sup>‡</sup>	100	3.25 <sup>‡</sup>	100	3.49 <sup>‡</sup>
150	2.45	150	2.91 <sup>‡</sup>	150	3.29 <sup>‡</sup>	150	3.56 <sup>‡</sup>	150	3.90 <sup>‡</sup>	150	4.01 <sup>‡</sup>
200	3.03	200	3.49 <sup>‡</sup>	200	3.87 <sup>‡</sup>	200	4.15 <sup>‡</sup>	200	4.39 <sup>‡</sup>	200	4.49 <sup>‡</sup>
250	3.61	250	4.06 <sup>‡</sup>	250	4.45 <sup>‡</sup>	250	4.74 <sup>‡</sup>	250	5.00 <sup>‡</sup>	250	5.14 <sup>‡</sup>
273	3.87	273	4.33 <sup>‡</sup>	273	4.72 <sup>‡</sup>	273	5.03 <sup>‡</sup>	273	5.01 <sup>‡</sup>	273	5.56 <sup>‡</sup>
293	4.10	293	4.58	293	4.98	293	5.31	293	5.61	293	5.88
300	4.19	300	4.67	300	5.07	300	5.41	300	5.71	300	5.99
350	4.79	350	5.21 <sup>‡</sup>	350	5.76 <sup>‡</sup>	350	6.14 <sup>‡</sup>	350	6.48 <sup>‡</sup>	350	6.77 <sup>‡</sup>
400	5.42	400	5.99 <sup>‡</sup>	400	6.49 <sup>‡</sup>	400	6.94 <sup>‡</sup>	400	7.30 <sup>‡</sup>	400	7.63 <sup>‡</sup>
500	6.76	500	7.42 <sup>‡</sup>	500	8.05 <sup>‡</sup>	500	8.62 <sup>‡</sup>	500	9.04 <sup>‡</sup>	500	9.49 <sup>‡</sup>
600	8.19	600	8.95 <sup>‡</sup>	600	9.68 <sup>‡</sup>	600	10.4 <sup>‡</sup>	600	10.9 <sup>‡</sup>	600	11.5 <sup>‡</sup>
700	9.69	700	10.6	700	11.4	700	12.2	700	12.8	700	13.5 <sup>‡</sup>
800	11.3	800	12.3	800	13.3	800	14.2	800	15.0	800	15.8 <sup>‡</sup>
821	11.7	821	12.7	821	13.6	821	14.6	821	15.4	821	16.2 <sup>‡</sup>

† Uncertainties in the electrical resistivity values are as follows:

- 85.00 Al - 15.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.
- 80.00 Al - 20.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.
- 75.00 Al - 25.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.
- 70.00 Al - 30.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.
- 65.00 Al - 35.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.
- 60.00 Al - 40.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 6\%$  above 600 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.



TABLE 1. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-COPPER ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Al: 55.00% (74.22 At. %) Cu: 45.00% (25.78 At. %)		Al: 50.00% (70.20 At. %) Cu: 50.00% (29.80 At. %)		Al: 45.00% (65.83 At. %) Cu: 55.00% (34.17 At. %)		Al: 40.00% (61.09 At. %) Cu: 60.00% (38.91 At. %)		Al: 35.00% (55.91 At. %) Cu: 65.00% (44.09 At. %)		Al: 30.00% (50.23 At. %) Cu: 70.00% (49.77 At. %)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	3.33*†	1	3.64*†								
4	3.33*†	4	3.64*†								
7	3.33*†	7	3.64*†								
10	3.33*†	10	3.64*†								
15	3.33*†	15	3.64*†								
20	3.33*†	20	3.64*†								
25	3.33*†	25	3.64*†								
30	3.34*†	30	3.65*†								
40	3.35*†	40	3.66*†								
50	3.38*†	50	3.69*†								
60	3.43*†	60	3.74*†								
70	3.48*†	70	3.79*†								
80	3.54*†	80	3.85*†								
90	3.64*†	90	3.92*†								
100	3.77*†	100	4.00*†								
150	4.27*†	150	4.52*†								
200	4.35*	200	5.15*								
250	5.51*	250	5.86*	250	6.39*	250	7.14*	250	8.27*	250	10.5*
273	5.84*	273	6.22*	273	6.78*	273	7.57*	273	8.75*	273	11.2*
293	6.16	293	6.55	293	7.14	293	7.96	293	9.19	293	11.8
300	6.28	300	6.67	300	7.26	300	8.10	300	9.36	300	12.0
350	7.11*	350	7.55	350	8.21	350	9.12*	350	10.6*	350	13.5*
400	8.00*	400	8.52	400	9.23	400	10.2*	400	11.9*	400	15.2*
500	9.96*	500	10.6	500	11.5	500	12.7*	500	14.7*	500	18.7*
600	12.1*	600	12.8	600	13.8	600	15.3*	600	17.6*	600	22.5*
700	14.2*	700	15.2*	700	16.3*	700	18.0*†	700	20.7*†	700	26.5*†
800	16.5*	800	17.6*	800	18.9*	800	20.9*†	800	24.0*†	800	30.8*†
821	17.0*	821	18.6*	821	20.6*†	821	22.8*†	821	26.0*†	821	33.6*†

† Uncertainties in the electrical resistivity values are as follows:

55.00 Al - 45.00 Cu:  $\pm 7\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 8\%$  above 600 K.50.00 Al - 50.00 Cu:  $\pm 10\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 8\%$  above 600 K.45.00 Al - 55.00 Cu:  $\pm 5\%$  up to 600 K and  $\pm 8\%$  above 600 K.40.00 Al - 60.00 Cu:  $\pm 5\%$  up to 600 K and  $\pm 10\%$  above 600 K.35.00 Al - 65.00 Cu:  $\pm 5\%$  up to 600 K and  $\pm 10\%$  above 600 K.30.00 Al - 70.00 Cu:  $\pm 5\%$  up to 600 K and  $\pm 10\%$  above 600 K.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 1. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-COPPER ALLOY SYSTEM<sup>†</sup> (continued)(Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-7} \Omega \text{ m}$ )

Al: 25.00% (43.49 At.%) Cu: 75.00% (56.42 At.%)		Al: 15.00% (29.36 At.%) Cu: 85.00% (70.64 At.%)		Al: 10.00% (20.77 At.%) Cu: 90.00% (79.23 At.%)		Al: 5.00% (11.03 At.%) Cu: 95.00% (88.97 At.%)		Al: 3.00% (6.79 At.%) Cu: 97.00% (93.21 At.%)		Al: 1.00% (2.32 At.%) Cu: 99.00% (97.68 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
250	15.3 <sup>‡</sup>	1	8.10 <sup>‡</sup>	1	7.32 <sup>‡</sup>	1	6.30 <sup>*</sup>	1	6.30 <sup>*</sup>	1	2.92 <sup>*</sup>
273	16.3 <sup>‡</sup>	4	8.10 <sup>‡</sup>	4	7.32 <sup>‡</sup>	4	6.30 <sup>*</sup>	4	6.30 <sup>*</sup>	4	2.92 <sup>*</sup>
293	17.2 <sup>‡</sup>	7	8.10 <sup>‡</sup>	7	7.32 <sup>‡</sup>	7	6.30 <sup>*</sup>	7	6.30 <sup>*</sup>	7	2.92 <sup>*</sup>
300	17.6 <sup>‡</sup>	10	8.10 <sup>‡</sup>	10	7.32 <sup>‡</sup>	10	6.30 <sup>*</sup>	10	6.30 <sup>*</sup>	10	2.92 <sup>*</sup>
350	19.8 <sup>‡</sup>	15	8.11 <sup>‡</sup>	15	7.34 <sup>‡</sup>	15	6.30 <sup>*</sup>	15	6.30 <sup>*</sup>	15	2.92 <sup>*</sup>
400	22.2 <sup>‡</sup>	20	8.12 <sup>‡</sup>	20	7.36 <sup>‡</sup>	20	6.30 <sup>*</sup>	20	6.30 <sup>*</sup>	20	2.92 <sup>*</sup>
500	27.2 <sup>‡</sup>	25	8.15 <sup>‡</sup>	25	7.39 <sup>‡</sup>	25	6.31 <sup>*</sup>	25	6.31 <sup>*</sup>	25	2.93 <sup>*</sup>
600	32.6 <sup>‡</sup>	30	8.18 <sup>‡</sup>	30	7.42 <sup>‡</sup>	30	6.33 <sup>*</sup>	30	6.33 <sup>*</sup>	30	2.94 <sup>*</sup>
700	38.4 <sup>‡</sup>	40	8.22 <sup>‡</sup>	40	7.49 <sup>‡</sup>	40	6.37 <sup>*</sup>	40	6.37 <sup>*</sup>	40	2.97 <sup>*</sup>
800	44.6 <sup>‡</sup>	50	8.29 <sup>‡</sup>	50	7.55 <sup>‡</sup>	50	6.42 <sup>*</sup>	50	6.42 <sup>*</sup>	50	3.00 <sup>*</sup>
900	51.1 <sup>‡</sup>	60	8.36 <sup>‡</sup>	60	7.61 <sup>‡</sup>	60	6.48 <sup>*</sup>	60	6.48 <sup>*</sup>	60	3.04 <sup>*</sup>
939	53.8 <sup>‡</sup>	70	8.41 <sup>‡</sup>	70	7.69 <sup>‡</sup>	70	6.50 <sup>*</sup>	70	6.50 <sup>*</sup>	70	3.08 <sup>*</sup>
		80	8.52 <sup>‡</sup>	80	7.78 <sup>‡</sup>	80	6.58 <sup>*</sup>	80	6.58 <sup>*</sup>	80	3.13 <sup>*</sup>
		90	8.61 <sup>‡</sup>	90	7.83 <sup>‡</sup>	90	6.62 <sup>*</sup>	90	6.62 <sup>*</sup>	90	3.17 <sup>*</sup>
		100	8.71 <sup>‡</sup>	100	7.92 <sup>‡</sup>	100	6.68 <sup>*</sup>	100	6.68 <sup>*</sup>	100	3.22 <sup>*</sup>
		150	9.29 <sup>‡</sup>	150	8.36 <sup>‡</sup>	150	6.92 <sup>*</sup>	150	6.92 <sup>*</sup>	150	3.52 <sup>*</sup>
		200	9.89 <sup>‡</sup>	200	8.79 <sup>‡</sup>	200	7.27 <sup>*</sup>	200	7.27 <sup>*</sup>	200	3.89 <sup>*</sup>
		250	10.5 <sup>‡</sup>	250	9.22 <sup>‡</sup>	250	7.68 <sup>*</sup>	250	7.68 <sup>*</sup>	250	4.29 <sup>*</sup>
		273	10.8 <sup>‡</sup>	273	9.43 <sup>‡</sup>	273	7.87 <sup>*</sup>	273	7.87 <sup>*</sup>	273	4.46 <sup>*</sup>
		293	11.0 <sup>‡</sup>	293	9.61 <sup>‡</sup>	293	8.01 <sup>*</sup>	293	8.01 <sup>*</sup>	293	4.60 <sup>*</sup>
		300	11.1 <sup>‡</sup>	300	9.68 <sup>‡</sup>	300	8.10 <sup>*</sup>	300	8.10 <sup>*</sup>	300	4.65 <sup>*</sup>
		350	11.7 <sup>‡</sup>	350	10.2 <sup>‡</sup>	350	8.59 <sup>*</sup>	350	8.59 <sup>*</sup>	350	5.00 <sup>*</sup>
		400	12.3 <sup>‡</sup>	400	10.7 <sup>‡</sup>	400	9.10 <sup>*</sup>	400	9.10 <sup>*</sup>	400	5.37 <sup>*</sup>
		500	13.4 <sup>‡</sup>	500	11.7 <sup>‡</sup>	500	10.1 <sup>*</sup>	500	10.1 <sup>*</sup>	500	6.11 <sup>*</sup>
		600	14.6 <sup>‡</sup>	600	12.7 <sup>‡</sup>	600	11.0 <sup>*</sup>	600	11.0 <sup>*</sup>	600	6.89 <sup>*</sup>
		700	15.8 <sup>‡</sup>	700	13.7 <sup>‡</sup>	700	12.0 <sup>*</sup>	700	12.0 <sup>*</sup>	700	7.75 <sup>*</sup>
		800	16.9 <sup>‡</sup>	800	14.8 <sup>‡</sup>	800	13.0 <sup>*</sup>	800	13.0 <sup>*</sup>	800	8.67 <sup>*</sup>
		900	18.1 <sup>‡</sup>	900	15.9 <sup>‡</sup>	900	14.1 <sup>*</sup>	900	14.1 <sup>*</sup>	900	9.65 <sup>*</sup>
		1000	19.3 <sup>‡</sup>	1000	17.0 <sup>‡</sup>	1000	15.2 <sup>*</sup>	1000	15.2 <sup>*</sup>	1000	10.7 <sup>*</sup>
		1100	20.5 <sup>‡</sup>	1100	18.2 <sup>‡</sup>	1100	16.3 <sup>*</sup>	1100	16.3 <sup>*</sup>	1100	11.7 <sup>*</sup>
		1200	21.6 <sup>‡</sup>	1200	19.3 <sup>‡</sup>	1200	17.5 <sup>*</sup>	1200	17.5 <sup>*</sup>	1200	12.7 <sup>*</sup>
		1300	22.9 <sup>‡</sup>	1300	20.5 <sup>‡</sup>	1300	18.7 <sup>*</sup>	1300	18.7 <sup>*</sup>	1300	13.8 <sup>*</sup>
		1313	23.0 <sup>‡</sup>	1313	20.8 <sup>‡</sup>	1313	19.1 <sup>*</sup>	1313	19.1 <sup>*</sup>	1313	14.3 <sup>*</sup>

<sup>†</sup> Uncertainties in the electrical resistivity values are as follows:25.00 Al - 75.00 Cu:  $\pm 8\%$  up to 600 K and  $\pm 15\%$  above 600 K.15.00 Al - 85.00 Cu:  $\pm 12\%$ .10.00 Al - 90.00 Cu:  $\pm 12\%$  up to 150 K and  $\pm 10\%$  above 150 K.5.00 Al - 95.00 Cu:  $\pm 7\%$ .3.00 Al - 97.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 800 K, and  $\pm 5\%$  above 800 K.1.00 Al - 99.00 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 800 K, and  $\pm 5\%$  above 800 K.<sup>‡</sup> Provisional value.

\* In temperature range where no experimental data are available.

TABLE 1. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-COPPER ALLOY SYSTEM † (continued)  
 (Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ )

T	$\rho$	T	$\rho$	T	$\rho$
Al: 0.50% (1.17 At.%) Cu: 99.50% (98.83 At.%)	1.49	Al: 0.00% (0.00 At.%) Cu: 100.00% (100.00 At.%)	0.00200	1	0.00200
	1.49		0.00200	4	0.00200
	1.49		0.00200	7	0.00200
	1.49		0.00218	10	0.00202
	1.49		0.00280	15	0.00218
	1.49		0.00450	20	0.00280
	1.50		0.00630	25	0.00450
	1.51		0.0240	30	0.00630
	1.54		0.0520	40	0.0240
	1.58		0.0974	50	0.0520
	1.62		0.154	60	0.0974
	1.67		0.216	70	0.154
	1.72		0.282	80	0.216
	1.77		0.349	90	0.282
	2.12		0.701	100	0.349
	2.49		1.048	150	0.701
	2.87		1.388	200	1.048
	3.04		1.544	250	1.388
	3.17		1.678	273	1.544
	3.21		1.725	293	1.678
	3.56		2.061	300	1.725
	3.90		2.398	350	2.061
	4.62		3.079	400	2.398
	5.37		3.771	500	3.079
	6.18		4.481	600	3.771
	7.02*		5.213	700	4.481
	7.90*		5.973	800	5.213
	8.79*		6.766	900	5.973
	9.71*		7.596	1000	6.766
	10.7*		8.470	1100	7.596
	11.7*		9.395	1200	8.470
	11.6*		9.946(s)	1300	9.395
			21.01(t)	1357.6	9.946(s)
			24.41	1358	21.01(t)
				1700	24.41

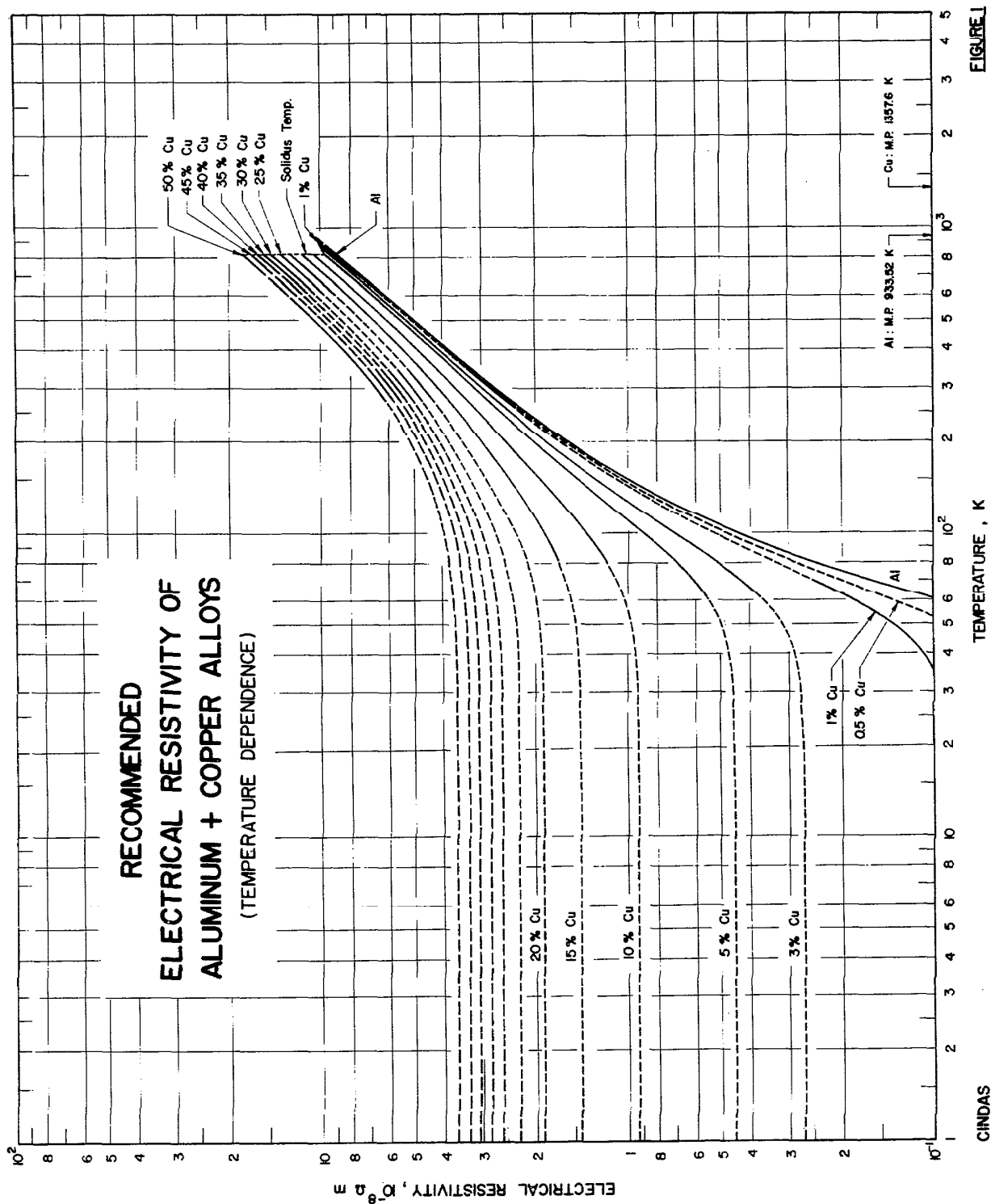
† Uncertainties in the electrical resistivity values are as follows:

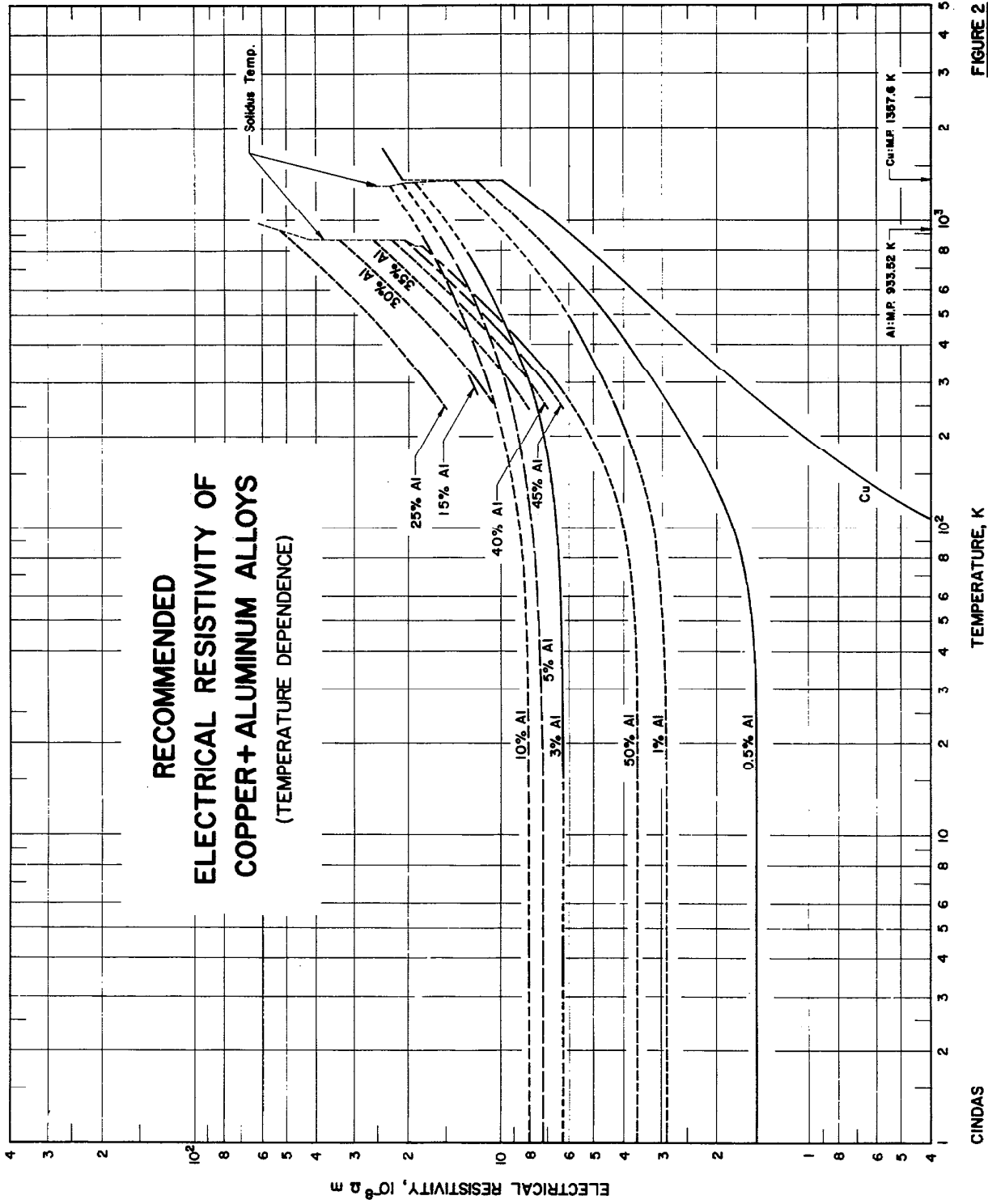
0.50 Al - 99.50 Cu:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 800 K, and  $\pm 5\%$  above 800 K.

0.00 Al - 100.00 Cu:  $\pm 3\%$  up to 100 K,  $\pm 1\%$  above 100 K to 250 K,  $\pm 0.5\%$  above 250 K to 350 K,  $\pm 1\%$  above 350 K to 500 K,  $\pm 4\%$  above 500 K to 1357.6 K, and  $\pm 5\%$  above 1357.6 K.

\* In temperature range where no experimental data are available.

\* In temperature range where no experimental data are available.





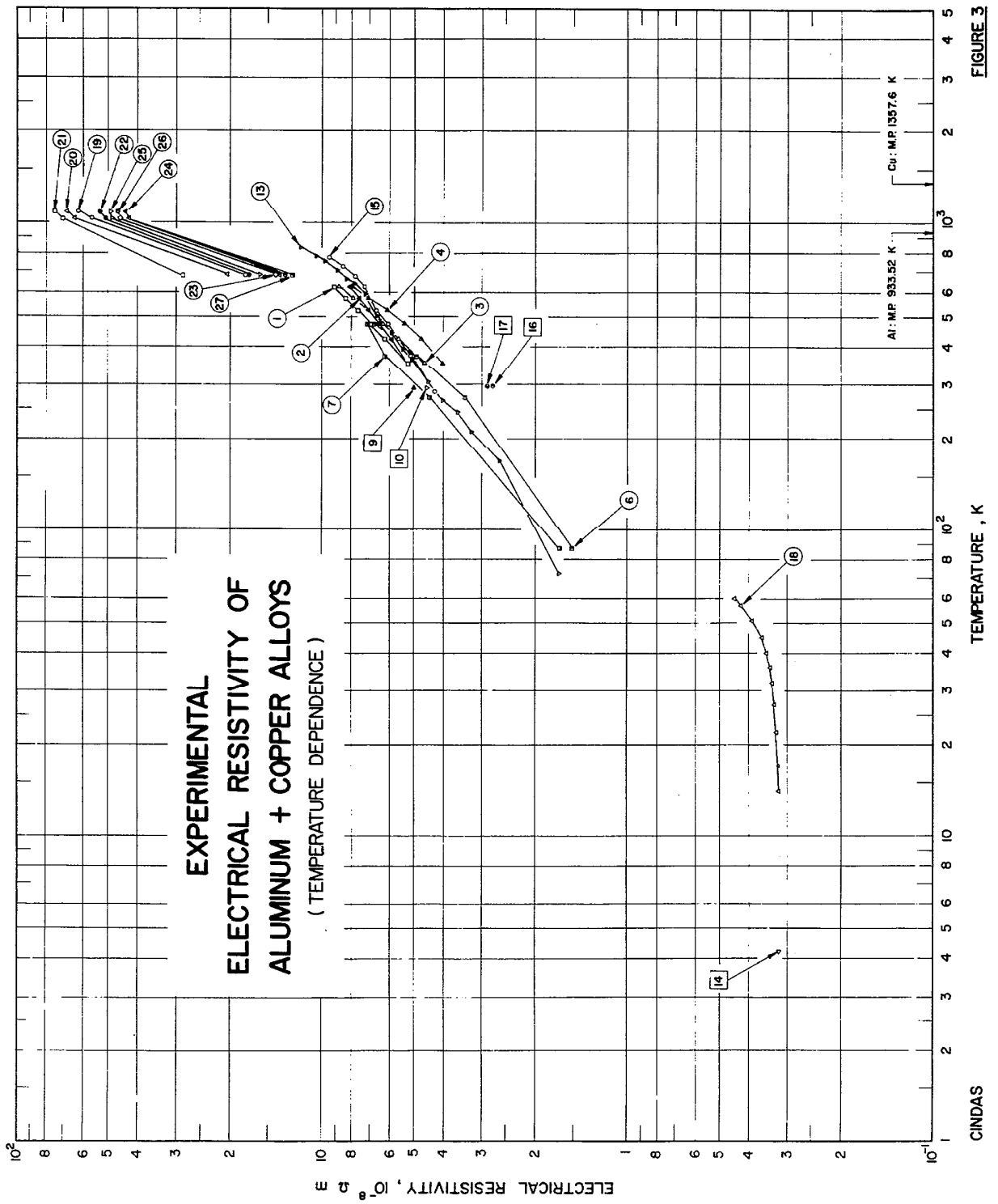


FIGURE 3

TEMPERATURE, K

CINDAS

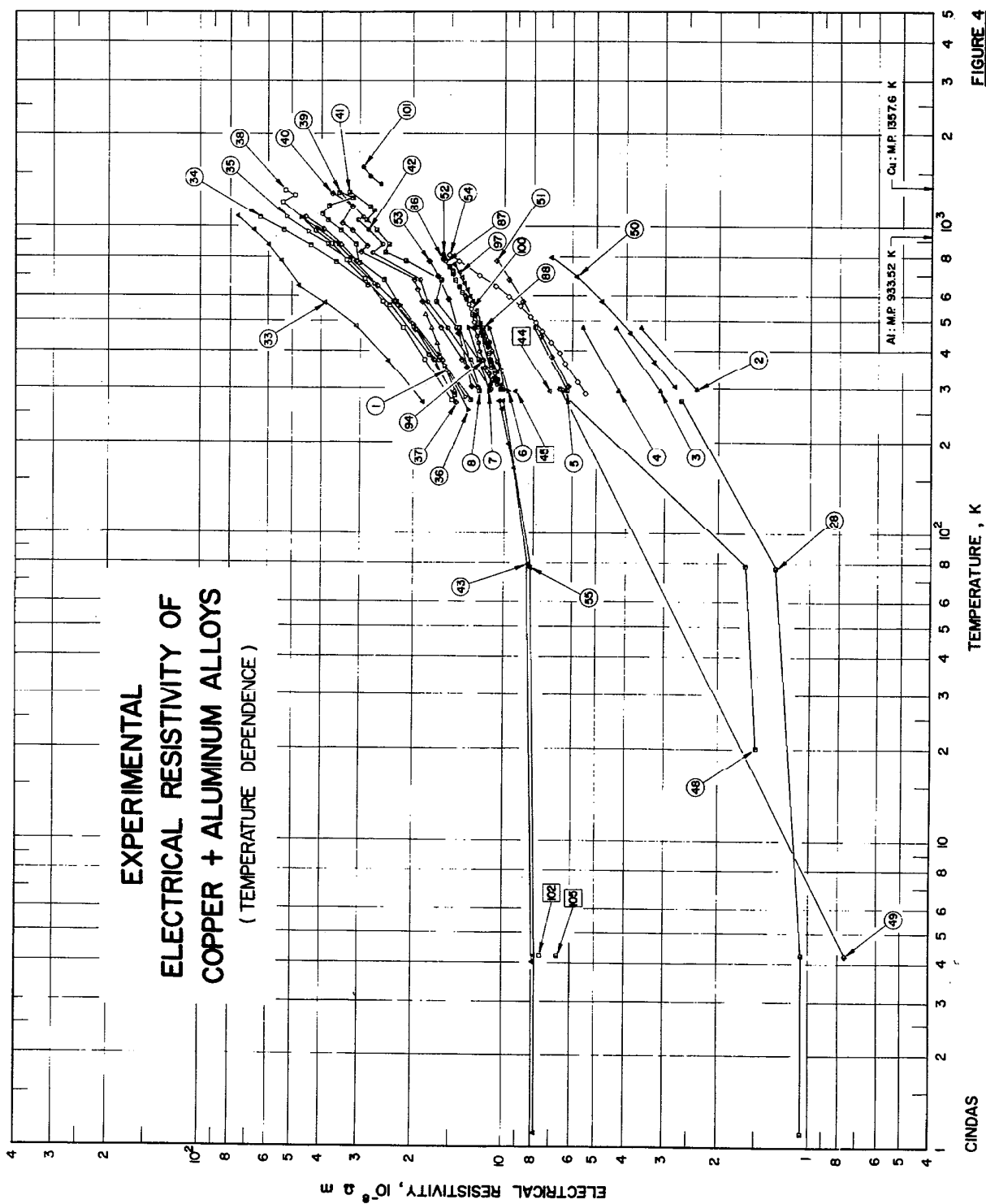
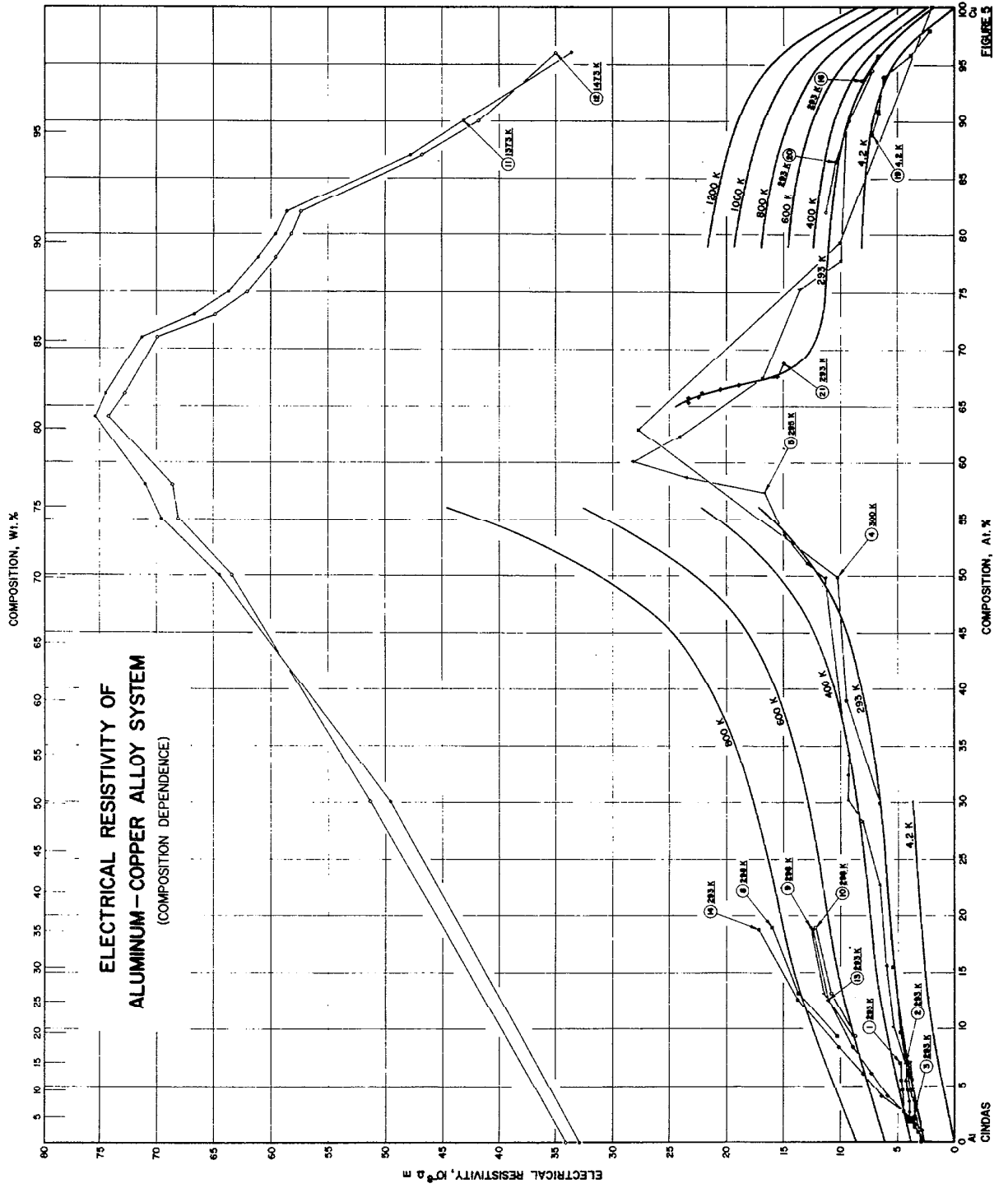


FIGURE 4

TEMPERATURE, K

CINDAS





### 3.2. Aluminum–Magnesium Alloy System

The aluminum–magnesium alloy system does not form a continuous series of solid solutions. The maximum solid solubility of magnesium in aluminum is 17.4% (18.9 at.%) at 723 K and the solubility decreases at higher and lower temperatures, being only 1.9% (2.1 at.%) at 373 K. The maximum solid solubility of aluminum in magnesium is 12.7% (11.6 at.%) at 710 K and likewise it decreases at higher and lower temperatures, being only about 1.5% (1.3 at.%) at 373 K. Thus the region of solid solution for this system is even more limited than that of the aluminum–copper alloy system.

There are 76 sets of experimental electrical resistivity data available for this system. Of the 43 data sets for Al + Mg alloys listed in Table S-7, tabulated in Table S-8, and shown in Fig. 8, 11 sets are merely single data points. Twelve of the 28 data sets for Mg + Al alloys listed in Table S-9, tabulated in Table S-10, and shown in Fig. 9 are single data points. Of the 5 resistivity–composition data sets listed in Table S-11, tabulated in Table S-12, and shown in Fig. 10, one set is for specimens in liquid state.

For the Al + Mg alloys, measurements were limited to alloys containing no more than 14% Mg. Recommended values were, therefore, generated only for 0.5% to 10% Mg alloys. For the electrical resistivity of these alloys, it appears that the deviation from the Matthiessen's rule due to alloying is small. Hence, a residual resistivity versus composition curve was constructed based on the slope of the data of Gulyaev and Trusova<sup>62</sup> (Al–Mg data set 4) measured at 293 K, and the total electrical resistivity of each alloy was then obtained by adding its residual electrical resistivity to the intrinsic electrical resistivity of pure Al.<sup>54</sup> The resulting recommended values agree well with the data of Idase *et al.*<sup>99</sup> (Al + Mg data sets 1–4) and of Cordier and Detert<sup>100</sup> (Al + Mg data sets 12–14) above room temperature, and agree with the data of Seth and Woods<sup>101</sup> (Al + Mg data sets

9–11), Clark *et al.*<sup>102,103</sup> (Al + Mg data sets 15, 26, 27), and Clark and Tryon<sup>104</sup> (Al + Mg data sets 28–36) between 100 and 300 K.

For the Mg + Al alloys, no measurements were made for alloys containing more than 12.2% Al. Accordingly, the recommended values were generated for 0.5 to 10% Al alloys only. For the electrical resistivity of these alloys, the deviation from the Matthiessen's rule due to alloying appears also to be small. The residual resistivity values of these alloys were derived based on the data of Smith<sup>55</sup> (Al–Mg data set 5) measured at 292 K, and the total electrical resistivity of each alloy was obtained by adding its residual resistivity to the intrinsic electric resistivity of pure Mg.<sup>51</sup> The resulting recommended values agree with the data of Staebler<sup>105</sup> (Mg + Al data sets 19–21) and of Powell *et al.*<sup>106</sup> (Mg + Al data set 28) above room temperature, and with the data of Hedgcock and Muir<sup>107</sup> (Mg + Al data sets 1–3) and Seth and Woods<sup>101</sup> (Mg + Al data sets 4–6) below room temperature.

The resulting recommended electrical resistivity values for Al, Mg, and 10 Al–Mg binary alloys are presented in Table 2 and shown in Figs. 6, 7, and 10. No values were generated for alloys containing 15% to 85% Mg. The recommended values for Al and for Mg are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Al and Mg having residual electrical resistivities as given at 1 K in Table 2. The alloys for which the recommended values are generated are not ordered and have not been quenched or cold-worked severely. The recommended values cover a full range of temperature from 1 K to the solidus temperature of the alloy where melting starts. These values are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 2. Some of the values in Table 2 are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

TABLE 2. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-MAGNESIUM ALLOY SYSTEM†  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Al : 100.00% (100.00 At.%) Mg: 0.00% ( 0.00 At.%)		Al : 99.50% (99.45 At.%) Mg: 0.50% ( 0.55 At.%)		Al : 99.00% (98.89 At.%) Mg: 1.00% ( 1.11 At.%)		Al : 97.00% (96.68 At.%) Mg: 3.00% ( 3.32 At.%)		Al : 95.00% (94.48 At.%) Mg: 5.00% ( 5.52 At.%)		Al : 90.00% (89.02 At.%) Mg: 10.00% (10.98 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.00100*	1	0.254*†	1	0.512*†	1	1.53*†	1	2.54*†	1	4.93*†
4	0.00100	4	0.254*†	4	0.512*†	4	1.53*†	4	2.54*†	4	4.93*†
7	0.00100	7	0.254*†	7	0.512*†	7	1.53*†	7	2.54*†	7	4.93*†
10	0.00103	10	0.254*†	10	0.512*†	10	1.53*†	10	2.54*†	10	4.93*†
15	0.00117	15	0.254*†	15	0.512*†	15	1.53*†	15	2.54*†	15	4.93*†
20	0.00168	20	0.255*†	20	0.513*†	20	1.53*†	20	2.54*†	20	4.93*†
25	0.00296	25	0.256*†	25	0.514*†	25	1.53*†	25	2.54*†	25	4.93*†
30	0.00564	30	0.259*†	30	0.517*†	30	1.54*†	30	2.55*†	30	4.94*†
40	0.0188	40	0.273*†	40	0.531*†	40	1.55*†	40	2.56*†	40	4.95*†
50	0.0480	50	0.302*†	50	0.561*†	50	1.58*†	50	2.59*†	50	4.99*†
60	0.0960	60	0.351*†	60	0.609*†	60	1.63*†	60	2.64*†	60	5.04*†
70	0.163	70	0.418*†	70	0.673*†	70	1.70*†	70	2.71*†	70	5.12*†
80	0.246	80	0.500*†	80	0.754*†	80	1.78*†	80	2.80*†	80	5.21*†
90	0.340	90	0.595*†	90	0.851*†	90	1.88*†	90	2.90*†	90	5.31*†
100	0.443	100	0.697*†	100	0.958*†	100	1.98*†	100	3.01*†	100	5.42*†
150	1.010	150	1.27*†	150	1.53*†	150	2.56*†	150	3.59*†	150	6.02*†
200	1.593	200	1.85*†	200	2.11*†	200	3.15*†	200	4.19*†	200	6.63*†
250	2.167	250	2.43	250	2.69	250	3.74*	250	4.78	250	7.24
273	2.429	273	2.69	273	2.96	273	4.01*	273	5.05	273	7.52
293	2.653	293	2.92	293	3.18	293	4.23	293	5.28	293	7.76
300	2.731	300	2.99	300	3.26	300	4.31	300	5.36	300	7.85
350	3.292	350	3.56*	350	3.82*	350	4.88*	350	5.93	350	8.93
400	3.854	400	4.12*	400	4.39*	400	5.45*	400	6.51	400	9.02
500	4.992	500	5.26*	500	5.53*	500	6.59*	500	7.67	500	10.2
600	6.155	600	6.42*	600	6.69*	600	7.75*	600	8.86	600	11.4
700	7.353	700	7.62*	700	7.90*	700	8.97*	700	10.1*	700	12.6*
800	8.622	800	8.90*	800	9.18*	800	10.3*	800	11.4*	800	13.7*
900	10.019	900	10.3	900	10.6	900	11.4*	849	12.1*	789	
999.52	10.510*	923	10.0	919	10.8						

† Uncertainties in the electrical resistivity values are as follows:

- 100.00 Al - 0.00 Mg:  $\pm 2\%$  below 80 K,  $\pm 1\%$  from 80 to 200 K,  $\pm 0.5\%$  above 200 K to 500 K, and  $\pm 2\%$  above 500 K.
- 99.50 Al - 0.50 Mg:  $+10\%$  up to 200 K and  $\pm 5\%$  above 200 K.
- 99.00 Al - 1.00 Mg:  $\pm 10\%$  up to 200 K and  $\pm 5\%$  above 200 K.
- 97.00 Al - 3.00 Mg:  $\pm 10\%$  up to 200 K and  $\pm 5\%$  above 200 K.
- 95.00 Al - 5.00 Mg:  $\pm 10\%$  up to 200 K and  $\pm 5\%$  above 200 K.
- 90.00 Al - 10.00 Mg:  $\pm 10\%$  up to 200 K and  $\pm 5\%$  above 200 K.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 2. RECOMMENDED ELECTRICAL RESISTIVITY OF ALUMINUM-MAGNESIUM ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Al: 10.00% (9.10 At.%) Mg: 90.00% (90.90 At.%)		Al: 5.00% (4.53 At.%) Mg: 95.00% (95.47 At.%)		Al: 3.00% (2.71 At.%) Mg: 97.00% (97.29 At.%)		Al: 1.00% (0.90 At.%) Mg: 99.00% (99.10 At.%)		Al: 0.50% (0.45 At.%) Mg: 99.50% (99.55 At.%)		Al: 0.00% (0.00 At.%) Mg: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	13.1*	1	9.02*	1	5.64*	1	1.87*	1	0.936*	1	0.0062
4	13.1	4	9.02	4	5.64	4	1.87	4	0.936	4	0.0062
7	13.1	7	9.02	7	5.64	7	1.87	7	0.937	7	0.0064
10	13.1	10	9.02	10	5.64	10	1.87	10	0.937	10	0.0069
15	13.1	15	9.02	15	5.64	15	1.87	15	0.939	15	0.0086 <sup>‡</sup>
20	13.1	20	9.03	20	5.65	20	1.88	20	0.942	20	0.0124 <sup>‡</sup>
25	13.1	25	9.04	25	5.66	25	1.89	25	0.949	25	0.0194 <sup>‡</sup>
30	13.1	30	9.05	30	5.67	30	1.90	30	0.960	30	0.0310
40	13.1	40	9.09	40	5.70	40	1.94	40	1.00	40	0.0746
50	13.2	50	9.17	50	5.78	50	2.02	50	1.08	50	0.152
60	13.3	60	9.26	60	5.90	60	2.14	60	1.19	60	0.262
70	13.4	70	9.42	70	6.04	70	2.27	70	1.34	70	0.400
80	13.6	80	9.58	80	6.20	80	2.43	80	1.50	80	0.559
90	13.8	90	9.75	90	6.37	90	2.60	90	1.67	90	0.731
100	14.0	100	9.93	100	6.55	100	2.78	100	1.85	100	0.912
150	14.9	150	10.9	150	7.50	150	3.73	150	2.80	150	1.84
200	15.8	200	11.8	200	8.42	200	4.65	200	3.72	200	2.75
250	16.7	250	12.7	250	9.30	250	5.53	250	4.59	250	3.61
273	17.1	273	13.1	273	9.69	273	5.92	273	4.98	273	4.05
293	17.4	293	13.4	293	10.0	293	6.25	293	5.31	293	4.39
300	17.6	300	13.5	300	10.1	300	6.37	300	5.43	300	4.51
350	18.4	350	14.3	350	11.0	350	7.20	350	6.26	350	5.36
400	19.2	400	15.2	400	11.8*	400	8.03	400	7.10*	400	6.18
500	20.9*	500	16.9*	500	13.5*	500	9.74	500	8.79*	500	7.82
600	22.7*	600	18.6*	600	15.2*	600	11.5	600	10.5*	600	9.44
700	24.4*	700	20.4*	700	17.0*	700	13.2	700	12.3*	700	11.0
756	25.2*	800	22.1*	800	18.7*	800	14.9*	800	14.0*	800	12.5
		839	22.7*	872	20.0*	900	16.6*	900	15.7*	900	14.2
						903	16.6*	913	15.9*	922	14.5 (s)
										923	26.1 <sup>‡</sup> (t)
										1000	26.0 <sup>‡</sup>
										1100	25.8 <sup>‡</sup>
										1200	25.6 <sup>‡</sup>

† Uncertainties in the electrical resistivity values are as follows:

10.00 Al - 90.00 Mg:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.

5.00 Al - 95.00 Mg:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.

3.00 Al - 97.00 Mg:  $\pm 5\%$  below 200 K,  $\pm 3\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.

1.00 Al - 99.00 Mg:  $\pm 5\%$  below 200 K,  $\pm 2\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.

0.50 Al - 99.50 Mg:  $\pm 5\%$  below 200 K,  $\pm 2\%$  from 200 to 600 K, and  $\pm 5\%$  above 600 K.

0.00 Al - 100.00 Mg:  $\pm 5\%$  up to 10 K,  $\pm 8\%$  between 10 and 30 K,  $\pm 5\%$  from 30 to 100 K,  $\pm 3\%$  above 100 K to 600 K,  $\pm 5\%$  above 600 K to 922 K, and  $\pm 10\%$  above 922 K.

<sup>‡</sup> Provisional value.

\* In temperature range where no experimental data are available.

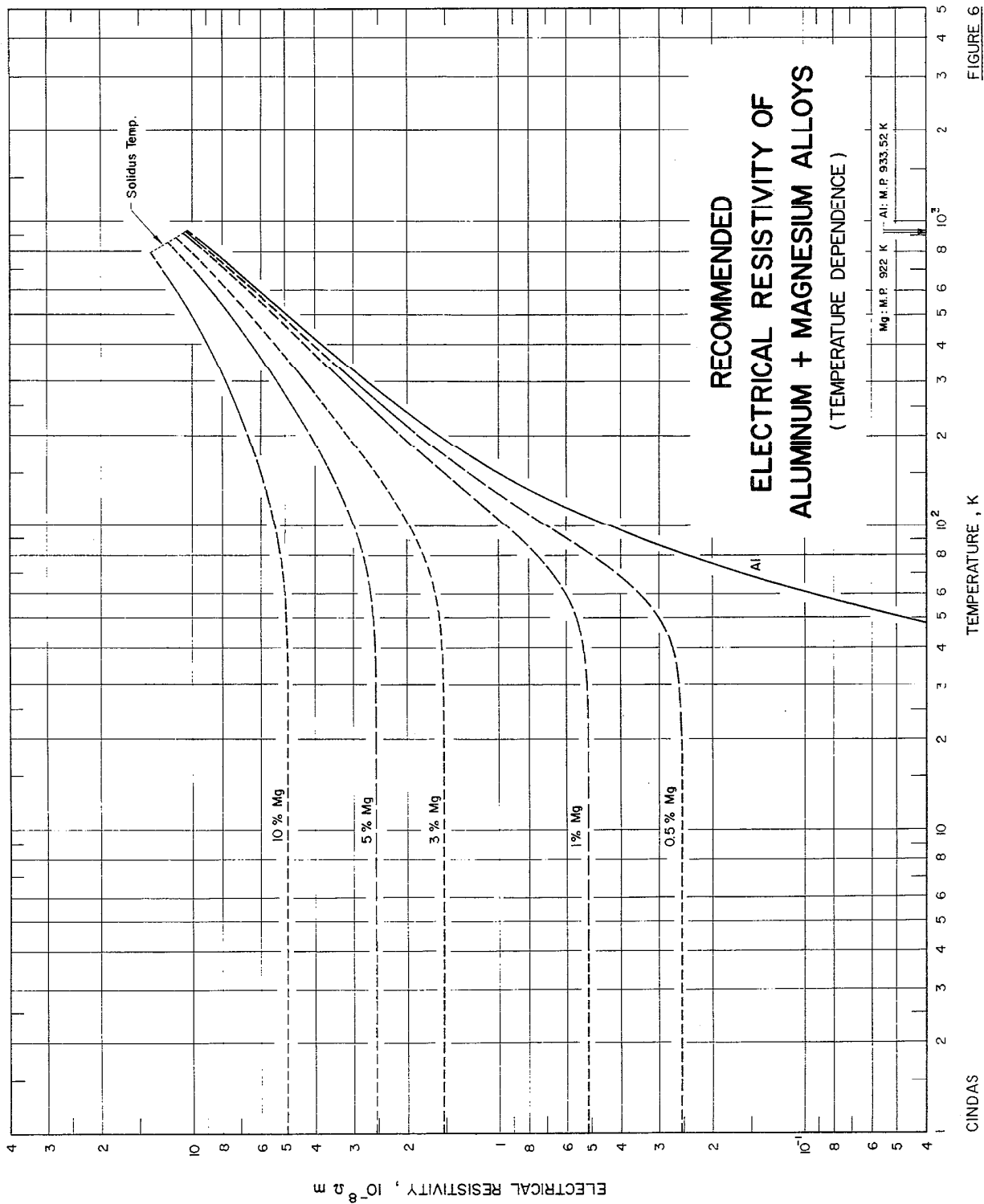


FIGURE 6

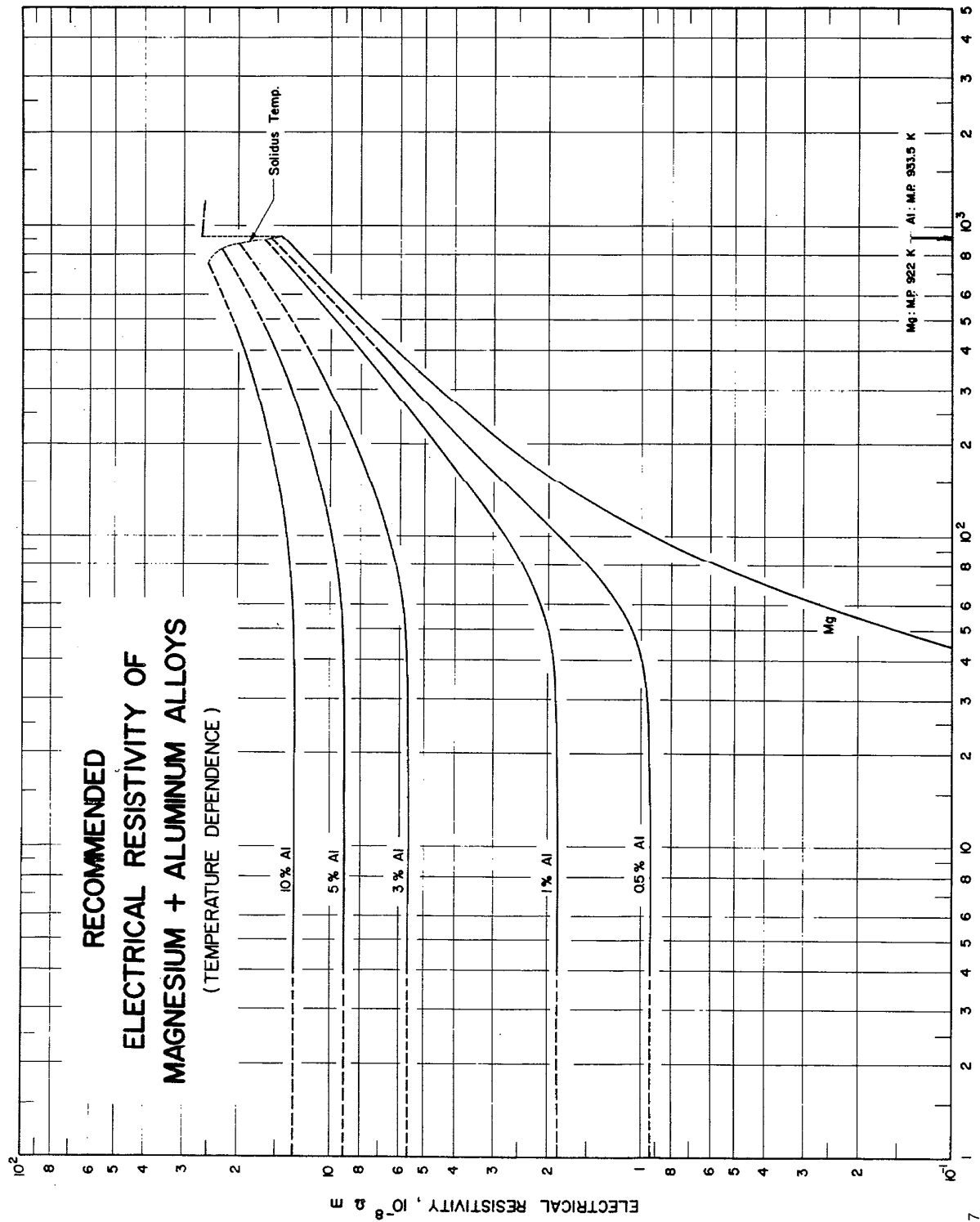


FIGURE 7

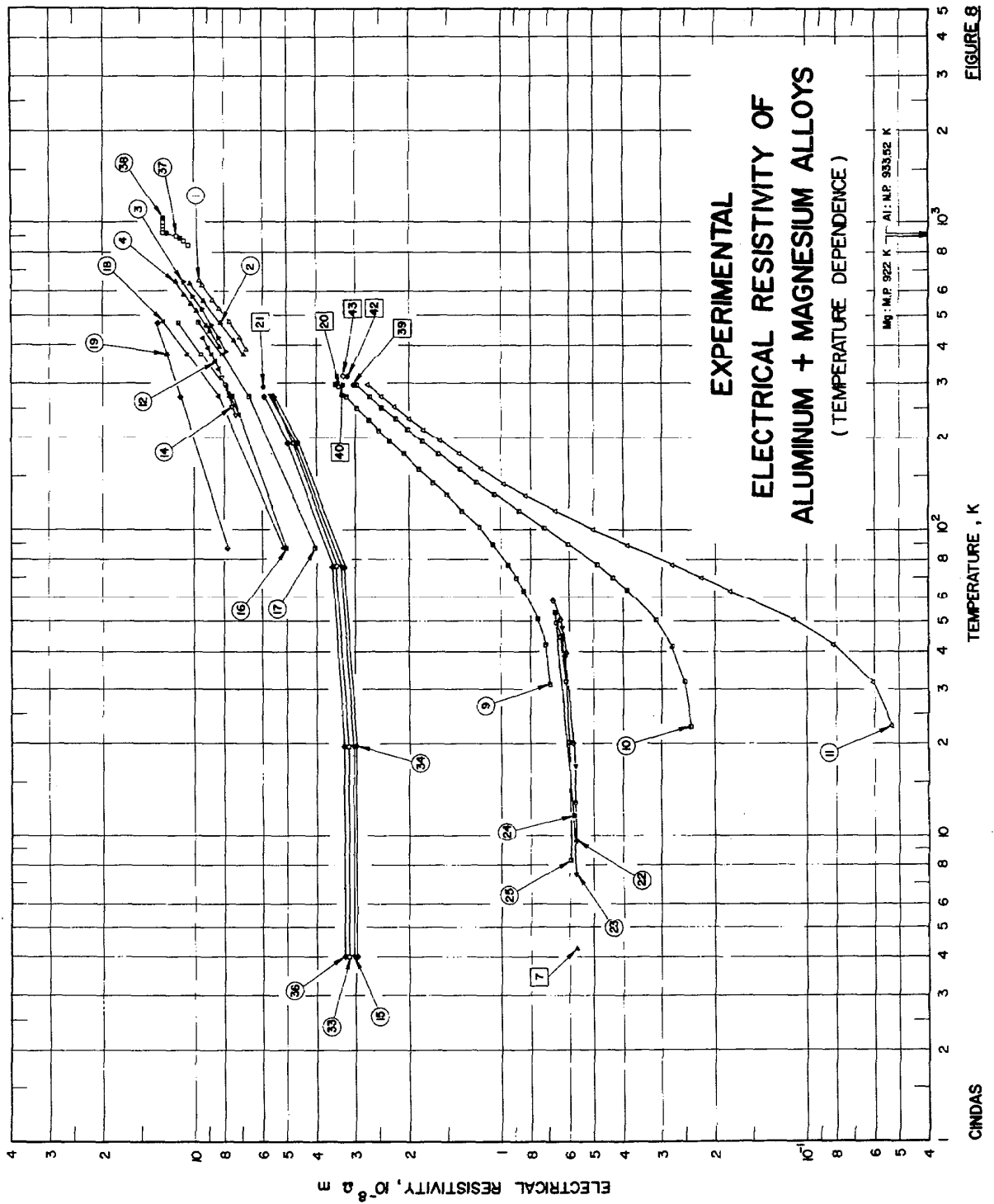


FIGURE 8

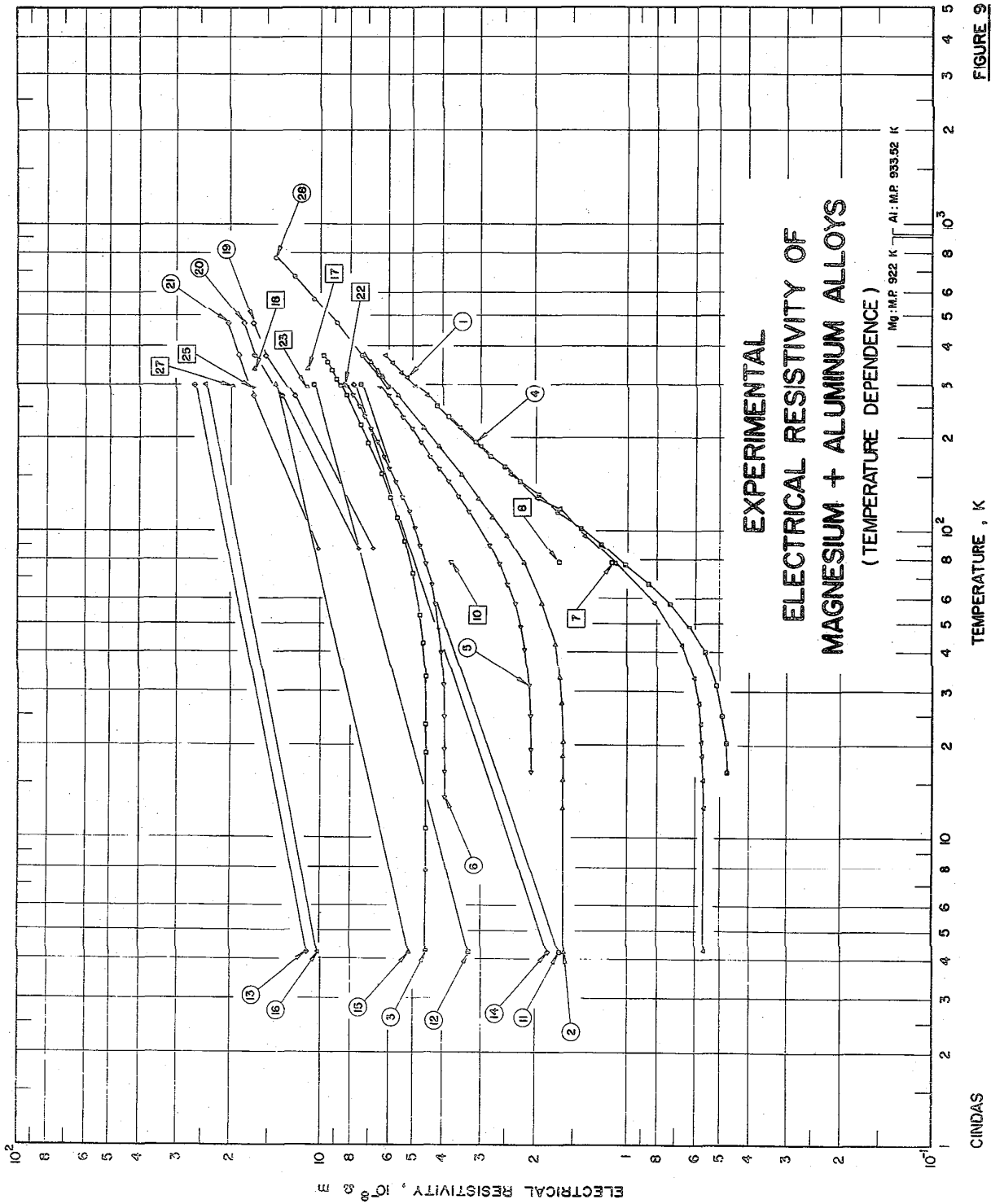


FIGURE 9

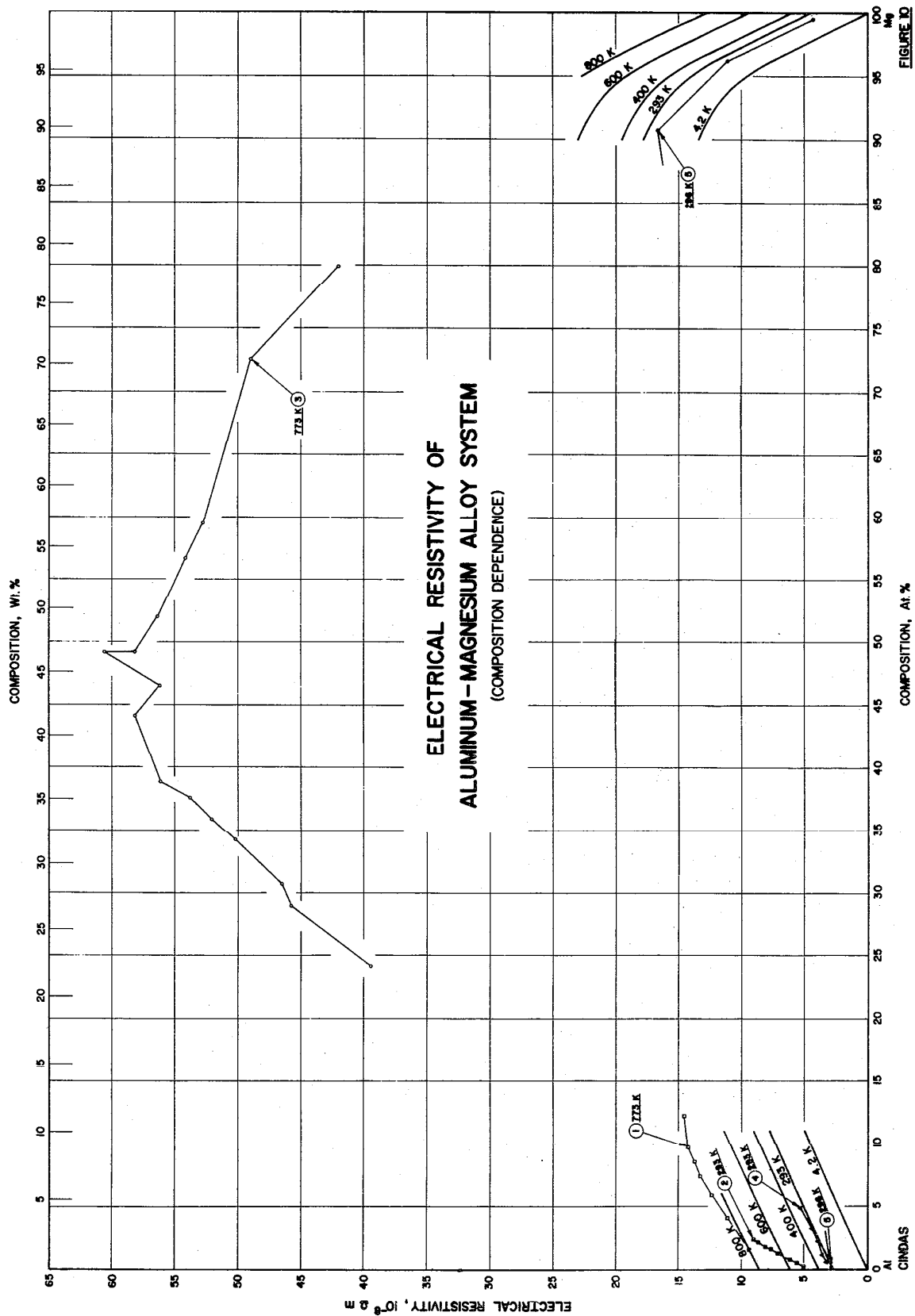


FIGURE 10



### 3.3. Copper–Gold Alloy System

The copper–gold alloy system forms a continuous series of solid solutions over the entire range of compositions. However, ordered structures are formed at temperatures below 663 K for compositions ranging from about 40% to 63% Au (17.7 to 35.5 at. % Au) and below 683 K for compositions ranging from about 63% to 94% Au (35.5 to 83.5 at. % Au). These ordered structures are due to the formation of intermetallic compounds  $\text{Cu}_3\text{Au}$  (50.85% Au),  $\text{CuAu}$  (75.63% Au), and  $\text{CuAu}_3$  (90.30% Au). For  $\text{Cu}_3\text{Au}$  and  $\text{CuAu}$ , the ordered state possesses a remarkably lower resistivity than that of the disordered state. However, for  $\text{CuAu}_3$  it has been found that the electrical resistivity increases as ordering proceeds below the transition point, but the residual resistivity is slightly lower in the highly ordered state.<sup>119–121</sup>

The experiments by Johansson and Linde<sup>122</sup> (Cu–Au data sets 1–3) showed the dependence of the electrical resistivity on the degree of ordering. Solid solutions of metals are usually of the substitutional type in which the different atoms are positioned randomly at sites of the crystal lattice. In a number of alloys with stoichiometric composition and at sufficiently low temperatures, the atoms are arranged in such a manner that each species of atom occupies only a certain type of site in the crystal lattice; an alloy in this state is called ordered. As the temperature increases, there is a transition of some of the atoms from their sites to foreign sites; such an alloy is called partially ordered. The concentration of atoms of a given type on foreign sites increases with temperature and at some temperature the concentration of atoms on sites of different types becomes identical; such an alloy is called disordered. The temperature at which such a transition occurs is called the order–disorder phase transition temperature or the critical temperature. The order–disorder phase transition occurs not only in alloys with stoichiometric composition and the critical temperature is a well defined function of composition. In this work experimental data on intermetallic compounds and ordered alloys are excluded, though data on partially ordered alloys are compiled and presented in the figures and tables. However, these data are not evaluated or analyzed since recommended values are generated for disordered alloys only.

There are 243 sets of experimental data available for this alloy system. These experimental data sets are listed in Tables S-13, S-15, and S-17, tabulated in Tables S-14, S-16, and S-18, and shown partially in Figs. 13, 14, and 15. Unfortunately, most of the available data are for specimens in partially ordered state. For the disordered state, more impor-

tant experimental data and information are from the following. Johansson and Linde<sup>122</sup> (Cu–Au data sets 1–3) reported a complete curve of resistivity versus composition at 293 K. Borelius, Johansson, and Linde<sup>123</sup> (Cu + Au data sets 6–8 and Au + Cu data sets 1–22) measured a series of alloys containing 20.2, 22.6, 25.0, 27.7, 30.1, 45.0, 50.0, and 55.0 at. % Au during both heating and cooling of the specimens. Passaglia and Love<sup>124</sup> (Au + Cu data sets 23–26) measured the resistivity of Au + Cu alloys from liquid helium temperature to about 90 K for both quenched and annealed specimens. Tainsh and White<sup>125</sup> (Cu + Au data sets 9, 10) reported the resistivity of alloys containing 20.1 and 38.0 wt. % Au at 4.2, 90, and 293 K. Linde<sup>126</sup> (Cu + Au data sets 1–5) reported the resistivity at 291.2 K of alloys containing 1.53, 3.00, 5.92, 7.05, and 8.75 wt. % Au.

The smoothing and synthesizing of the electrical resistivity data was based mainly on the results reported in the above five research papers. Since Cu, Ag, and Au are in the same column of the periodic table, the properties of Au + Cu alloys and Au + Ag alloys may be similar in some respects. Accordingly, in the composition range where ordering occurs, some of the resistivity versus temperature curves have been obtained by taking a point on the resistivity versus composition isotherm and drawing a curve parallel to the electrical resistivity curve of an Au + Ag alloy of the same atomic concentration; values obtained in this way for the electrical resistivity are considered only provisional. Using this method, the values obtained for the gold-rich alloys would appear to be more reliable than those for the copper-rich alloys.

The resulting recommended electrical resistivity values for Cu, Au, and for 25 Cu–Au binary alloys are presented in Table 3 and shown in Figs. 11, 12, and 15. The recommended values for Cu and for Au are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Cu and Au having residual electrical resistivities as given at 1 K in Table 3. The alloys for which the recommended values are generated are not ordered and have not been quenched or cold-worked severely. The recommended values cover a full range of temperature from 1 K to the solidus temperature of the alloy where melting starts. These values are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 3. Many of the values in Table 3 are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

TABLE 3. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-GOLD ALLOY SYSTEM†  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 100.00% (100.00 At.%) Au: 0.00% ( 0.00 At.%)		Cu: 99.50% (99.84 At.%) Au: 0.50% ( 0.16 At.%)		Cu: 99.00% (99.68 At.%) Au: 1.00% ( 0.32 At.%)		Cu: 97.00% (99.01 At.%) Au: 3.00% ( 0.99 At.%)		Cu: 95.00% (98.33 At.%) Au: 5.00% ( 1.67 At.%)		Cu: 90.00% (96.54 At.%) Au: 10.00% ( 3.46 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.00200	1	0.100*†	1	0.200*†	1	0.530*†	1	0.870*†	1	1.72*†
4	0.00200	4	0.100†	4	0.200†	4	0.530*†	4	0.870†	4	1.72*†
7	0.00200	7	0.100*†	7	0.200*†	7	0.530*†	7	0.870*†	7	1.72*†
10	0.00202	10	0.100*†	10	0.200*†	10	0.530*†	10	0.870*†	10	1.72*†
15	0.00218	15	0.100*†	15	0.200*†	15	0.530*†	15	0.870*†	15	1.72*†
20	0.00280	20	0.100*†	20	0.200*†	20	0.530*†	20	0.870*†	20	1.72*†
25	0.00450	25	0.102*†	25	0.200*†	25	0.530*†	25	0.870*†	25	1.72*†
30	0.00830	30	0.108*†	30	0.201*†	30	0.531*†	30	0.871*†	30	1.73*†
40	0.0240	40	0.120*†	40	0.210*†	40	0.540*†	40	0.879*†	40	1.75*†
50	0.0520	50	0.141*†	50	0.229*†	50	0.559*†	50	0.901*†	50	1.78*†
60	0.0974	60	0.180*†	60	0.261*†	60	0.591*†	60	0.941*†	60	1.84*†
70	0.154	70	0.237*†	70	0.311*†	70	0.641*†	70	0.997*†	70	1.90*†
80	0.216	80	0.302*†	80	0.378*†	80	0.709*†	80	1.06*†	80	1.96*†
90	0.282	90	0.370*†	90	0.450*†	90	0.780*†	90	1.14*†	90	2.04*†
100	0.349	100	0.439*†	100	0.520*†	100	0.850*†	100	1.21*†	100	2.11*†
150	0.701	150	0.790*	150	0.871*	150	1.20*	150	1.56*	150	2.46*
200	1.048	200	1.14*	200	1.22*	200	1.56*	200	1.91*	200	2.80*
250	1.388	250	1.49*	250	1.57*	250	1.91*	250	2.25*	250	3.14*
273	1.644	273	1.64	273	1.73	273	2.06	273	2.41	273	3.20
293	1.678	293	1.77*	293	1.86*	293	2.20*	293	2.54*	293	3.42*
300	1.725	300	1.82*	300	1.91*	300	2.24*	300	2.59*	300	3.46*
350	2.061	350	2.14*	350	2.24*	350	2.58*	350	2.92*	350	3.79*
400	2.398	400	2.48*	400	2.58*	400	2.91*	400	3.26*	400	4.12*
500	3.079	500	3.17*†	500	3.27*†	500	3.60*†	500	3.95*†	500	4.81*†
600	3.771	600	3.88*†	600	3.98*†	600	4.31*†	600	4.66*†	600	5.52*†
700	4.481	700	4.58*†	700	4.69*†	700	5.01*†	700	5.37*†	700	6.22*†
800	5.213	800	5.31*†	800	5.42*†	800	5.74*†	800	6.10*†	800	6.94*†
900	5.973	900	6.06*†	900	6.16*†	900	6.50*†	900	6.86*†	900	7.69*†
1000	6.766	1000	6.86*†	1000	6.96*†	1000	7.29*†	1000	7.64*†	1000	8.48*†
1100	7.596	1100	7.69*†	1100	7.80*†	1100	8.11*†	1100	8.46*†	1100	9.30*†
1200	8.470	1200	8.55*†	1200	8.66*†	1200	8.98*†	1200	9.32*†	1200	10.16*†
1300	9.395	1300	9.41*†	1300	9.52*†	1300	9.85*†	1300	10.18*†	1300	11.02*†
1357.6	9.946 (s)	1355	9.88*†	1353	9.96*†	1346	10.25*†	1339	10.52*†	1320	11.19*†
1358	21.01 (t)										
1700	24.41										

† Uncertainties in the electrical resistivity values are as follows:

- 100.00 Cu - 0.00 Au:  $\pm 3\%$  up to 100 K,  $\pm 1\%$  above 100 K to 250 K,  $\pm 0.5\%$  above 250 K to 350 K,  $\pm 1\%$  above 350 K to 500 K,  $\pm 4\%$  above 500 K to 1357.6 K, and  $\pm 5\%$  above 1357.6 K.
- 99.50 Cu - 0.50 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 99.00 Cu - 1.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 97.00 Cu - 3.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 95.00 Cu - 5.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 90.00 Cu - 10.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 3. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-GOLD ALLOY SYSTEM<sup>†</sup> (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-9} \Omega \text{ m}$ ]

Cu: 85.00% (94.61 At.%) Au: 15.00% ( 5.39 At.%)		Cu: 80.00% (92.54 At.%) Au: 20.00% ( 7.46 At.%)		Cu: 75.00% (90.29 At.%) Au: 25.00% ( 9.71 At.%)		Cu: 70.00% (87.85 At.%) Au: 30.00% (12.15 At.%)		Cu: 65.00% (85.20 At.%) Au: 35.00% (14.80 At.%)		Cu: 60.00% (82.30 At.%) Au: 40.00% (17.70 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	2.58*†	1	3.52*†	1	4.45*†	1	5.47*†	1	6.52*†	1	7.52*†
4	2.58*†	4	3.52*†	4	4.45*†	4	5.47*†	4	6.52*†	4	7.52*†
7	2.58*†	7	3.52*†	7	4.45*†	7	5.47*†	7	6.52*†	7	7.52*†
10	2.58*†	10	3.52*†	10	4.45*†	10	5.47*†	10	6.52*†	10	7.52*†
15	2.58*†	15	3.52*†	15	4.45*†	15	5.48*†	15	6.53*†	15	7.53*†
20	2.59*†	20	3.52*†	20	4.45*†	20	5.49*†	20	6.54*†	20	7.54*†
25	2.60*†	25	3.53*†	25	4.46*†	25	5.50*†	25	6.55*†	25	7.56*†
30	2.61*†	30	3.54*†	30	4.47*†	30	5.51*†	30	6.57*†	30	7.59*†
40	2.63*†	40	3.57*†	40	4.49*†	40	5.54*†	40	6.81*†	40	7.66*†
50	2.68*†	50	3.61*†	50	4.52*†	50	5.57*†	50	6.67*†	50	7.72*†
60	2.73*†	60	3.67*†	60	4.58*†	60	5.63*†	60	6.74*†	60	7.78*†
70	2.80*†	70	3.74*†	70	4.64*†	70	5.70*†	70	6.80*†	70	7.85*†
80	2.87*†	80	3.80*†	80	4.72*†	80	6.77*†	80	6.97*†	80	7.92*†
90	2.94*†	90	3.88*†	90	4.79*†	90	6.84*†	90	6.93*†	90	7.98*†
100	3.01*†	100	3.95*†	100	4.86*†	100	6.91*†	100	7.00*†	100	8.04*†
150	3.36*	150	4.30	150	5.22	150	6.26	150	7.33*	150	8.37
200	3.70*	200	4.65	200	5.59	200	6.62	200	7.66*	200	8.70
250	4.04*	250	4.99	250	5.93	250	6.96	250	8.00*	250	9.03
273	4.20	273	5.15	273	6.09	273	7.12	273	8.16	273	9.18
293	4.33	293	5.28	293	6.23	293	7.25	293	8.29	293	9.31
300	4.38*	300	5.32	300	6.28	300	7.30	300	8.34*	300	9.36
350	4.71*	350	5.65	350	6.63	350	7.64	350	8.69*	350	9.70
400	5.05*	400	5.99	400	6.98	400	7.99	400	9.04*	400	10.05
500	5.72*†	500	6.68*†	500	7.66*†	500	8.67*†	500	9.72*†	500	10.75*†
600	6.42*†	600	7.37*†	600	8.37*†	600	9.37*†	600	10.43*†	600	11.47*†
700	7.13*†	700	8.09*†	700	9.08*†	700	10.08*†	700	11.14*†	700	12.19*†
800	7.87*†	800	8.82*†	800	9.81*†	800	10.81*†	800	11.87*†	800	12.93*†
900	8.62*†	900	9.55*†	900	10.56*†	900	11.55*†	900	12.61*†	900	13.69*†
1000	9.39*†	1000	10.30*†	1000	11.32*†	1000	12.30*†	1000	13.37*†	1000	14.49*†
1100	10.18*†	1100	11.07*†	1100	12.09*†	1100	13.08*†	1100	14.15*†	1100	15.31*†
1200	11.00*†	1200	11.86*†	1200	12.88*†	1200	13.87*†	1200	14.96*†	1200	16.15*†
1303	11.84*†	1289	12.56*†	1277	13.49*†	1265	14.38*†	1255	15.41*†	1245	16.53*†

<sup>†</sup> Uncertainties in the electrical resistivity values are as follows:

85.00 Cu - 15.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 80.00 Cu - 20.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 75.00 Cu - 25.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 70.00 Cu - 30.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 65.00 Cu - 35.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 60.00 Cu - 40.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

\* Provisional value.

\* In temperature range where no experimental data are available.

TABLE 3. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-GOLD ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 55.00% (79.12 At.%) Au: 45.00% (20.88 At.%)		Cu: 50.00% (75.61 At.%) Au: 50.00% (24.39 At.%)		Cu: 45.00% (71.72 At.%) Au: 55.00% (28.28 At.%)		Cu: 40.00% (67.39 At.%) Au: 60.00% (32.61 At.%)		Cu: 35.00% (62.54 At.%) Au: 65.00% (37.46 At.%)		Cu: 30.00% (57.05 At.%) Au: 70.00% (42.95 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	8.48 <sup>‡</sup>	1	9.34 <sup>‡</sup>	1	10.14 <sup>‡</sup>	1	10.88 <sup>‡</sup>	1	11.43 <sup>‡*</sup>	1	11.82 <sup>‡*</sup>
4	8.48 <sup>‡</sup>	4	9.34 <sup>‡</sup>	4	10.14 <sup>‡</sup>	4	10.88 <sup>‡</sup>	4	11.43 <sup>‡</sup>	4	11.82 <sup>‡</sup>
7	8.48 <sup>‡</sup>	7	9.34 <sup>‡</sup>	7	10.14 <sup>‡</sup>	7	10.88 <sup>‡</sup>	7	11.43 <sup>‡</sup>	7	11.82 <sup>‡*</sup>
10	8.48 <sup>‡</sup>	10	9.34 <sup>‡</sup>	10	10.14 <sup>‡</sup>	10	10.88 <sup>‡</sup>	10	11.43 <sup>‡</sup>	10	11.82 <sup>‡*</sup>
15	8.48 <sup>‡</sup>	15	9.35 <sup>‡*</sup>	15	10.15 <sup>‡</sup>	15	10.88 <sup>‡</sup>	15	11.43 <sup>‡</sup>	15	11.83 <sup>‡*</sup>
20	8.49 <sup>‡</sup>	20	9.37 <sup>‡</sup>	20	10.17 <sup>‡</sup>	20	10.89 <sup>‡</sup>	20	11.44 <sup>‡</sup>	20	11.84 <sup>‡</sup>
25	8.51 <sup>‡</sup>	25	9.39 <sup>‡</sup>	25	10.19 <sup>‡</sup>	25	10.90 <sup>‡</sup>	25	11.46 <sup>‡</sup>	25	11.86 <sup>‡*</sup>
30	8.54 <sup>‡</sup>	30	9.42 <sup>‡</sup>	30	10.22 <sup>‡</sup>	30	10.93 <sup>‡</sup>	30	11.50 <sup>‡</sup>	30	11.90 <sup>‡*</sup>
40	8.61 <sup>‡</sup>	40	9.48 <sup>‡</sup>	40	10.28 <sup>‡</sup>	40	11.00 <sup>‡</sup>	40	11.57 <sup>‡</sup>	40	11.97 <sup>‡*</sup>
50	8.67 <sup>‡</sup>	50	9.55 <sup>‡</sup>	50	10.36 <sup>‡</sup>	50	11.08 <sup>‡</sup>	50	11.65 <sup>‡</sup>	50	12.04 <sup>‡*</sup>
60	8.74 <sup>‡</sup>	60	9.63 <sup>‡</sup>	60	10.42 <sup>‡*</sup>	60	11.15 <sup>‡*</sup>	60	11.73 <sup>‡*</sup>	60	12.12 <sup>‡*</sup>
70	8.80 <sup>‡</sup>	70	9.68 <sup>‡</sup>	70	10.49 <sup>‡</sup>	70	11.22 <sup>‡</sup>	70	11.80 <sup>‡</sup>	70	12.20 <sup>‡</sup>
80	8.87 <sup>‡</sup>	80	9.74 <sup>‡</sup>	80	10.56 <sup>‡</sup>	80	11.30 <sup>‡</sup>	80	11.87 <sup>‡</sup>	80	12.27 <sup>‡*</sup>
90	8.94 <sup>‡</sup>	90	9.81 <sup>‡</sup>	90	10.63 <sup>‡</sup>	90	11.37 <sup>‡</sup>	90	11.95 <sup>‡</sup>	90	12.35 <sup>‡*</sup>
100	9.00 <sup>‡</sup>	100	9.88 <sup>‡</sup>	100	10.70 <sup>‡</sup>	100	11.44 <sup>‡</sup>	100	12.02 <sup>‡</sup>	100	12.43 <sup>‡*</sup>
150	9.33	150	10.22	150	11.05 <sup>*</sup>	150	11.80 <sup>*</sup>	150	12.40 <sup>*</sup>	150	12.81 <sup>*</sup>
200	9.66	200	10.57	200	11.41 <sup>*</sup>	200	12.18 <sup>*</sup>	200	12.78 <sup>*</sup>	200	13.20 <sup>*</sup>
250	10.00	250	10.91	250	11.76 <sup>*</sup>	250	12.54 <sup>*</sup>	250	13.16 <sup>*</sup>	250	13.59 <sup>*</sup>
273	10.16	273	11.07	273	11.92	273	12.70	273	13.33	273	13.77
293	10.30	293	11.20	293	12.06	293	12.85	293	13.48	293	13.93
300	10.35	300	11.25	300	12.11 <sup>*</sup>	300	12.90 <sup>*</sup>	300	13.54 <sup>*</sup>	300	13.99 <sup>*</sup>
350	10.68	350	11.60	350	12.46 <sup>*</sup>	350	13.27 <sup>*</sup>	350	13.92 <sup>*</sup>	350	14.38 <sup>*</sup>
400	11.03	400	11.94	400	12.81	400	13.65	400	14.31 <sup>*</sup>	400	14.78 <sup>*</sup>
500	11.72 <sup>‡</sup>	500	12.65 <sup>‡</sup>	500	13.54 <sup>‡</sup>	500	14.40 <sup>‡</sup>	500	15.09 <sup>‡*</sup>	500	15.58 <sup>‡*</sup>
600	12.43 <sup>‡</sup>	600	13.38 <sup>‡</sup>	600	14.30 <sup>‡</sup>	600	15.17 <sup>‡</sup>	600	15.89 <sup>‡*</sup>	600	16.40 <sup>‡*</sup>
700	13.16 <sup>‡</sup>	700	14.13 <sup>‡</sup>	700	15.07 <sup>‡</sup>	700	15.95 <sup>‡</sup>	700	16.69 <sup>‡*</sup>	700	17.24 <sup>‡*</sup>
800	13.92 <sup>‡</sup>	800	14.91 <sup>‡</sup>	800	15.87 <sup>‡</sup>	800	16.76 <sup>‡</sup>	800	17.53 <sup>‡*</sup>	800	18.11 <sup>‡*</sup>
900	14.71 <sup>‡</sup>	900	15.71 <sup>‡</sup>	900	16.71 <sup>‡</sup>	900	17.61 <sup>‡</sup>	900	18.42 <sup>‡*</sup>	900	19.02 <sup>‡*</sup>
1000	15.52 <sup>‡*</sup>	1000	16.53 <sup>‡*</sup>	1000	17.69 <sup>‡*</sup>	1000	18.62 <sup>‡*</sup>	1000	19.36 <sup>‡*</sup>	1000	20.00 <sup>‡*</sup>
1100	16.35 <sup>‡*</sup>	1100	17.37 <sup>‡*</sup>	1100	18.53 <sup>‡*</sup>	1100	19.47 <sup>‡*</sup>	1100	20.33 <sup>‡*</sup>	1100	20.96 <sup>‡*</sup>
1200	17.19 <sup>‡*</sup>	1200	18.23 <sup>‡*</sup>	1200	19.47 <sup>‡*</sup>	1200	20.45 <sup>‡*</sup>	1196	21.30 <sup>‡*</sup>	1188	21.85 <sup>‡*</sup>
1236	17.49 <sup>‡*</sup>	1226	18.45 <sup>‡*</sup>	1216	19.62 <sup>‡*</sup>	1206	20.51 <sup>‡*</sup>				

† Uncertainties in the electrical resistivity values are as follows:

55.00 Cu - 45.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 50.00 Cu - 50.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 45.00 Cu - 55.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 40.00 Cu - 60.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 35.00 Cu - 65.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 30.00 Cu - 70.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.

TABLE 3. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-GOLD ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \cdot m$ ]

Cu: 25.00% (50.82 At.%) Au: 75.00% (49.18 At.%)		Cu: 20.00% (43.66 At.%) Au: 80.00% (56.34 At.%)		Cu: 15.00% (35.36 At.%) Au: 85.00% (64.64 At.%)		Cu: 10.00% (25.62 At.%) Au: 90.00% (74.38 At.%)		Cu: 5.00% (14.05 At.%) Au: 95.00% (85.95 At.%)		Cu: 3.00% (8.75 At.%) Au: 97.00% (91.25 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	11.95†	1	11.72**	1	10.73**	1	8.72**	1	5.27**	1	3.44**
4	11.95†	4	11.72**	4	10.75**	4	8.72**	4	5.27**	4	3.44†
7	11.95†	7	11.72**	7	10.75**	7	8.72**	7	5.27**	7	3.44**
10	11.96†	10	11.72**	10	10.75**	10	8.72**	10	5.28**	10	3.44**
15	11.97†	15	11.73**	15	10.76**	15	8.72**	15	5.29**	15	3.45**
20	11.98†	20	11.75**	20	10.77**	20	8.73**	20	5.31**	20	3.46†
25	12.00†	25	11.77**	25	10.79**	25	8.75**	25	5.33**	25	3.49**
30	12.04†	30	11.80**	30	10.83**	30	8.78**	30	5.36**	30	3.52**
40	12.12†	40	11.87**	40	10.91**	40	8.86**	40	5.44**	40	3.60**
50	12.20†	50	11.95**	50	10.99**	50	8.94**	50	5.52**	50	3.68**
60	12.27†	60	12.03**	60	11.07**	60	9.02**	60	5.60**	60	3.76**
70	12.35†	70	12.10**	70	11.15**	70	9.10**	70	5.68**	70	3.84**
80	12.43†	80	12.18**	80	11.22**	80	9.17**	80	5.75**	80	3.92**
90	12.51†	90	12.26**	90	11.30**	90	9.25**	90	5.83**	90	4.00**
100	12.59†	100	12.35**	100	11.38**	100	9.33**	100	5.91**	100	4.08**
150	12.98	150	12.74*	150	11.78*	150	9.73	150	6.30*	150	4.48*
200	13.36	200	13.12*	200	12.18*	200	10.12	200	6.68*	200	4.88*
250	13.75	250	13.52*	250	12.57*	250	10.52	250	7.07*	250	5.28*
273	13.93	273	13.70*	273	12.75	273	10.70	273	7.25	273	5.47
293	14.09	293	13.86*	293	12.91	293	10.86	293	7.41*	293	5.64
300	14.14	300	13.92*	300	12.96*	300	10.91	300	7.46*	300	5.69*
350	14.54	350	14.32*	350	13.36*	350	11.31	350	7.87	350	6.10
400	14.94	400	14.73*	400	13.77	400	11.72	400	8.28	400	6.49
500	15.73†	500	15.57**	500	14.60†	500	12.58**	500	9.14†	500	7.32†
600	16.63†	600	16.41**	600	15.44†	600	13.47**	600	10.02†	600	8.19†
700	17.49†	700	17.26**	700	16.29†	700	14.38**	700	10.92†	700	9.10†
800	18.38†	800	18.14**	800	17.16†	800	15.32**	800	11.86†	800	10.05†
900	19.31†	900	19.09**	900	18.15†	900	16.30**	900	12.84†	900	11.05†
1000	20.32†	1000	20.12**	1000	19.23†	1000	17.36**	1000	13.90**	1000	12.13**
1100	21.34†	1100	21.14**	1100	20.30†	1100	18.47**	1100	15.01**	1100	13.30**
1184	22.29†	1182	22.09**	1185	21.30†	1199	19.61**	1200	16.14**	1200	14.56**
								1241	16.60**	1270	15.44**

† Uncertainties in the electrical resistivity values are as follows:

- 25.00 Cu - 75.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 20.00 Cu - 80.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 15.00 Cu - 85.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 10.00 Cu - 90.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 5.00 Cu - 95.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.
- 3.00 Cu - 97.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.

TABLE 3. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-GOLD ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 1.00% ( 3.04 At.%) Au: 99.00% (96.96 At.%)		Cu: 0.50% ( 1.53 At.%) Au: 99.50% (98.47 At.%)		Cu: 0.00% ( 0.00 At.%) Au: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	1.40‡	1	0.770*‡	1	0.0220
4	1.40‡	4	0.770‡	4	0.0220
7	1.40‡	7	0.770*‡	7	0.0221
10	1.40‡	10	0.770*‡	10	0.0226
15	1.40‡	15	0.770*‡	15	0.0258
20	1.41‡	20	0.780‡	20	0.0346‡
25	1.43‡	25	0.801*‡	25	0.0503‡
30	1.45‡	30	0.828*‡	30	0.0727‡
40	1.51‡	40	0.892*‡	40	0.141‡
50	1.60‡	50	0.966*‡	50	0.222
60	1.68‡	60	1.04*‡	60	0.309
70	1.76‡	70	1.13‡	70	0.396
80	1.84‡	80	1.21*‡	80	0.482
90	1.92‡	90	1.29*‡	90	0.567
100	2.00‡	100	1.37*‡	100	0.652
150	2.41	150	1.78*	150	1.063
200	2.81	200	2.18*	200	1.464
250	3.22	250	2.59*	250	1.865
273	3.40	273	2.78	273	2.052
293	3.57	293	2.94*	293	2.214
300	3.62	300	3.00*	300	2.271
350	4.03	350	3.41*	350	2.683
400	4.45	400	3.82*	400	3.102
500	5.30*‡	500	4.68*‡	500	3.962
600	6.18*‡	600	5.62*‡	600	4.853
700	7.10*‡	700	6.51*‡	700	5.780
800	8.07*‡	800	7.45*‡	800	6.755
900	9.10*‡	900	8.47*‡	900	7.787
1000	10.23*‡	1000	9.57*‡	1000	8.884
1100	11.46*‡	1100	10.77*‡	1100	10.057
1200	12.77*‡	1200	12.10*‡	1200	11.312
1296	14.07*‡	1300	13.47*‡	1300	12.632
		1323	13.73*‡	1337.58	13.146(s)
				1338	31.06(t)
				1700	36.26

† Uncertainties in the electrical resistivity values are as follows:

1.00 Cu - 99.00 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

0.50 Cu - 99.50 Au:  $\pm 7\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

0.00 Cu - 100.00 Au:  $\pm 1\%$  up to 10 K,  $\pm 2.5\%$  above 10 K to 15 K,  $\pm 6\%$  above 15 K to 40 K,  $\pm 3\%$  above 40 k to 80 K,  $\pm 1\%$  above 80 K to 500 K, and  $\pm 2.5\%$  above 500 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.

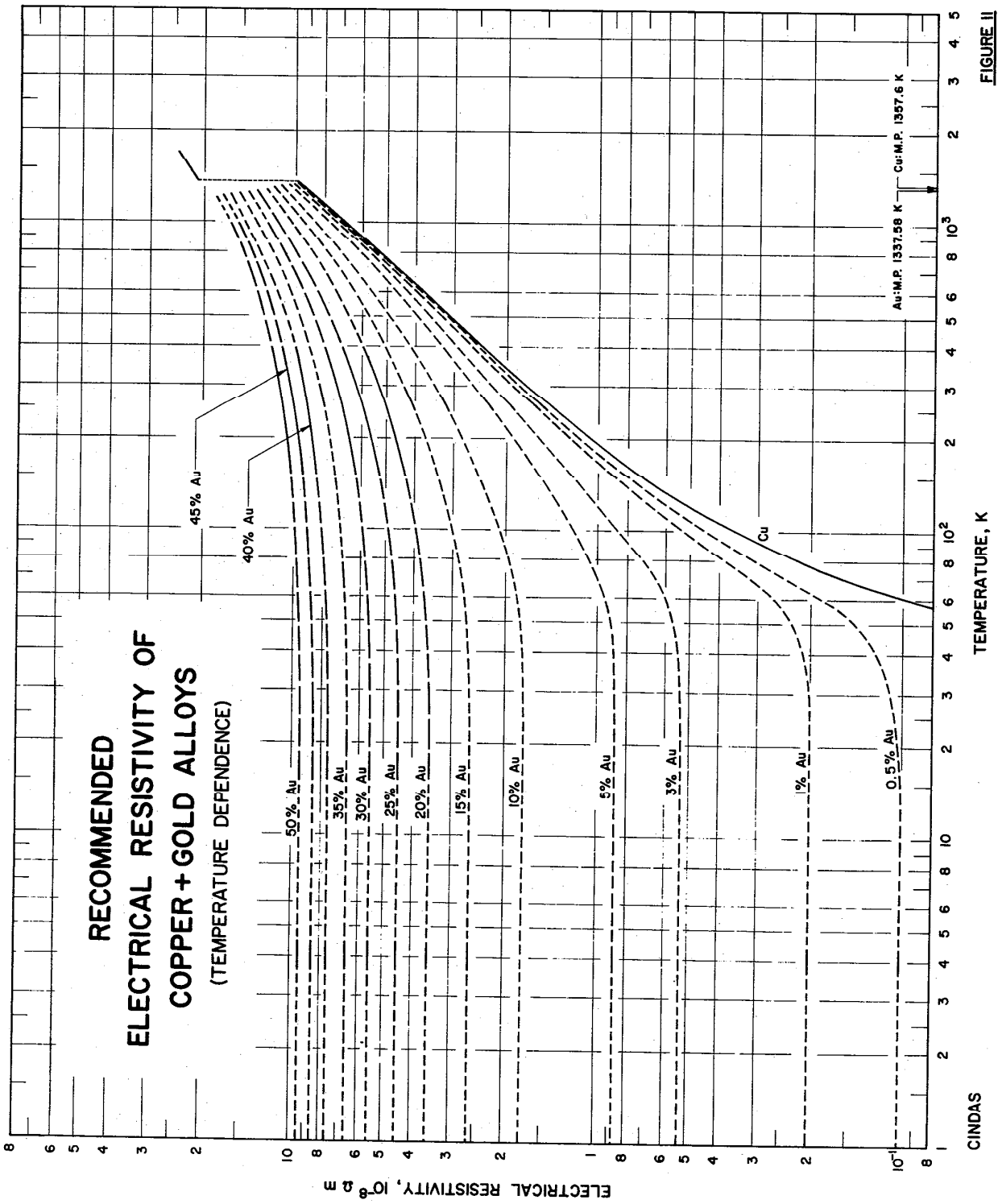


FIGURE II

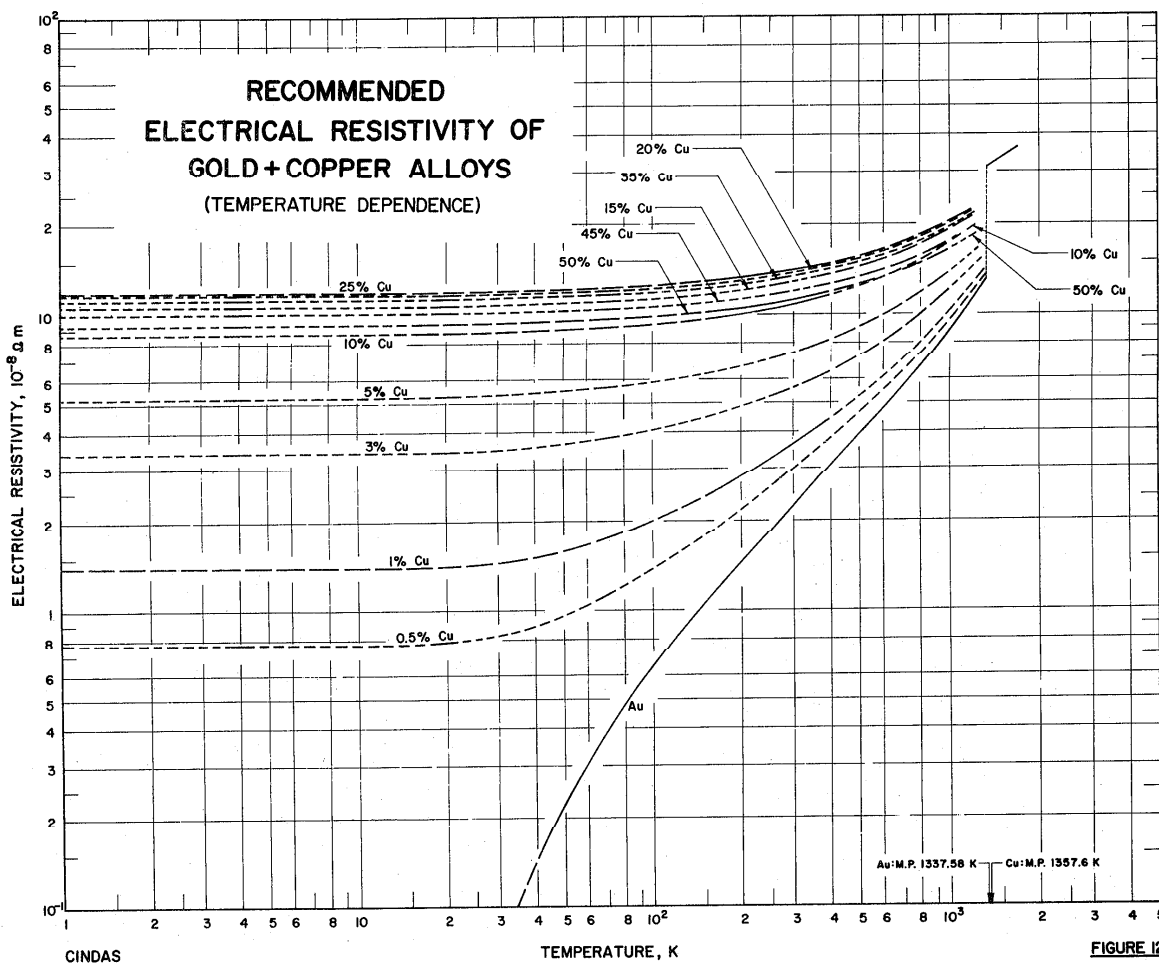




FIGURE 12

TEMPERATURE, K

CINDAS

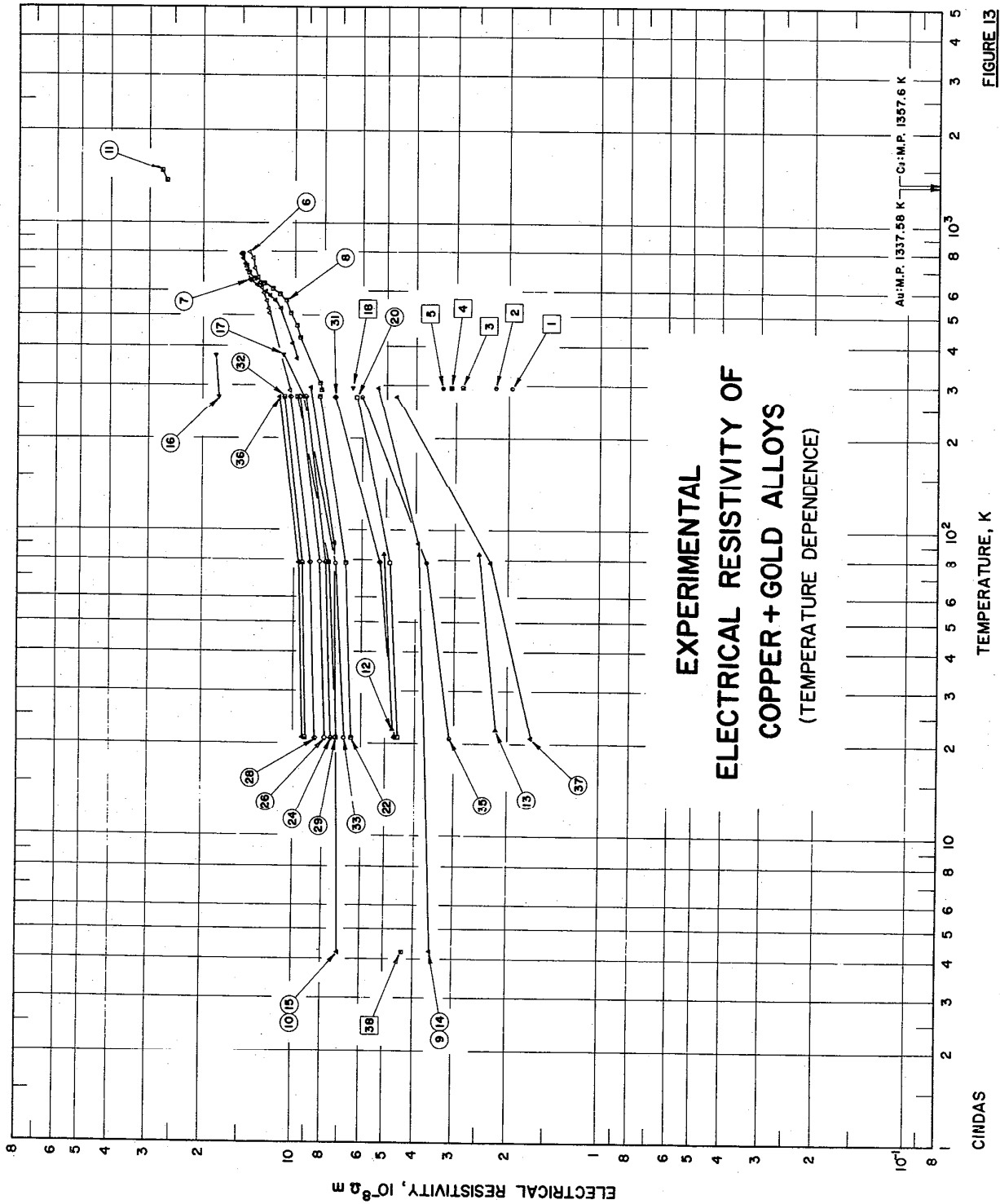


FIGURE 13

TEMPERATURE, K

CINDAS

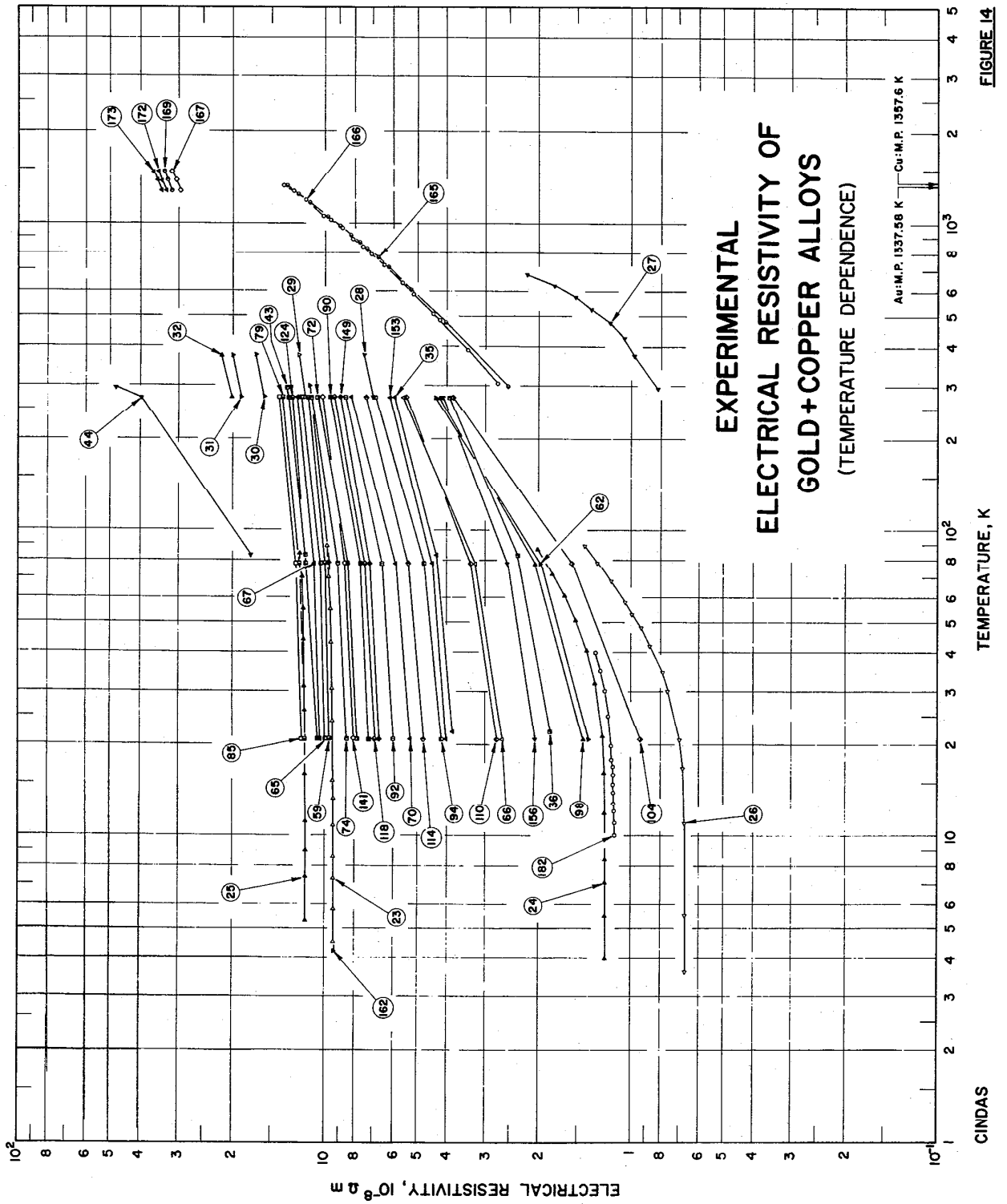


FIGURE 14

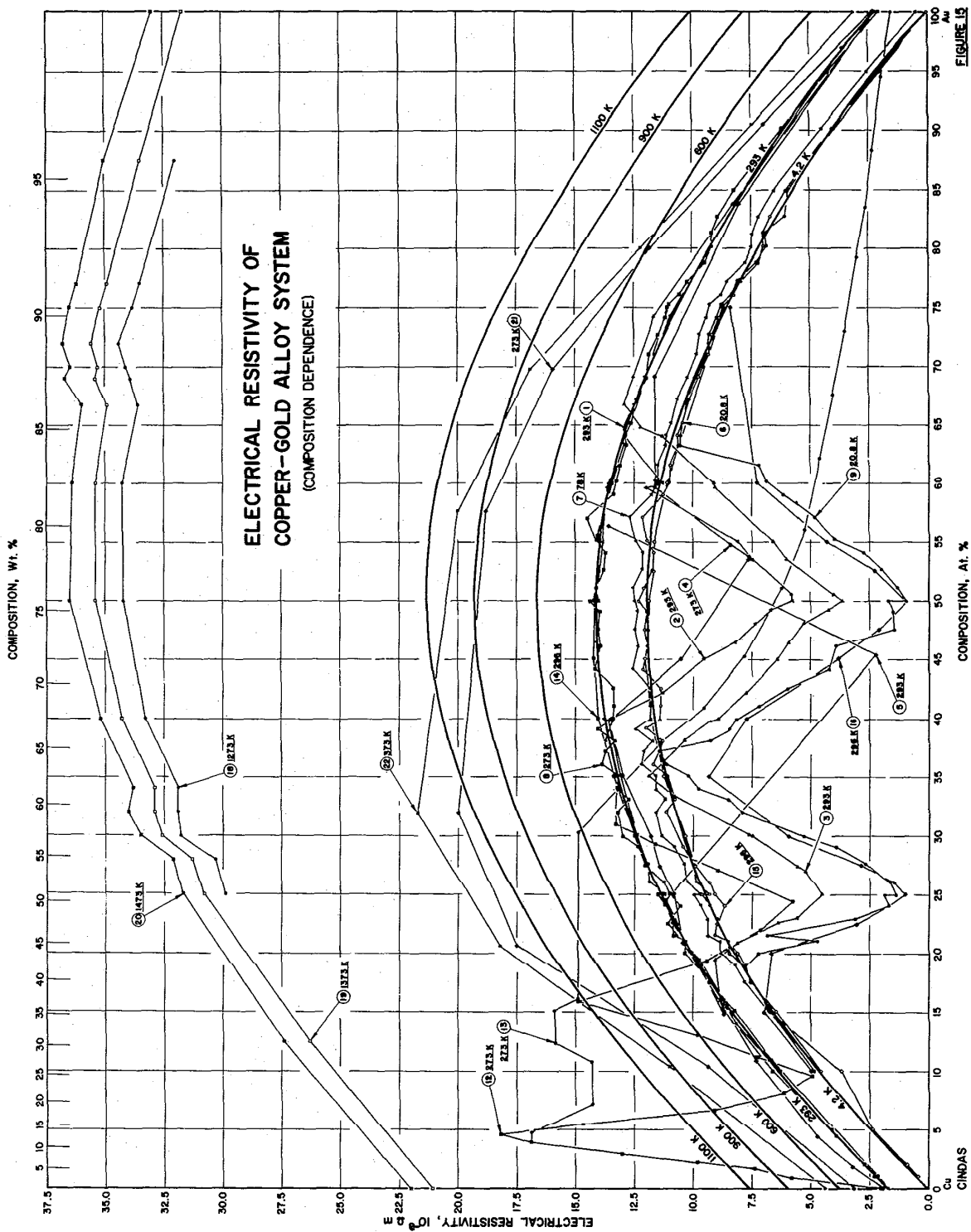


FIGURE 15

### 3.4. Copper-Nickel Alloy System

Sixty-five data-source references are available in the literature on the electrical resistivity of the Cu-Ni alloy system. From these references, a total of 244 data sets, 18 of which are merely single data points, have been extracted along with sample characterization and measurement information. 155 of the data sets are for the electrical resistivity of Cu + Ni alloys as a function of temperature covering the temperature range from 1 to 1273 K, which are listed in Table S-19, tabulated in Table S-20, and shown in Fig. 19; 71 of the data sets are for the electrical resistivity of Ni + Cu alloys as a function of temperature covering the range from 1.8 to 1273 K, which are listed in Table S-21, tabulated in Table S-22, and shown in Fig. 20; and 18 of the data sets are isotherms of the electrical resistivity as a function of composition, which are listed in Table S-23, tabulated in Table S-24, and shown in Fig. 22. In order to show both functional dependencies of the electrical resistivity, a few of the data sets have been presented in the tables and figures both for temperature dependence and for composition dependence.

Considerable evidence now exists to support the assertion that the Cu-Ni alloy system does not form a continuous series of solid solutions with truly random atomic arrangements. Rather it appears that, for certain alloy compositions and thermal treatments, Ni atoms tend to segregate from the random mixture to form short-range clusters. Some of the earliest evidence for this effect came from electrical resistivity and Hall constant measurements by Köster and Schüle<sup>142</sup> who concluded that short-range ordering occurs in alloys with from 15 to 45 wt.% Ni at temperatures below 923 K, with a maximum degree of order at about 723 K. The effect of the short-range ordering was to decrease the electrical resistivity. In a similar series of experiments, Schüle and Kehrer<sup>143</sup> (Cu + Ni data sets 56-63 and Ni + Cu data sets 40-41) concluded that clustering begins to form below 873 K and increases down to 623 K under conditions of slow cooling. In specimens quenched from homogenization temperatures of greater than 1273 K at a rate of at least  $10\,000\text{ K s}^{-1}$ , Schüle and Kehrer found a greater degree of clustering at lower temperatures, which they attributed to the presence of excess vacancies frozen-in by the quench from high temperatures. Hedman and Mattuck<sup>144</sup> (Cu + Ni data sets 16-18) quenched alloys with 41 to 47 wt.% Ni from 1273 K and found that subsequent annealing at temperatures from about 473 to 723 K resulted in a decrease in the room temperature resistivity, with a minimum resistivity for annealing temperatures between 553 and 608 K. They explained these results by suggesting that quenched-in vacancies, by their migration, allow the formation of clusters which produce the observed decrease in resistivity. Robbins *et al.*<sup>145</sup> came to a very similar interpretation from an analysis of magnetic susceptibility and cluster specific heat data. Mozer *et al.*<sup>146</sup> found direct evidence for the existence of Ni clusters in a diffuse neutron scattering experiment on a 47.5 at.% Ni specimen prepared with Ni<sup>62</sup> to enhance the difference in scattering powers of Cu and Ni. The specimen, which was furnace-cooled from a temperature of 1294 K, showed a type of clustering in which "the probability of finding a Ni atom in the first-neighbor shell around a Ni atom increases from

the random probability of 0.475 to 0.539. The clustering was found to be most pronounced for the first-neighbor shell, and in fact the solid solution is essentially random beyond this shell." By a consideration of diffusion rates in alloys near the composition of their specimen, Mozer *et al.* concluded that no cooling rate would successfully quench-in the local atomic arrangements characteristic of the alloy at 1273 K because the diffusion rates are too great at this elevated temperature. On the other hand, according to the authors, at around 773 to 873 K the diffusion rates become slow enough that any reasonable cooling rate, even furnace cooling, will freeze-in the atomic structure and prevent changes below 773 K. Hicks *et al.*<sup>147</sup> have confirmed this short-range clustering effect in neutron experiments of their own on specimens with compositions near the ferromagnetic critical composition.

The magnetic critical composition for Cu-Ni alloys and the Curie temperature for specific compositions are dependent on the degree of clustering present. Hedman and Mattuck<sup>144</sup> and Kussmann and Wollenberger<sup>148</sup> prepared specimens with different degrees of clustering by using appropriate heat and mechanical treatments. Their results are shown in Fig. 21. In both cases, specimens annealed in the 553 to 673 K range, where clustering is greatest, showed higher Curie temperatures than alloys quenched from 1073 or 1273 K. Cold-work, which presumably reduces the degree of clustering, produced specimens whose Curie temperatures were much lower than those of specimens quenched from higher temperatures. The effect of clustering on the Curie temperature is evident in alloys with as much as 70 at.% Ni and as little as 43 at.% Ni.

In addition to the data mentioned above, Fig. 21 shows a rather eclectic collection of measurements of Curie temperatures produced by a wide diversity of methods for alloy compositions from the critical composition to pure Ni. Mott<sup>44</sup> predicted a linear dependence of the Curie temperature on atomic composition and predicted a critical composition of 40 at.% Ni. As shown in the figure, this linear dependence is supported by the data for compositions with more than about 75 at.% Ni, but for lower concentrations of Ni, a discrepancy arises. In this region, the data of Hedman and Mattuck<sup>144</sup> and Kussmann and Wollenberger<sup>148</sup> for specimens quenched from high temperature fall very near a straight line which is determined by a critical composition of 40 at.% Ni (at which the Curie temperature is zero) and a Curie temperature for pure Ni of 631 K (represented by the dashed line in Fig. 21). However, measurements by Hicks *et al.*,<sup>147</sup> Rode *et al.*,<sup>150</sup> Ahmad and Greig,<sup>151</sup> and Ahern *et al.*<sup>152</sup> show Curie temperatures which are not only considerably lower, but also show a nonlinear dependence on composition near the critical composition. Two considerations might contribute to an explanation of this discrepancy, which is particularly evident for the composition range studied by Hedman and Mattuck. First, the degree of clustering may be lower for the nonlinear group of measurements, resulting in lowered Curie temperatures. Indeed, the Curie temperature determined by Hedman and Mattuck and by Kussmann and Wollenberger for deformed specimens with a low degree of clustering show remarkable agreement with the Curie temperatures determined by Hicks *et al.*, Rode *et al.*

*al.*, and Ahmad and Greig. However, with the information available, it is difficult to determine what specific differences in thermal and mechanical histories of the specimens gave rise to this difference in degree of clustering. For example, both Hicks *et al.* and Hedman and Mattuck quenched specimens from 1273 K after homogenization, yet apparently produced specimens of greatly differing degrees of clustering. Second, the experimental arrangement used by Hedman and Mattuck did not allow measurements of the magnetic susceptibility at sufficiently low temperatures, and in some cases required extrapolation of the inverse susceptibility from temperatures as much as 165 K above the Curie temperature.

In this work the lower set of nonlinear Curie temperatures, which are believed to be representative of the Curie temperatures of alloy specimens with a low degree of clustering, has been selected. The selected Curie temperatures are shown in Fig. 21 by a solid line and follow the data of Hicks *et al.*, Rode *et al.*, and Ahmad and Greig closely. The data of Ahern *et al.* are greater in magnitude than the selected values, though they follow the trend of selected values as a function of composition. Above about 77 at. % Ni, the solid line and the dashed line, representing the linear relationship suggested by Mott, are congruent.

A number of features of the temperature dependence of the electrical resistivity have received considerable interest in the research literature and are worth noting. First, at low temperatures (up to about 80 K), alloys with from about 30 to 45 wt. % Ni show shallow minima in the electrical resistivity, as shown in Fig. 19. This feature has been noted and discussed by Skoskiewicz and Baranowski,<sup>170</sup> Crangle and Butcher,<sup>171</sup> Houghton *et al.*,<sup>172,173</sup> Kondorskii *et al.*,<sup>174</sup> Ahmad and Greig,<sup>175</sup> Eagen,<sup>176</sup> Eagen and Legvold,<sup>177</sup> and Legvold *et al.*,<sup>178</sup> among others. Second, alloys with from about 35 to 55 wt. % Ni also show a high temperature (near 700 K) minimum in the electrical resistivity, which has been noted and discussed by Ahmad and Greig,<sup>151,175</sup> Houghton *et al.*,<sup>173</sup> and Schüle and Kehrer,<sup>143</sup> among others. Third, according to Ahmad and Greig<sup>151</sup> and Schüle and Kehrer,<sup>143</sup> the electrical resistivity of specimens with from about 30 to 60 wt. % Ni measured during heating is appreciably greater than the electrical resistivity measured during cooling, for temperatures below about 700 to 770 K. Above 700 to 770 K, the heating and cooling curves are the same. Ahmad and Greig found differences of about 1% and Schüle and Kehrer found differences of as much as  $3.5 \times 10^{-8} \Omega\text{m}$ . Ahmad and Greig suggested differences in the degree of clustering as an explanation of this phenomenon.

One feature of the composition-dependent resistivity worthy of note is the shape of the  $\rho_{4.2\text{K}}$  isotherm shown in Fig. 22. It does not have the rounded, parabolic shape characteristic of the Cu–Au alloy system, but instead is similar to the Matterhorn silhouette of the Cu–Pd alloy system. As the maximum (about 48 at. % Ni) of the residual electrical resistivity is approached from the Ni-rich side, a rapid increase in slope is observed at around 60 to 65 at. % Ni. Another feature is the slight change of slope in the isotherms at the transition from ferromagnetic to paramagnetic behavior. This can be seen, for example, at around 70 at. % Ni in the 293 K isotherm of Fig. 22. Finally, it should be noted that, as the

temperature increases, the maxima in the isotherms of the electrical resistivity as a function of composition are shifted to increasingly greater Ni concentrations.

The recommended values for the electrical resistivity of Cu–Ni alloys were generated by a careful examination and critical analysis of the entire body of experimental data shown in Figs. 19, 20, and 22. In order to assist in the generation of recommended values for the selected compositions, selected more reliable data were plotted as isotherms of the electrical resistivity as a function of composition at 4.2, 30, 80, 150, 230, 300, 400, 500, 600, 700, 900, and 1100 K. The data were graphically interpolated and smoothed as a function of composition and temperature successively in order to produce the final recommendations, which are shown in Figs. 16, 17, and 18 as a function of temperature, in Fig. 22 as a function of composition at selected temperatures, and in Table 4. The additional Fig. 18 in linear scale is given for showing more clearly the recommended curves at high temperatures.

In the generation of recommended values for the resistivity of the Cu–Ni system, we have relied heavily upon the data of Ahmad and Greig<sup>151,175</sup> (Cu + Ni data sets 145–147, 152, Ni + Cu data sets 56–59, and Cu–Ni data sets 14–15), which constitute one of the most comprehensive sets of data in their coverage of a wide range of both temperature and composition. From 30 to 50 wt. % Ni at low temperatures, the data of Houghton *et al.*<sup>172</sup> (Cu + Ni data sets 38–44) are about  $1.0$  to  $1.5 \times 10^{-8} \Omega\text{m}$  higher than the data of Ahmad and Greig, while the data of Crangle and Butcher<sup>171</sup> (Cu + Ni data sets 51–55) are about the same amount lower. The data of Legvold *et al.*<sup>178</sup> (Cu + Ni data sets 103–108) are in good agreement. In this range, the recommended values are consistent with all these data. However, near 50 wt. % Ni at low temperatures, only the specimens of Ahmad and Greig<sup>151</sup> (Ni + Cu data sets 58–59) and Crangle and Butcher<sup>171</sup> (Ni + Cu data set 39) are available, yet their resistivities differ by as much as  $6 \times 10^{-8} \Omega\text{m}$ . (Near room temperature the resistivities for these specimens are in good agreement.) In this region of composition, the data of Ahmad and Greig have been given preference and a large uncertainty is assigned to the recommended values. Again at high temperatures, there is a conflict between the data of Ahmad and Greig<sup>151</sup> (Ni + Cu data sets 56–59) for alloys with greater than 50 wt. % Ni and the data of Yao<sup>158</sup> (Ni + Cu data sets 60–63) and Svensson<sup>164</sup> (Ni + Cu data sets 19–22). Both Yao and Svensson report resistivities which are as much as  $3$  to  $4 \times 10^{-8} \Omega\text{m}$  higher than the data of Ahmad and Greig. The data of Yao are believed to show too great an increase with temperature above the Curie temperature, as can be seen with his pure Ni specimen. The data of Svensson were disregarded because they were often too high over the whole composition range and because the specimens were not well characterized.

The resulting recommended electrical resistivity values for Cu, Ni, and for 25 Cu–Ni binary alloys are presented in Table 4 and shown in Figs. 16, 17, 18, and 22. The recommended values for Cu and for Ni are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Cu and Ni having residual electrical resistivities as given at 1 K in Table 4. The alloys

TABLE 4. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-NICKEL ALLOY SYSTEM†  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 100.00% (100.00 At.%) Ni: 0.00% (0.00 At.%)		Cu: 99.50% (99.46 At.%) Ni: 0.50% (0.54 At.%)		Cu: 99.00% (98.92 At.%) Ni: 1.00% (1.08 At.%)		Cu: 97.00% (96.26 At.%) Ni: 3.00% (3.24 At.%)		Cu: 95.00% (94.61 At.%) Ni: 5.00% (5.39 At.%)		Cu: 90.00% (89.27 At.%) Ni: 10.00% (10.73 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.00200	1	0.58*	1	1.16*	1	3.53*	1	5.00	1	11.79
4	0.00200	4	0.58	4	1.16	4	3.53	4	5.89	4	11.79
7	0.00200	7	0.58*	7	1.16*	7	3.53*	7	5.89	7	11.79
10	0.00202	10	0.58*	10	1.16*	10	3.53*	10	5.89	10	11.79
15	0.00218	15	0.58*	15	1.16*	15	3.53*	15	5.89	15	11.79
20	0.00280	20	0.59*	20	1.17	20	3.53	20	5.89	20	11.79
25	0.00450	25	0.59*	25	1.17	25	3.53	25	5.90	25	11.79
30	0.00830	30	0.59*	30	1.17	30	3.54	30	5.90	30	11.80
40	0.0240	40	0.61*	40	1.19	40	3.56	40	5.93	40	11.80
50	0.0520	50	0.63*	50	1.21	50	3.59	50	5.97	50	11.82
60	0.0974	60	0.67*	60	1.25	60	3.62	60	6.00	60	11.88
70	0.154	70	0.71	70	1.28	70	3.67	70	6.02	70	11.91
80	0.216	80	0.77	80	1.33	80	3.71	80	6.09	80	11.97
90	0.282	90	0.82*	90	1.39	90	3.76	90	6.13	90	12.01
100	0.349	100	0.88*	100	1.45	100	3.82	100	6.19	100	12.08
150	0.701	150	1.21*	150	1.81	150	4.15	150	6.52	150	12.46
200	1.048	200	1.59	200	2.20	200	4.55	200	6.94	200	12.93
250	1.900	250	1.95	250	2.56	250	4.97	250	7.38	250	13.44
273	1.544	273	2.10	273	2.71	273	5.17	273	7.60	273	13.69
293	1.678	293	2.23	293	2.85	293	5.32	293	7.77	293	13.89
300	1.725	300	2.30	300	2.91	300	5.39	300	7.82	300	13.96
350	2.061	350	2.66	350	3.27	350	5.77	350	8.22	350	14.40
400	2.398	400	3.00	400	3.62	400	6.18	400	8.62	400	14.81
500	3.079	500	3.69	500	4.34	500	6.96	500	9.47	500	15.58
600	3.771	600	4.37	600	5.03	600	7.65	600	10.18	600	16.28
700	4.481	700	5.09	700	5.78	700	8.37	700	10.90	700	16.96
800	5.213	800	5.87	800	6.54	800	9.13	800	11.69	800	17.62
900	5.973	900	6.61	900	7.31	900	9.98	900	12.54	900	18.36
1000	6.766	1000	7.39*	1000	8.10*	1000	10.78*	1000	13.41*	1000	19.10*
1100	7.596	1100	8.25*	1100	8.99*	1100	11.69*	1100	14.31*	1100	19.99*
1200	8.470										
1300	9.395										
1357.6	9.946(s)										
1358	21.01(L)										
1700	24.41										

† Uncertainties in the electrical resistivity values are as follows:

- 100.00 Cu - 0.00 Ni:  $\pm 3\%$  up to 100 K,  $\pm 1\%$  above 100 K to 250 K,  $\pm 0.5\%$  above 250 K to 350 K,  $\pm 1\%$  above 350 K to 500 K,  $\pm 4\%$  above 500 K to 1357.6 K, and  $\pm 5\%$  above 1357.6 K.
- 99.50 Cu - 0.50 Ni:  $\pm 5\%$ .
- 99.00 Cu - 1.00 Ni:  $\pm 5\%$ .
- 97.00 Cu - 3.00 Ni:  $\pm 5\%$ .
- 95.00 Cu - 5.00 Ni:  $\pm 5\%$  below 400 K and  $\pm 4\%$  from 400 to 1100 K.
- 90.00 Cu - 10.00 Ni:  $\pm 5\%$  below 400 K and  $\pm 3\%$  from 400 to 1100 K.

\* In temperature range where no experimental data are available.

TABLE 4. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-NICKEL ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 85.00% (83.96 At.%) Ni: 15.00% (16.04 At.%)		Cu: 80.00% (78.71 At.%) Ni: 20.00% (21.29 At.%)		Cu: 75.00% (73.49 At.%) Ni: 25.00% (26.51 At.%)		Cu: 70.00% (68.31 At.%) Ni: 30.00% (31.69 At.%)		Cu: 65.00% (63.18 At.%) Ni: 35.00% (36.82 At.%)		Cu: 60.00% (58.09 At.%) Ni: 40.00% (41.91 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	17.69*	1	23.61	1	29.55*	1	35.48*	1	41.43*	1	46.19*
4	17.69	4	23.61	4	29.55	4	35.47	4	41.39	4	46.17
7	17.69*	7	23.61	7	29.55*	7	35.45*	7	41.35	7	46.13*
10	17.69*	10	23.61	10	29.55*	10	35.42*	10	41.32	10	46.11*
15	17.69*	15	23.61	15	29.55*	15	35.41*	15	41.29	15	46.09*
20	17.69	20	23.61	20	29.55	20	35.40	20	41.27	20	46.04
25	17.69	25	23.61	25	29.55	25	35.40	25	41.25	25	46.02
30	17.69	30	23.61	30	29.55	30	35.41	30	41.24	30	45.99
40	17.71	40	23.63	40	29.58	40	35.42	40	41.23	40	45.93
50	17.75	50	23.68	50	29.60	50	35.46	50	41.27	50	45.90
60	17.79	60	23.71	60	29.62	60	35.52	60	41.30	60	45.86
70	17.83	70	23.73	70	29.68	70	35.58	70	41.32	70	45.82
80	17.90	80	23.79	80	29.71	80	35.63	80	41.37	80	45.80
90	17.97	90	23.82	90	29.76	90	35.69	90	41.39	90	45.78
100	18.01	100	23.89	100	29.82	100	35.73	100	41.40	100	45.76
150	18.39	150	24.22*	150	30.16	150	36.05	150	41.48	150	45.70
200	18.87	200	24.69*	200	30.56	200	36.32	200	41.50	200	45.62
250	19.39	250	25.21*	250	30.99	250	36.58	250	41.50	250	45.51
273	19.63	273	25.46	273	31.19	273	36.67	273	41.50	273	45.43
293	19.83	293	25.66	293	31.35	293	36.72	293	41.49	293	45.38
300	19.90	300	25.72	300	31.40	300	36.76	300	41.48	300	45.35
350	20.32	350	26.12*	350	31.72	350	36.85	350	41.40	350	45.20
400	20.70	400	26.44*	400	31.92	400	36.89	400	41.30	400	45.01
500	21.42	500	26.96*	500	32.18	500	36.82	500	41.10	500	44.70
600	22.04	600	27.41*	600	32.39	600	36.82	600	40.90	600	44.40
700	22.59	700	27.98*	700	32.60	700	36.92	700	40.90	700	44.29
800	23.31	800	28.50*	800	32.88	800	37.10	800	41.09	800	44.52
900	23.95	900	28.98*	900	33.19	900	37.46	900	41.46	900	44.98
1000	24.49*	1000	29.38*	1000	33.60*	1000	37.82	1000	41.86	1000	45.42*
1100	25.06*	1100	29.79*	1100	34.18*	1100	38.34	1100	42.32	1100	45.92*

† Uncertainties in the electrical resistivity values are as follows:

- 85.00 Cu - 15.00 Ni:  $\pm 5\%$  below 400 K and  $\pm 3\%$  from 400 to 1100 K.
- 80.00 Cu - 20.00 Ni:  $\pm 5\%$  below 400 K and  $\pm 3\%$  from 400 to 1100 K.
- 75.00 Cu - 25.00 Ni:  $\pm 5\%$  below 400 K and  $\pm 3\%$  from 400 to 1100 K.
- 70.00 Cu - 30.00 Ni:  $\pm 4\%$ .
- 65.00 Cu - 35.00 Ni:  $\pm 4\%$ .
- 60.00 Cu - 40.00 Ni:  $\pm 4\%$ .

\* In temperature range where no experimental data are available.

TABLE 4. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-NICKEL ALLOY SYSTEM<sup>†</sup> (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 55.00% (53.04 At.%) Ni: 45.00% (46.96 At.%)		Cu: 50.00% (48.02 At.%) Ni: 50.00% (51.98 At.%)		Cu: 45.00% (43.05 At.%) Ni: 55.00% (56.95 At.%)		Cu: 40.00% (38.12 At.%) Ni: 60.00% (61.88 At.%)		Cu: 35.00% (33.22 At.%) Ni: 65.00% (66.78 At.%)		Cu: 30.00% (28.37 At.%) Ni: 70.00% (71.63 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	49.00*	1	46.60 <sup>†</sup> *	1	39.34*	1	32.16*	1	27.30*	1	23.40*
4	49.00	4	46.73 <sup>†</sup>	4	39.41	4	32.19	4	27.37	4	23.43
7	49.00*	7	46.87 <sup>†</sup> *	7	39.48*	7	32.21*	7	27.43*	7	23.50*
10	49.00*	10	47.01 <sup>†</sup> *	10	39.57*	10	32.24*	10	27.50*	10	23.56*
15	49.00*	15	47.23 <sup>†</sup> *	15	39.70*	15	32.32*	15	27.62*	15	23.67*
20	49.00	20	47.49 <sup>†</sup>	20	39.85	20	32.42	20	27.76*	20	23.78
25	49.00	25	47.73 <sup>†</sup>	25	40.01	25	32.55	25	27.90*	25	23.89
30	49.00	30	47.98 <sup>†</sup>	30	40.20	30	32.69	30	28.06*	30	24.01
40	49.00	40	48.40 <sup>†</sup>	40	40.63	40	33.03	40	28.39*	40	24.28
50	49.00	50	48.82 <sup>†</sup>	50	41.09	50	33.47	50	28.75*	50	24.56
60	49.00	60	49.21 <sup>†</sup>	60	41.59	60	33.97	60	29.17*	60	24.89
70	49.00	70	49.52 <sup>†</sup>	70	42.12	70	34.60	70	29.59	70	25.28
80	49.00	80	49.81 <sup>†</sup>	80	42.70	80	35.31	80	30.08	80	25.71
90	49.00	90	50.02 <sup>†</sup>	90	43.30	90	36.02	90	30.62*	90	26.20
100	49.00	100	50.22 <sup>†</sup>	100	43.92	100	36.77	100	31.27*	100	26.73
150	49.00*	150	50.68	150	47.18	150	40.56	150	35.05*	150	29.98
200	48.89*	200	50.56	200	48.44	200	44.27	200	39.41*	200	33.91
250	48.72*	250	50.31	250	49.07	250	46.92	250	43.28*	250	38.29
273	48.65	273	50.19	273	49.23	273	47.42	273	44.62	273	40.19
293	48.58	293	50.06	293	49.34	293	47.73	293	45.47	293	41.79
300	48.55	300	50.01	300	49.38	300	47.82	300	45.67	300	42.34
350	48.33*	350	49.73	350	49.47	350	48.28	350	46.61*	350	44.51
400	48.09*	400	49.50	400	49.40	400	48.49	400	47.18*	400	45.40
500	47.60	500	49.03	500	49.19	500	48.68	500	47.76*	500	46.39
600	47.17	600	48.74	600	49.02	600	48.81	600	48.15*	600	47.08
700	46.98	700	48.63	700	49.18	700	49.18	700	48.08*	700	47.69
800	47.19	800	48.86	800	49.62	800	49.72	800	49.43*	800	48.82
900	47.62	900	49.39	900	50.29	900	50.53	900	50.39*	900	49.98
1000	48.07	1000	49.92	1000	51.10*	1000	51.49	1000	51.61*	1000	51.27*
1100	48.58	1100	50.49*	1100	52.00*	1100	52.83	1100	53.10*	1100	52.76*

<sup>†</sup> Uncertainties in the electrical resistivity values are as follows:

- 55.00 Cu - 45.00 Ni:  $\pm 4\%$ .
- 50.00 Cu - 50.00 Ni:  $\pm 10\%$  below 40 K,  $\pm 6\%$  from 40 up to 150 K, and  $\pm 4\%$  from 150 to 1100 K.
- 45.00 Cu - 55.00 Ni:  $\pm 5\%$ .
- 40.00 Cu - 60.00 Ni:  $\pm 5\%$ .
- 35.00 Cu - 65.00 Ni:  $\pm 5\%$ .
- 30.00 Cu - 70.00 Ni:  $\pm 5\%$ .

\* Provisional values.

\* In temperature range where no experimental data are available.



\* In temperature range where no experimental data are available.

TABLE 4. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-NICKEL ALLOY SYSTEM† (continued)  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \cdot m$ ]

Cu: 25.00% (23.55 At.%) Ni: 75.00% (76.45 At.%)		Cu: 20.00% (18.76 At.%) Ni: 80.00% (81.24 At.%)		Cu: 15.00% (14.02 At.%) Ni: 85.00% (85.98 At.%)		Cu: 10.00% ( 9.31 At.%) Ni: 90.00% (90.69 At.%)		Cu: 5.00% ( 4.64 At.%) Ni: 95.00% (95.36 At.%)		Cu: 3.00% ( 2.78 At.%) Ni: 97.00% (97.22 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	19.50*	1	15.60*	1	11.70*	1	7.81*	1	3.90*	1	2.34*
4	19.53	4	15.64	4	11.72	4	7.82	4	3.90	4	2.34
7	19.58*	7	15.68*	7	11.76*	7	7.83*	7	3.90*	7	2.34*
10	19.61*	10	15.72*	10	11.79*	10	7.85*	10	3.91	10	2.35*
15	19.70*	15	15.78*	15	11.82*	15	7.89*	15	3.92*	15	2.37*
20	19.80	20	15.85	20	11.89	20	7.92	20	3.97	20	2.38*
25	19.91	25	15.92	25	11.95	25	7.97	25	4.00	25	2.40*
30	20.03	30	16.01	30	12.01	30	8.02	30	4.03	30	2.42*
40	20.25	40	16.18	40	12.13	40	8.12	40	4.14	40	2.50*
50	20.50	50	16.36	50	12.30	50	8.27	50	4.28	50	2.61*
60	20.79	60	16.56	60	12.49	60	8.41	60	4.41	60	2.73*
70	21.11	70	16.79	70	12.69	70	8.58	70	4.59	70	2.89
80	21.48	80	17.02	80	12.92	80	8.76	80	4.78	80	3.09
90	21.83	90	17.26	90	13.19	90	8.96	90	4.98	90	3.25*
100	22.22	100	17.66	100	13.49	100	9.28	100	5.20	100	3.50*
150	24.68*	150	19.68	150	15.30	150	10.90	150	6.57	150	4.79*
200	27.82*	200	22.37	200	17.62	200	12.93	200	8.26	200	6.41*
250	31.50*	250	25.64	250	20.50	250	15.38	250	10.37	250	8.34*
273	33.46	273	27.38	273	22.00	273	16.65	273	11.49	273	9.33
293	35.11	293	28.98	293	23.35	293	17.82	293	12.50	293	10.26
300	35.69	300	29.53	300	23.85	300	18.26	300	12.90	300	10.58
350	39.67*	350	33.63	350	27.60	350	21.51	350	15.69	350	13.14*
400	42.81*	400	37.57	400	31.38	400	25.19	400	18.78	400	15.98*
500	44.60*	500	42.12	500	38.61	500	32.70	500	25.77	500	22.69*
600	45.68*	600	43.86	600	41.28	600	37.78	600	33.17	600	30.60*
700	46.60*	700	45.23	700	43.21	700	40.42	700	36.67	700	34.99
800	47.77*	800	46.56	800	44.72*	800	42.37	800	39.11*	800	37.68
900	49.13*	900	47.92	900	46.19*	900	44.02	900	41.43*	900	40.31
1000	50.61*	1000	49.39*	1000	47.68*	1000	46.02*	1000	43.89*	1000	42.94*
1100	52.10*	1100	51.11*	1100	49.90*	1100	48.47*	1100	46.43*	1100	45.57*

† Uncertainties in the electrical resistivity values are as follows:

- 25.00 Cu - 75.00 Ni:  $\pm 5\%$ .
- 20.00 Cu - 80.00 Ni:  $\pm 5\%$ .
- 15.00 Cu - 85.00 Ni:  $\pm 5\%$ .
- 10.00 Cu - 90.00 Ni:  $\pm 5\%$ .
- 5.00 Cu - 95.00 Ni:  $\pm 5\%$ .
- 3.00 Cu - 97.00 Ni:  $\pm 5\%$ .

\* In temperature range where no experimental data are available.

TABLE 4. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-NICKEL ALLOY SYSTEM † (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 1.00% ( 0.92 At.%) Ni: 99.00% (99.08 At.%)		Cu: 0.50% ( 0.46 At.%) Ni: 99.50% (99.54 At.%)		Cu: 0.00% ( 0.00 At.%) Ni: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	0.78*	1	0.39*	1	0.00320
4	0.78	4	0.39	4	0.00360
7	0.78*	7	0.39*	7	0.00443
10	0.78	10	0.39	10	0.00573
15	0.78*	15	0.39*	15	0.00901
20	0.79	20	0.39	20	0.0140
25	0.80*	25	0.40*	25	0.0212
30	0.82	30	0.41	30	0.0317
40	0.88	40	0.44	40	0.0678
50	0.97*	50	0.52*	50	0.135
60	1.08*	60	0.62*	60	0.242
70	1.21	70	0.76	70	0.377
80	1.37	80	0.93	80	0.545
90	1.57*	90	1.13*	90	0.741
100	1.81*	100	1.36*	100	0.959
150	3.09*	150	2.62*	150	2.21
200	4.57*	200	4.10*	200	3.67
250	6.32*	250	5.82*	250	5.32
273	7.23	273	6.71	273	6.16
293	8.08	293	7.52	293	6.93
300	8.37	300	7.82	300	7.20
350	10.63*	350	10.01*	350	9.34
400	13.18*	400	12.49*	400	11.78
500	19.33*	500	18.46*	500	17.67
600	27.28*	600	26.39*	600	25.54
700	33.11*	700	32.64*	700	32.14
800	36.33*	800	35.94*	800	33.32
900	39.19*	900	38.88*	900	38.58
1000	41.93*	1000	41.60*	1000	41.41
1100	44.61*	1100	44.27*	1200	46.62
				1400	51.73
				1600	56.94
				1728	60.22(s)
				1729	82.24†(t)
				2000	85.22†

† Uncertainties in the electrical resistivity values are as follows:

1.00 Cu - 99.00 Ni:  $\pm 5\%$  below 400 K and  $\pm 3\%$  from 400 to 1100 K.0.50 Cu - 99.50 Ni:  $\pm 5\%$  below 400 K and  $\pm 3\%$  from 400 to 1100 K.0.00 Cu - 100.00 Ni:  $\pm 5\%$  below 150 K,  $\pm 3\%$  from 150 to 1300 K,  $\pm 5\%$  above 1300 K to 1728 K, and  $\pm 10\%$  above 1728 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.

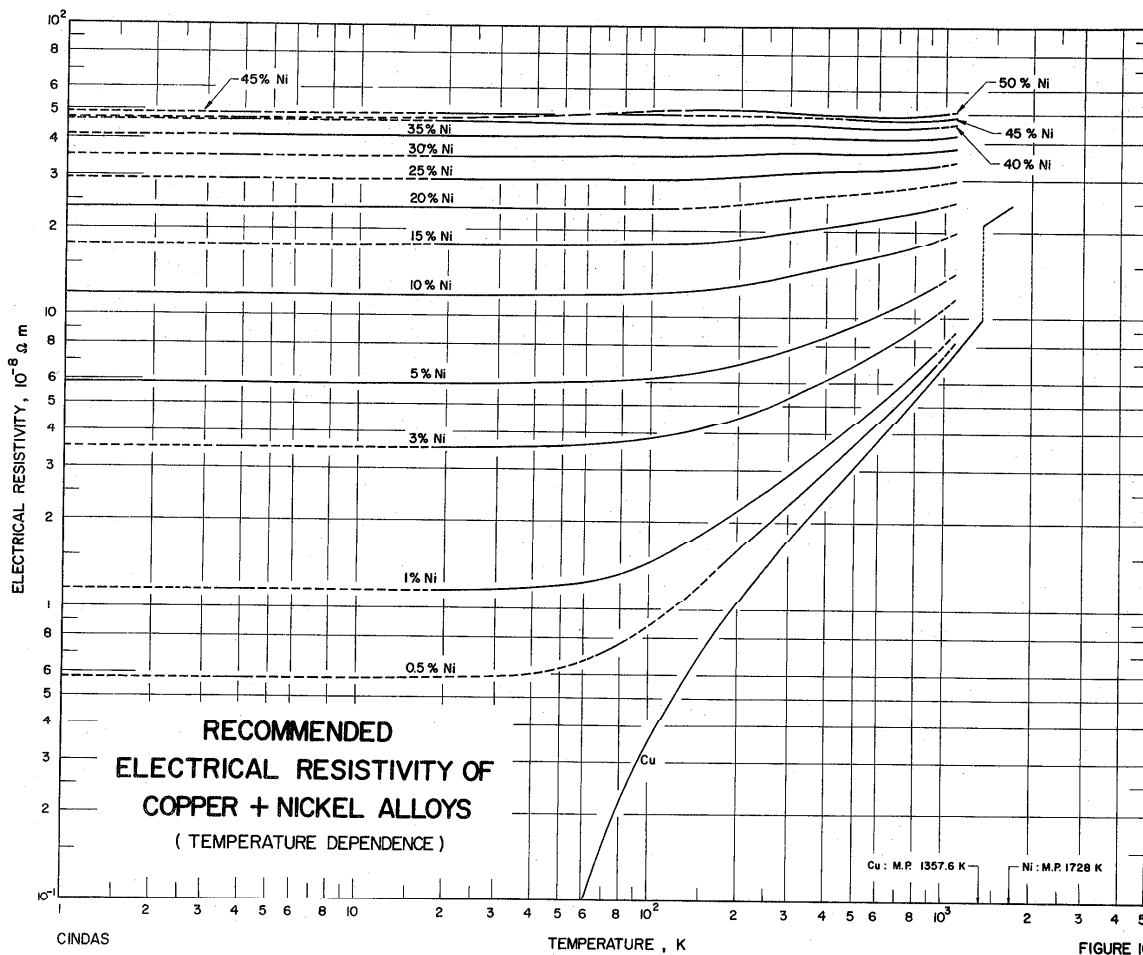
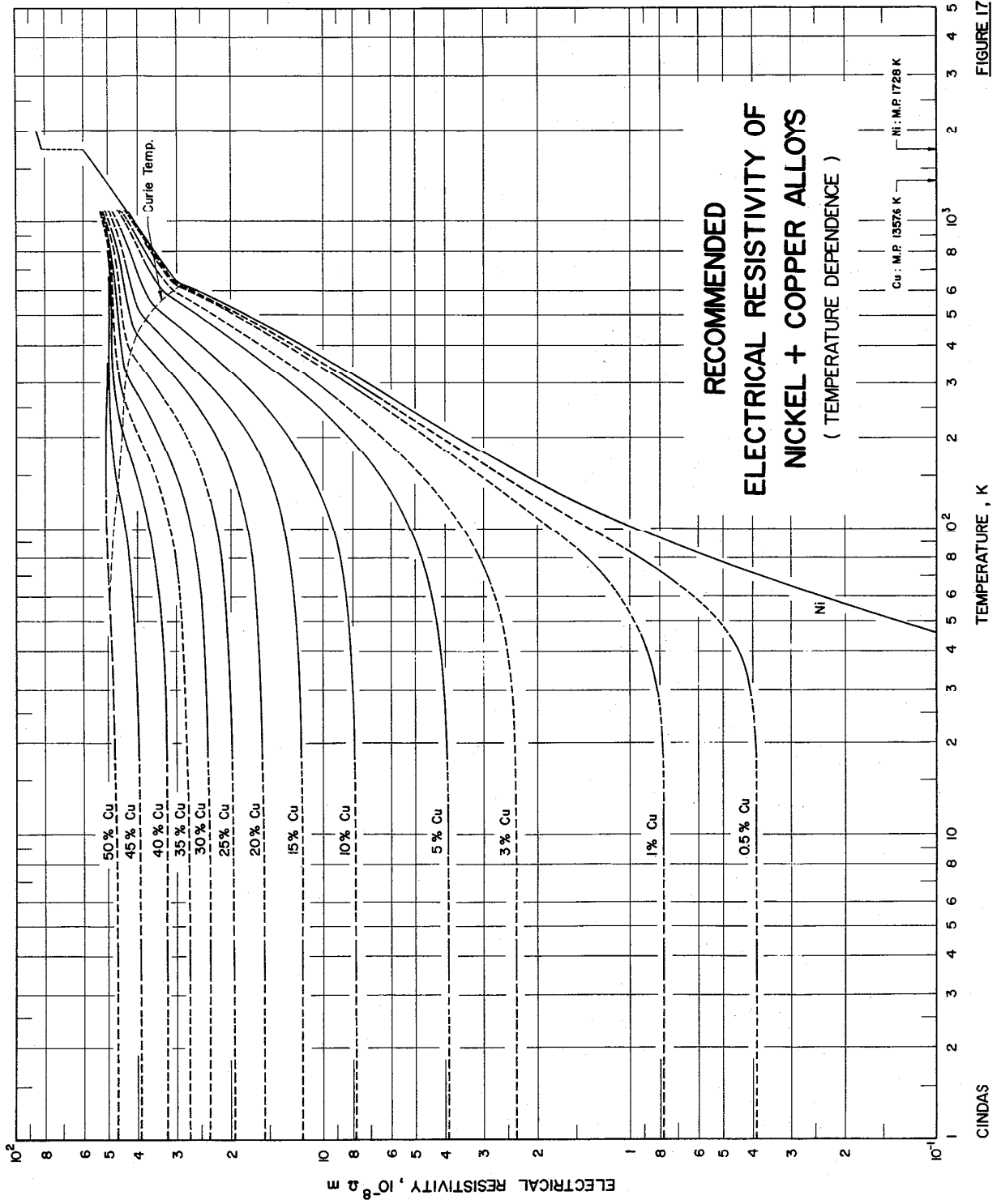
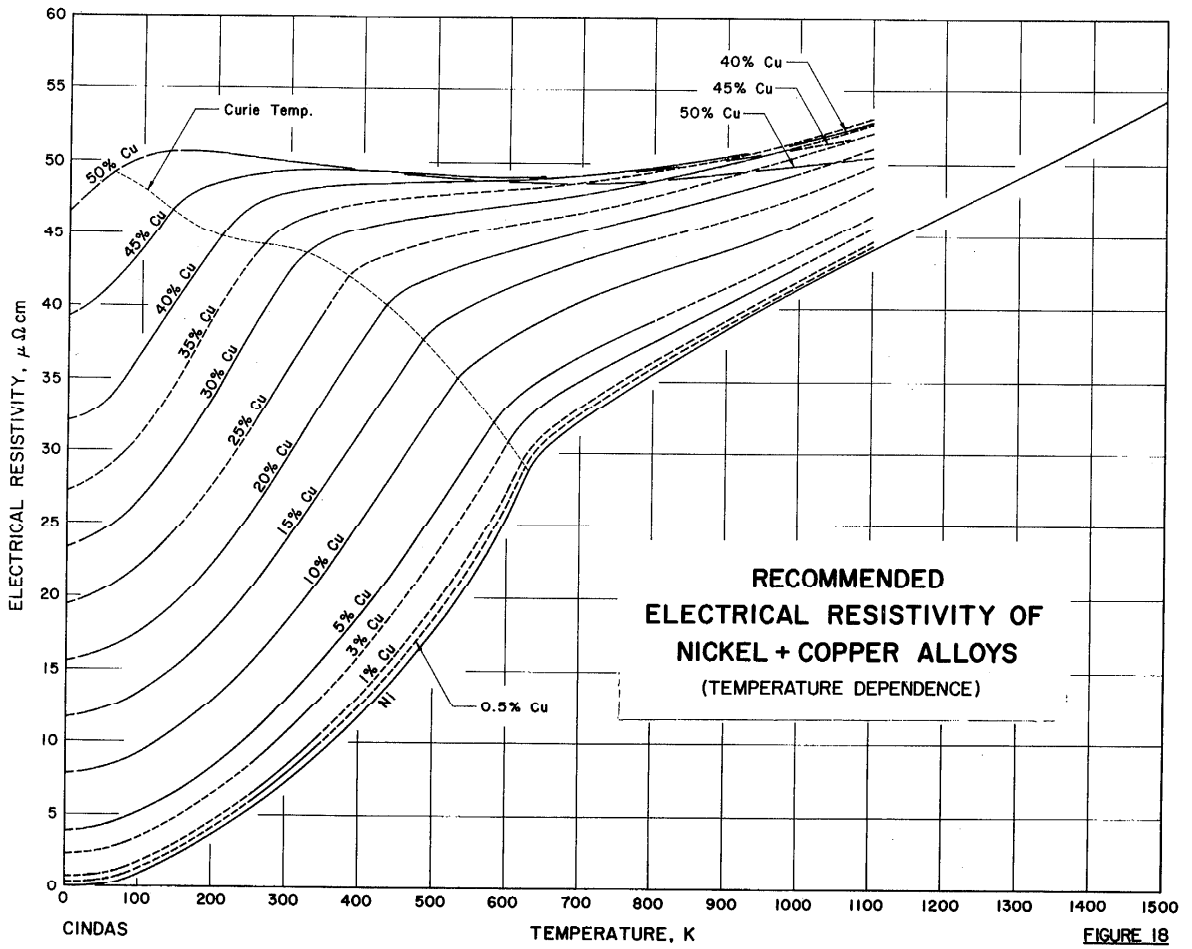


FIGURE 16

J. Phys. Chem. Ref. Data, Vol. 12, No. 2, 1983





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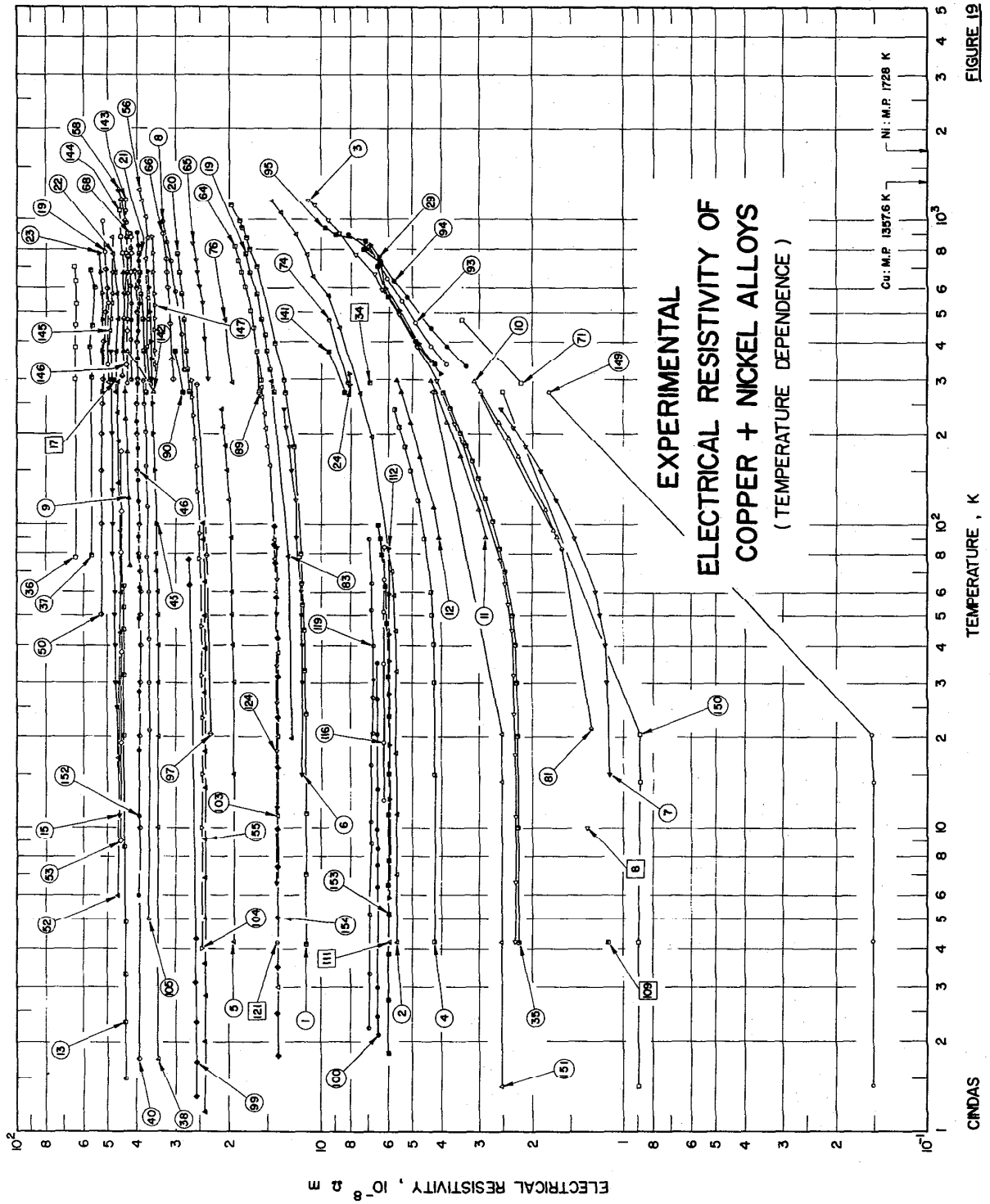


FIGURE 19

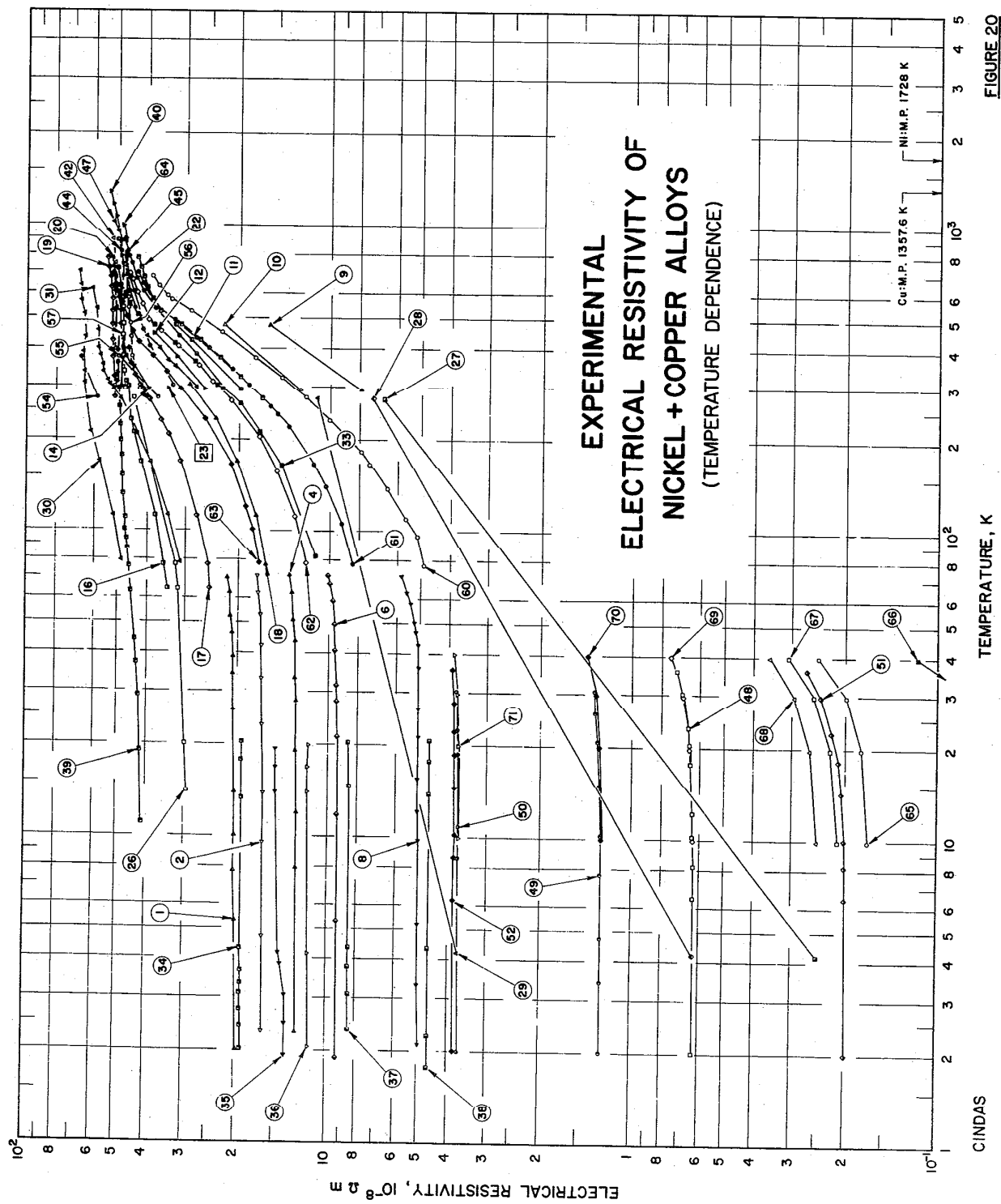
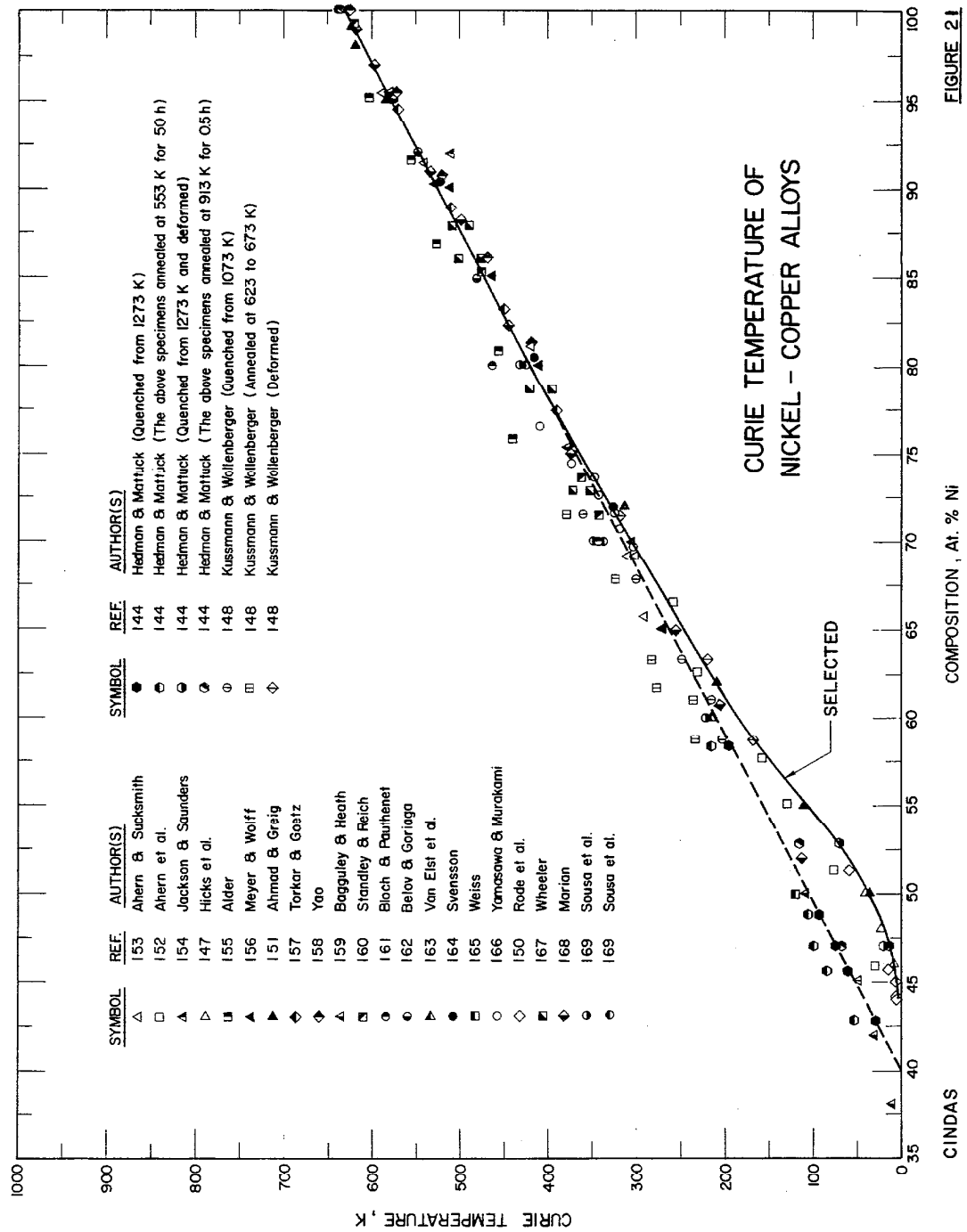


FIGURE 20





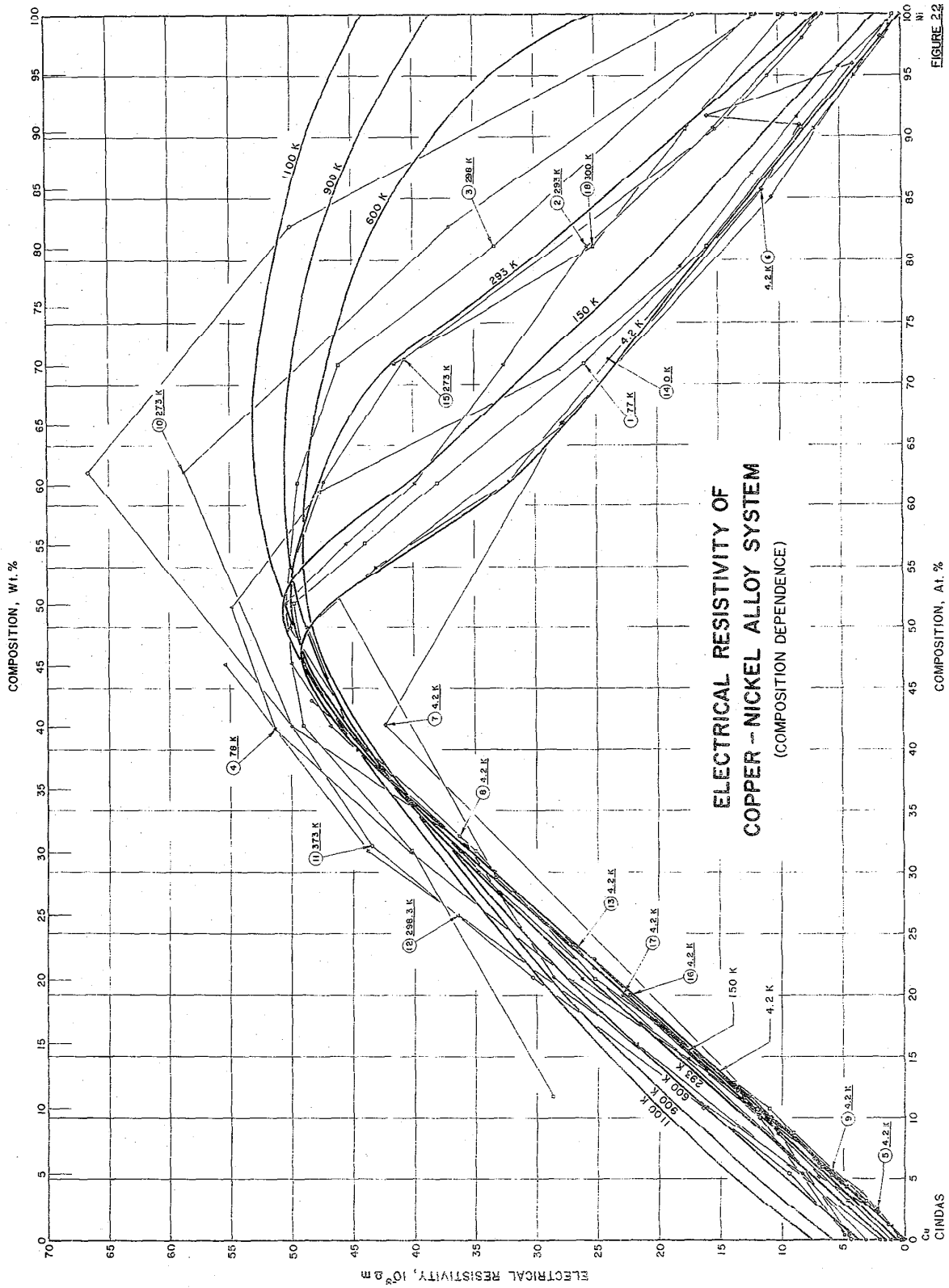


FIGURE 2.2

for which the recommended values are generated are well-homogenized alloys with a low degree of clustering and have not been quenched or cold-worked severely. The recommended values cover a full range of temperature from 1 to 1100 K. These values are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 4. A few of the low-temperature values for molten Ni are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

### 3.5. Copper-Palladium Alloy System

The copper-palladium alloy system forms a continuous series of solid solutions over the entire range of compositions. However, ordered structures are formed at temperatures below about 775 K for compositions ranging from slightly below 10 to somewhat above 25 at. % (16 to 36 wt. %) palladium and at temperatures below about 975 K for compositions ranging from slightly below 30 to somewhat above 50 at. % (42 to 63 wt. %) palladium. The maxima of the temperatures of transformation suggest that these ordered structures are due to the formation of PdCu<sub>5</sub> and Pd<sub>3</sub>Cu<sub>5</sub>, respectively. Structure ordering decreases the resistivity of these alloys.

There are 124 sets of experimental data available for this system, which are listed in Tables S-25, S-27, and S-29, tabulated in Tables S-26, S-28, and S-30, and shown in Figs. 25, 26, and 27. However, since many of the resistivity measurements were made to determine the maximum degree of order and the minimum value of electrical resistivity of individual alloys in this system with various compositions, a large portion of the data was not useful for the purpose of this study.

For this alloy system most of the data for disordered alloys are room-temperature values. The data of Svensson<sup>221</sup> (Cu-Pd data set 7) agree quite well with the pure element data and were chosen as the best resistivity versus composition curve at 291 K. Johansson and Linde<sup>222</sup> (Cu-Pd data set 3) also reported resistivity values for the entire spectrum of compositions; these data support the shape of Svensson's curve but are generally higher. At low Pd concentrations the agreement between the data of these authors is fairly good, but at concentrations above 60 wt. % Pd there is almost a 20% discrepancy. Pott's data<sup>223</sup> (Cu + Pd data sets 58-61 and Pd + Cu data sets 34-39) at 291 K agree quite well with the values from Svensson's isotherm. Köster and Lang<sup>224</sup> (Cu-Pd data sets 16-19) and Jaumot and Sawatzky<sup>225</sup> (Cu-

Pd data sets 11-15) reported values only slightly higher than Svensson's.

At temperatures above and below 291 K there were not many useful data to work with. Otter<sup>226</sup> (Cu + Pd data sets 9-12) reported resistivity versus temperature for low Pd concentrations, but his data at higher Pd concentrations were limited and conflicting. As a result, a procedure similar to that used for the Cu-Au alloy system was followed. Since Cu, Ag, and Au lie in the same column of the Periodic Table, it was assumed that their alloying properties with Pd should be similar. Accordingly, for a point on the 291 K resistivity versus composition isotherm a curve was drawn parallel to the recommended resistivity versus temperature curve for the same atomic percent of Ag in Pd. As in the case of the Cu-Au alloy system, values obtained in this way are only provisional. In the Ag-Pd alloy system at 65 to 70 wt. % Pd, the smoothed resistivity values as a function of temperature showed a change in slope (i.e., + to - to +). When these curves were followed for the Cu-Pd alloy system, a peculiar shape in the resistivity versus composition curves resulted. Since these values are only provisional, the bends were taken out so that the slope was always positive, and a family of resistivity versus composition isotherms similar to that of the Au-Pd alloy system was obtained.

Supporting data for the provisional values obtained by the above procedure are provided by Otter<sup>226</sup> (Cu + Pd data sets 9-12) at all temperatures for low Pd concentrations. At low temperatures Bäcklund<sup>227</sup> (Cu + Pd data sets 1-3) provides supporting data. The greatest uncertainty occurs between 60 and 80 wt. % Pd where few data exist and pure element resistivity provides no guidance.

The resulting recommended or provisional electrical resistivity values for Cu, Pd, and for 25 Cu-Pd binary alloys are presented in Table 5 and shown in Figs. 23, 24, and 27. The recommended values for Cu and for Pd are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Cu and Pd having residual electrical resistivities as given at 1 K in Table 5. The alloys for which the recommended or provisional values are generated are not ordered and have not been quenched or cold-worked severely. The values cover a full range of temperature from 1 to 1200 K, and are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 5. The values for the alloys at temperatures below 150 K and above 400 K are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

TABLE 5. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-PALLADIUM ALLOY SYSTEM†

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 100.00% (100.00 At.%) Pd: 0.00% ( 0.00 At.%)		Cu: 99.50% (99.70 At.%) Pd: 0.50% ( 0.30 At.%)		Cu: 99.00% (99.40 At.%) Pd: 1.00% ( 0.60 At.%)		Cu: 97.00% (98.19 At.%) Pd: 3.00% ( 1.81 At.%)		Cu: 95.00% (96.95 At.%) Pd: 5.00% ( 3.05 At.%)		Cu: 90.00% (93.78 At.%) Pd: 10.00% ( 6.22 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.00200	1	0.280*†	1	0.580*†	1	1.62*†	1	2.70*†	1	5.32*†
4	0.00200	4	0.280*†	4	0.580*†	4	1.62*†	4	2.70*†	4	5.32*†
7	0.00200	7	0.280*†	7	0.580*†	7	1.62*†	7	2.70*†	7	5.32*†
10	0.00202	10	0.280*†	10	0.580*†	10	1.62*†	10	2.70*†	10	5.32*†
15	0.00218	15	0.280*†	15	0.580*†	15	1.62*†	15	2.70*†	15	5.32*†
20	0.00280	20	0.280*†	20	0.580*†	20	1.62*†	20	2.70*†	20	5.32*†
25	0.00450	25	0.282*†	25	0.580*†	25	1.62*†	25	2.70*†	25	5.33*†
30	0.00830	30	0.289*†	30	0.580*†	30	1.62*†	30	2.70*†	30	5.34*†
40	0.0240	40	0.298*†	40	0.592*†	40	1.63*†	40	2.70*†	40	5.36*†
50	0.0520	50	0.313*†	50	0.617*†	50	1.66*†	50	2.71*†	50	5.38*†
60	0.0974	60	0.350*†	60	0.652*†	60	1.69*†	60	2.74*†	60	5.41*†
70	0.154	70	0.407*†	70	0.699*†	70	1.75*†	70	2.80*†	70	5.46*†
80	0.216	80	0.471*†	80	0.763*†	80	1.83*†	80	2.86*†	80	5.52*†
90	0.282	90	0.540*†	90	0.837*†	90	1.90*†	90	2.93*†	90	5.60*†
100	0.340	100	0.612*†	100	0.909*†	100	1.98*†	100	2.99*†	100	5.69*†
150	0.701	150	0.982*	150	1.26*	150	2.35*	150	3.35*	150	6.07
200	1.048	200	1.33*	200	1.60*	200	2.68*	200	3.70*	200	6.40
250	1.388	250	1.67*	250	1.94*	250	3.01*	250	4.05*	250	6.74
273	1.544	273	1.83	273	2.10	273	3.17	273	4.21	273	6.89
293	1.678	293	1.96	293	2.23	293	3.31	293	4.35	293	7.03
300	1.725	300	2.01	300	2.27	300	3.36	300	4.40	300	7.08
350	2.061	350	2.34*	350	2.59	350	3.69	350	4.74	350	7.41
400	2.398	400	2.67*	400	2.92	400	4.02	400	5.08	400	7.74
500	3.079	500	3.32*†	500	3.59*†	500	4.67*†	500	5.72*†	500	8.40*†
600	3.771	600	4.01*†	600	4.29*†	600	5.32*†	600	6.39*†	600	9.05*†
700	4.481	700	4.72*†	700	5.00*†	700	6.03*†	700	7.09*†	700	9.20*†
800	5.213	800	5.47*†	800	5.74*†	800	6.78*†	800	7.82*†	800	10.39*†
900	5.973	900	6.25*†	900	6.51*†	900	7.53*†	900	8.60*†	900	11.12*†
1000	6.766	1000	7.06*†	1000	7.29*†	1000	8.34*†	1000	9.43*†	1000	11.91*†
1100	7.596	1100	7.88*†	1100	8.11*†	1100	9.20*†	1100	10.30*†	1100	12.74*†
1200	8.470	1200	8.71*†	1200	9.00*†	1200	10.08*†	1200	11.18*†	1200	13.62*†
1300	9.395										
1357.6	9.946(s)										
1358	21.01(t)										
1700	24.41										

† Uncertainties in the electrical resistivity values are as follows:

100.00 Cu - 0.00 Pd:  $\pm 3\%$  up to 100K,  $\pm 1\%$  above 100K to 250K,  $\pm 0.5\%$  above 250K to 350K,  $\pm 1\%$  above 350K to 500K,  $\pm 4\%$  above 500K to 1357.6K, and  $\pm 5\%$  above 1357.6K.99.50 Cu - 0.50 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.99.00 Cu - 1.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.97.00 Cu - 3.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.95.00 Cu - 5.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.90.00 Cu - 10.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 5. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-PALLADIUM ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \cdot m$ ]

Cu: 85.00% (90.47 At.%) Pd: 15.00% (9.53 At.%)		Cu: 80.00% (87.01 At.%) Pd: 20.00% (12.99 At.%)		Cu: 75.00% (83.40 At.%) Pd: 25.00% (16.60 At.%)		Cu: 70.00% (79.62 At.%) Pd: 30.00% (20.38 At.%)		Cu: 65.00% (75.67 At.%) Pd: 35.00% (24.33 At.%)		Cu: 60.00% (71.52 At.%) Pd: 40.00% (28.48 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	7.91*†	1	10.43*†	1	12.90*†	1	15.30*†	1	17.68*†	1	20.01*†
4	7.91*†	4	10.43*†	4	12.90*†	4	15.30*†	4	17.68*†	4	20.01*†
7	7.91*†	7	10.43*†	7	12.90*†	7	15.30*†	7	17.68*†	7	20.01*†
10	7.91*†	10	10.43*†	10	12.90*†	10	15.30*†	10	17.68*†	10	20.01*†
15	7.91*†	15	10.43*†	15	12.90*†	15	15.30*†	15	17.68*†	15	20.01*†
20	7.91*†	20	10.43*†	20	12.90*†	20	15.30*†	20	17.68*†	20	20.01*†
25	7.92*†	25	10.43*†	25	12.91*†	25	15.31*†	25	17.68*†	25	20.02*†
30	7.92*†	30	10.43*†	30	12.91*†	30	15.32*†	30	17.69*†	30	20.03*†
40	7.94*†	40	10.44*†	40	12.92*†	40	15.34*†	40	17.70*†	40	20.05*†
50	7.98*†	50	10.46*†	50	12.96*†	50	15.38*†	50	17.71*†	50	20.10*†
60	8.02*†	60	10.50*†	60	13.00*†	60	15.42*†	60	17.74*†	60	20.16*†
70	8.09*†	70	10.55*†	70	13.06*†	70	15.47*†	70	17.79*†	70	20.23*†
80	8.16*†	80	10.61*†	80	13.11*†	80	15.53*†	80	17.85*†	80	20.30*†
90	8.23*†	90	10.67*†	90	13.19*†	90	15.60*†	90	17.92*†	90	20.38*†
100	8.30*†	100	10.74*†	100	13.28*†	100	15.67*†	100	17.98*†	100	20.45*†
150	8.66	150	11.11*	150	13.62*	150	16.01	150	18.33*	150	20.82
200	9.00	200	11.47*	200	13.97*	200	16.37	200	18.71*	200	21.20
250	9.32	250	11.81*	250	14.32*	250	16.73	250	19.09*	250	21.56
273	9.48	273	11.99	273	14.48	273	16.87	273	19.26	273	21.73
293	9.61	293	12.12	293	14.62	293	17.01	293	19.41	293	21.87
300	9.66	300	12.16	300	14.67	300	17.06	300	19.46	300	21.92
350	10.01	350	12.51*	350	15.03*	350	17.41	350	19.82	350	22.30
400	10.36	400	12.87	400	15.39	400	17.78	400	20.17	400	22.69
500	11.00†	500	13.51†	500	16.07†	500	18.47†	500	20.82†	500	23.39†
600	11.64†	600	14.10†	600	16.70†	600	19.10†	600	21.44†	600	24.01†
700	12.29†	700	14.78†	700	17.32†	700	19.72†	700	22.06†	700	24.61†
800	12.98†	800	15.49†	800	17.96†	800	20.35†	800	22.68†	800	25.23†
900	13.70†	900	16.18†	900	18.60†	900	21.00†	900	23.31†	900	25.86†
1000	14.48*†	1000	16.91*†	1000	19.24*†	1000	21.68*†	1000	23.95*†	1000	26.51*†
1100	15.31*†	1100	17.70*†	1100	19.91*†	1100	22.39*†	1100	24.62*†	1100	27.20*†
1200	16.20*†	1200	18.55*†	1200	20.61*†	1200	23.11*†	1200	25.31*†	1200	27.91*†

† Uncertainties in the electrical resistivity values are as follows:

85.00 Cu - 15.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 80.00 Cu - 20.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 75.00 Cu - 25.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 70.00 Cu - 30.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 65.00 Cu - 35.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 60.00 Cu - 40.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.

TABLE 5. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-PALLADIUM ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \cdot m$ ]

Cu: 55.00% (67.18 At.%) Pd: 45.00% (32.82 At.%)		Cu: 50.00% (62.61 At.%) Pd: 50.00% (37.39 At.%)		Cu: 45.00% (57.81 At.%) Pd: 55.00% (42.19 At.%)		Cu: 40.00% (52.75 At.%) Pd: 60.00% (47.25 At.%)		Cu: 35.00% (47.41 At.%) Pd: 65.00% (52.59 At.%)		Cu: 30.00% (41.78 At.%) Pd: 70.00% (58.22 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	22.60**	1	25.53**	1	29.00**	1	32.63**	1	40.03**	1	44.19**
4	22.60**	4	25.53**	4	29.00**	4	32.63**	4	40.03**	4	44.19**
7	22.60**	7	25.53**	7	29.00**	7	32.63**	7	40.03**	7	44.19**
10	22.60**	10	25.53**	10	29.00**	10	32.65**	10	40.03**	10	44.27**
15	22.60**	15	25.54**	15	29.00**	15	32.68**	15	40.10**	15	44.31**
20	22.60**	20	25.55**	20	29.00**	20	32.73**	20	40.15**	20	44.36**
25	22.60**	25	25.56**	25	29.01**	25	32.77**	25	40.18**	25	44.40**
30	22.61**	30	25.57**	30	29.03**	30	32.81**	30	40.22**	30	44.43**
40	22.64**	40	25.59**	40	29.07**	40	32.91**	40	40.31**	40	44.51**
50	22.70**	50	25.63**	50	29.13**	50	33.01**	50	40.40**	50	44.60**
60	22.75**	60	25.71**	60	29.27**	60	33.12**	60	40.49**	60	44.70**
70	22.82**	70	25.80**	70	29.31**	70	33.22**	70	40.53**	70	44.79**
80	22.90**	80	25.89**	80	29.40**	80	33.32**	80	40.68**	80	44.86**
90	22.98**	90	25.98**	90	29.49**	90	33.43**	90	40.73**	90	44.94**
100	23.06**	100	26.07**	100	29.58**	100	33.53**	100	40.81**	100	45.03**
150	23.45**	150	26.52**	150	30.03**	150	34.05**	150	41.28**	150	45.47
200	23.87**	200	26.97**	200	30.48**	200	34.56**	200	41.69**	200	45.90
250	24.27**	250	27.42**	250	30.92**	250	35.08**	250	42.11**	250	46.31
273	24.47	273	27.62	273	31.12	273	35.31	273	42.31	273	46.50
293	24.63	293	27.79	293	31.30	293	35.51	293	42.48	293	46.66
300	24.68	300	27.86	300	31.36	300	35.57	300	42.53	300	46.71
350	25.05**	350	28.25	350	31.29	350	36.03	350	42.97	350	47.11
400	25.42**	400	28.64	400	32.22	400	36.47	400	43.33	400	47.47
500	26.12**	500	29.40†	500	30.04†	500	37.30†	500	44.16†	500	48.13**
600	26.78**	600	30.10†	600	33.80†	600	38.09†	600	44.90†	600	48.73**
700	27.41**	700	30.75†	700	34.52†	700	38.89†	700	45.59†	700	49.27**
800	28.05**	800	31.38†	800	35.20†	800	39.52†	800	46.21†	800	49.74**
900	28.72**	900	32.01†	900	35.84†	900	40.20†	900	46.77†	900	50.23**
1000	29.41**	1000	32.68**	1000	36.50**	1000	40.89**	1000	47.27**	1000	50.68**
1100	30.13**	1100	33.37**	1100	37.19**	1100	41.60**	1100	47.71**	1100	51.07**
1200	30.89**	1200	34.07**	1200	37.90**	1200	42.36**	1200	48.08**	1200	51.40**

† Uncertainties in the electrical resistivity values are as follows:

55.00 Cu - 45.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 50.00 Cu - 50.00 Pd:  $\pm 8\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 45.00 Cu - 55.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 40.00 Cu - 60.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 35.00 Cu - 65.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.  
 30.00 Cu - 70.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

‡ Provisional value.

\* In temperature range where no experimental data are available.

TABLE 5. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-PALLADIUM ALLOY SYSTEM† (continued)

(Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \cdot m$ )

Cu: 25.00% (35.82 At.%) Pd: 75.00% (64.18 At.%)		Cu: 20.00% (39.51 At.%) Pd: 80.00% (70.49 At.%)		Cu: 15.00% (22.81 At.%) Pd: 85.00% (77.19 At.%)		Cu: 10.00% (15.69 At.%) Pd: 90.00% (84.31 At.%)		Cu: 5.00% ( 8.10 At.%) Pd: 95.00% (91.90 At.%)		Cu: 3.00% ( 4.92 At.%) Pd: 97.00% (95.08 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	42.40*†	1	36.26**†	1	28.68**†	1	20.10**†	1	10.31**†	1	6.20**†
4	42.40*†	4	36.26**†	4	28.68**†	4	20.10**†	4	10.31**†	4	6.20**†
7	42.45*†	7	36.33**†	7	28.78**†	7	20.17**†	7	10.34**†	7	6.20**†
10	42.52*†	10	36.43**†	10	28.93**†	10	20.28**†	10	10.39**†	10	6.20**†
15	42.64*†	15	36.59**†	15	29.13**†	15	20.44**†	15	10.46**†	15	6.21**†
20	42.76*†	20	36.75**†	20	29.31**†	20	20.58**†	20	10.54**†	20	6.25**†
25	42.88*†	25	36.90**†	25	29.47**†	25	20.72**†	25	10.63**†	25	6.30**†
30	42.97*†	30	37.03**†	30	29.61**†	30	20.85**†	30	10.74**†	30	6.36**†
40	43.12*†	40	37.29**†	40	29.92**†	40	21.11**†	40	11.00**†	40	6.60**†
50	43.30*†	50	37.54**†	50	30.23**†	50	21.40**†	50	11.31**†	50	6.89**†
60	43.49*†	60	37.80**†	60	30.54**†	60	21.70**†	60	11.64**†	60	7.24**†
70	43.65*†	70	38.06**†	70	30.85**†	70	22.00**†	70	11.97**†	70	7.66**†
80	43.81*†	80	38.32**†	80	31.17**†	80	22.31**†	80	12.32**†	80	8.09**†
90	43.97*†	90	38.58**†	90	31.48**†	90	22.64**†	90	12.69**†	90	8.52**†
100	44.12*†	100	38.83**†	100	31.79**†	100	23.00**†	100	13.09**†	100	8.97**†
150	44.82*†	150	40.06**†	150	33.29	150	24.79*	150	15.12*	150	11.12*
200	45.45*†	200	41.16**†	200	34.66	200	25.52*	200	17.15*	200	13.20*
250	46.01*†	250	42.13**†	250	35.95	250	26.18*	250	19.11*	250	15.20*
273	46.25	273	42.54	273	36.52	273	26.90	273	20.00	273	16.09
293	46.45	293	42.87	293	36.99	293	27.51	293	20.75	293	16.85
300	46.52	300	42.98	300	37.16	300	27.73	300	21.02	300	17.11
350	46.99*†	350	43.74**†	350	38.28	350	31.19**†	350	22.84**†	350	18.96**†
400	47.43*†	400	44.47**†	400	39.35	400	32.56**†	400	24.54**†	400	20.78**†
500	48.20*†	500	45.74**†	500	41.27**†	500	35.09**†	500	27.64**†	500	24.20**†
600	48.85*†	600	46.79**†	600	42.91**†	600	37.46**†	600	30.49**†	600	27.36**†
700	49.41*†	700	47.68**†	700	44.34**†	700	39.65**†	700	33.18**†	700	30.25**†
800	49.94*†	800	48.48**†	800	45.66**†	800	41.60**†	800	35.70**†	800	32.90**†
900	50.42*†	900	49.29**†	900	46.90**†	900	43.35**†	900	38.11**†	900	35.38**†
1000	50.85*†	1000	49.91**†	1000	48.10**†	1000	45.02**†	1000	40.45**†	1000	37.78**†
1100	51.21*†	1100	50.54**†	1100	49.23**†	1100	46.62**†	1100	42.68**†	1100	40.11**†
1200	51.49*†	1200	51.07**†	1200	50.26**†	1200	48.11**†	1200	44.76**†	1200	42.33**†

† Uncertainties in the electrical resistivity values are as follows:

25.00 Cu - 75.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.20.00 Cu - 80.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.15.00 Cu - 85.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.10.00 Cu - 90.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.5.00 Cu - 95.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.3.00 Cu - 97.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 5. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-PALLADIUM ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 1.00% ( 1.66 At.%) Pd: 99.00% (98.34 At.%)		Cu: 0.50% ( 0.83 At.%) Pd: 99.50% (99.17 At.%)		Cu: 0.00% ( 0.00 At.%) Pd: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	2.10*†	1	1.10*†	1	0.0200
4	2.10*†	4	1.10*†	4	0.0205
7	2.10*†	7	1.10*†	7	0.0217
10	2.10*†	10	1.10*†	10	0.0242
15	2.10*†	15	1.10*†	15	0.0346
20	2.11*†	20	1.10*†	20	0.0564
25	2.14*†	25	1.13*†	25	0.0938
30	2.21*†	30	1.19*†	30	0.151
40	2.45*†	40	1.40*†	40	0.335
50	2.78*†	50	1.68*†	50	0.607
60	3.15*†	60	2.00*†	60	0.940
70	3.52*†	70	2.38*†	70	1.32
80	3.92*†	80	2.79*†	80	1.75
90	4.34*†	90	3.23*†	90	2.19
100	4.78*†	100	3.68*†	100	2.63
150	6.91*†	150	5.85*†	150	4.81
200	9.00*†	200	7.92*†	200	6.89
250	11.00	250	9.91*†	250	8.88
273	11.90	273	10.29	273	9.78
293	12.67	293	11.55	293	10.54
300	12.93*†	300	11.81	300	10.80
350	14.82*†	350	13.69*†	350	12.66
400	16.68*†	400	15.54*†	400	14.46
500	20.19*†	500	19.05*†	500	17.89
600	23.41*†	600	22.28*†	600	21.10
700	26.42*†	700	25.26*†	700	24.10
800	29.25*†	800	28.07*†	800	26.89
900	31.88*†	900	30.68*†	900	29.50
1000	34.27*†	1000	33.09*†	1000	31.92
1100	36.46*†	1100	35.32*†	1200	36.21
1200	38.50*†	1200	37.40*†	1400	39.80
				1600	42.70
				1827	45.14 (s)
				1830	83.0 (L)
				2000	83.0

† Uncertainties in the electrical resistivity values are as follows:

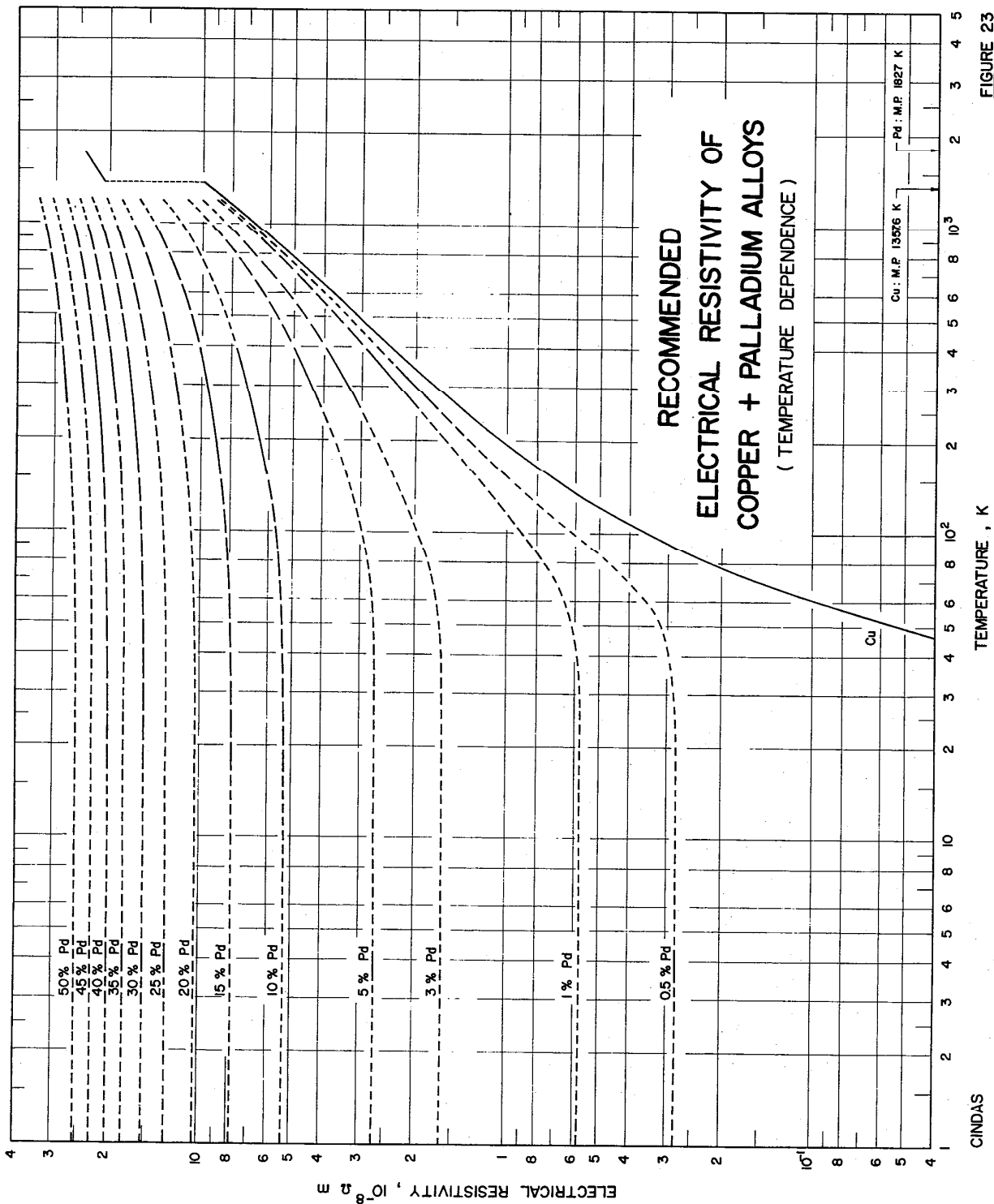
1.00 Cu - 99.00 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

0.50 Cu - 99.50 Pd:  $\pm 10\%$  below 150 K,  $\pm 5\%$  from 150 to 400 K, and  $\pm 10\%$  above 400 K.

0.00 Cu - 100.00 Pd:  $\pm 2\%$  up to 40 K,  $\pm 1\%$  above 40 K to 350 K,  $\pm 2\%$  above 350 K to 1600 K,  $\pm 2.5\%$  above 1600 K to 1827 K, and  $\pm 5\%$  above 1827 K.

\* Provisional value.

\* In temperature range where no experimental data are available.





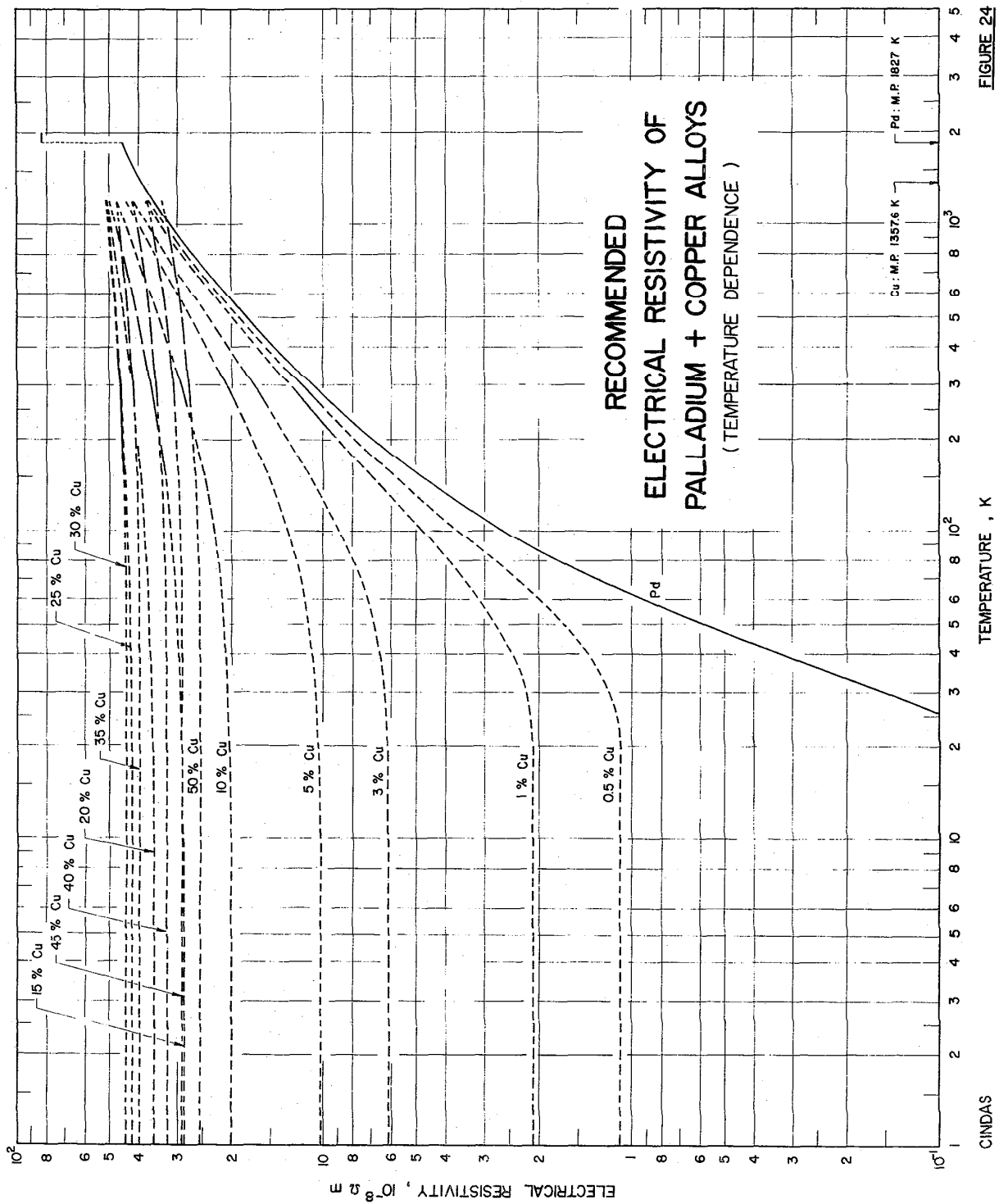


FIGURE 24

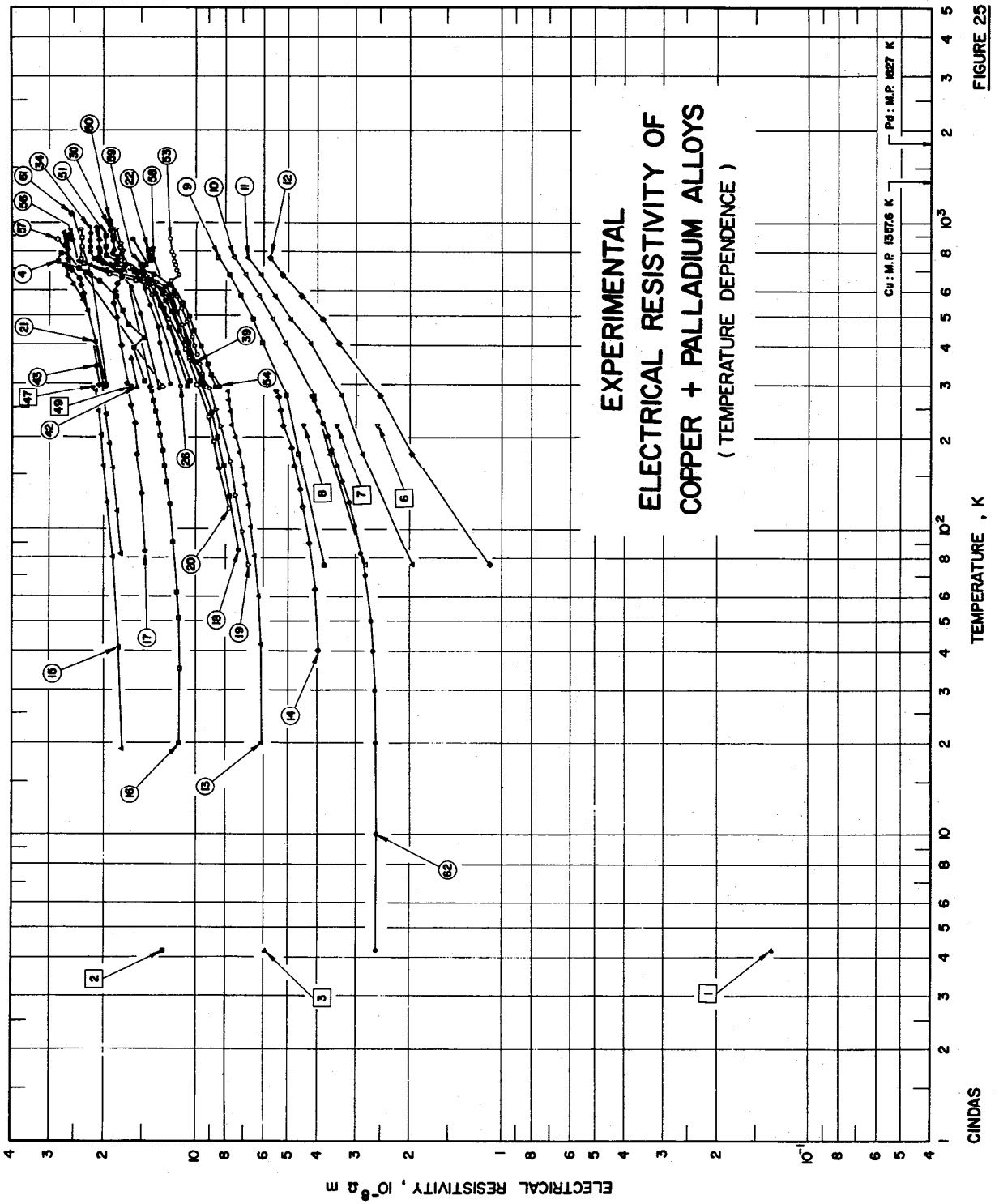
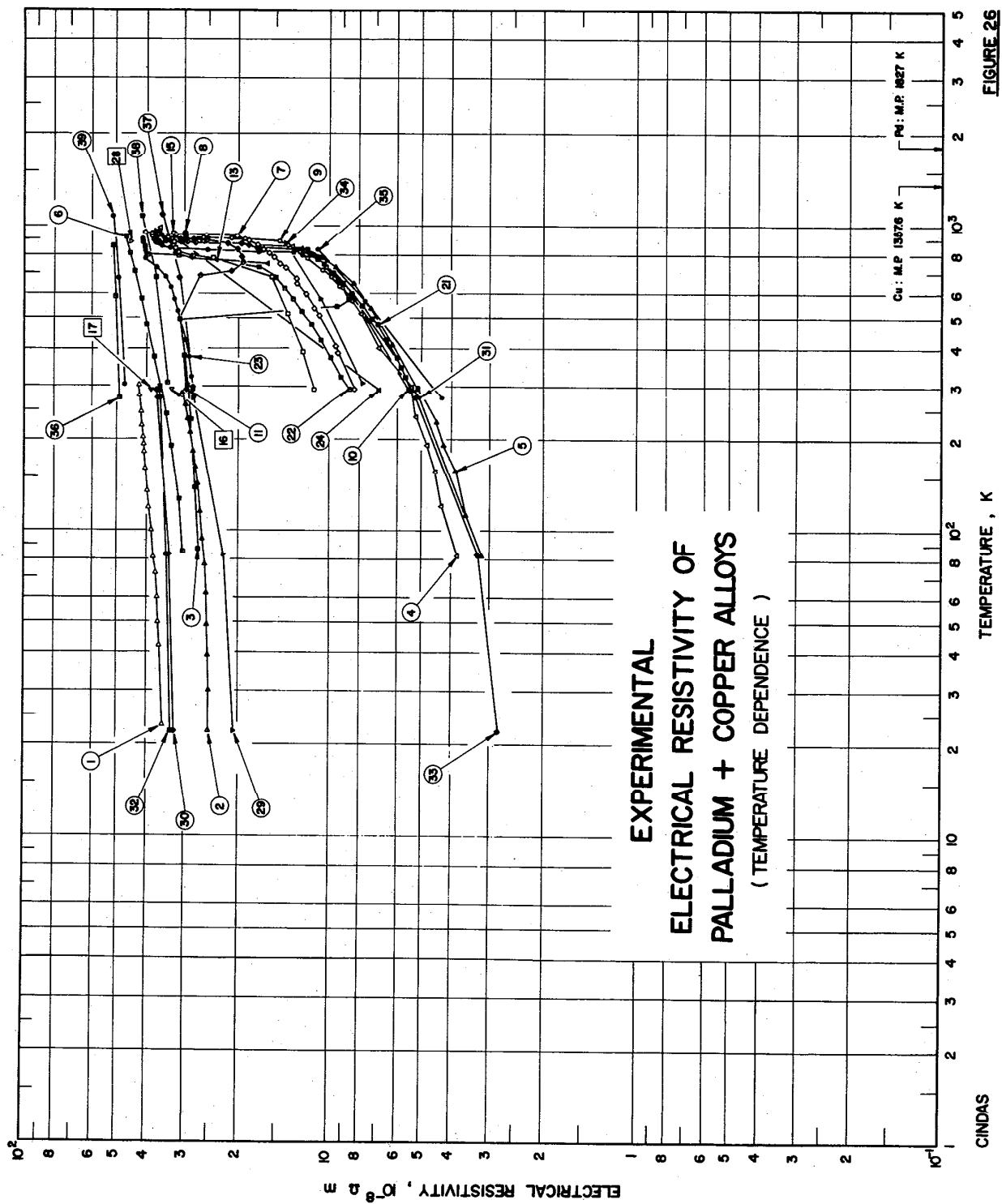


FIGURE 25



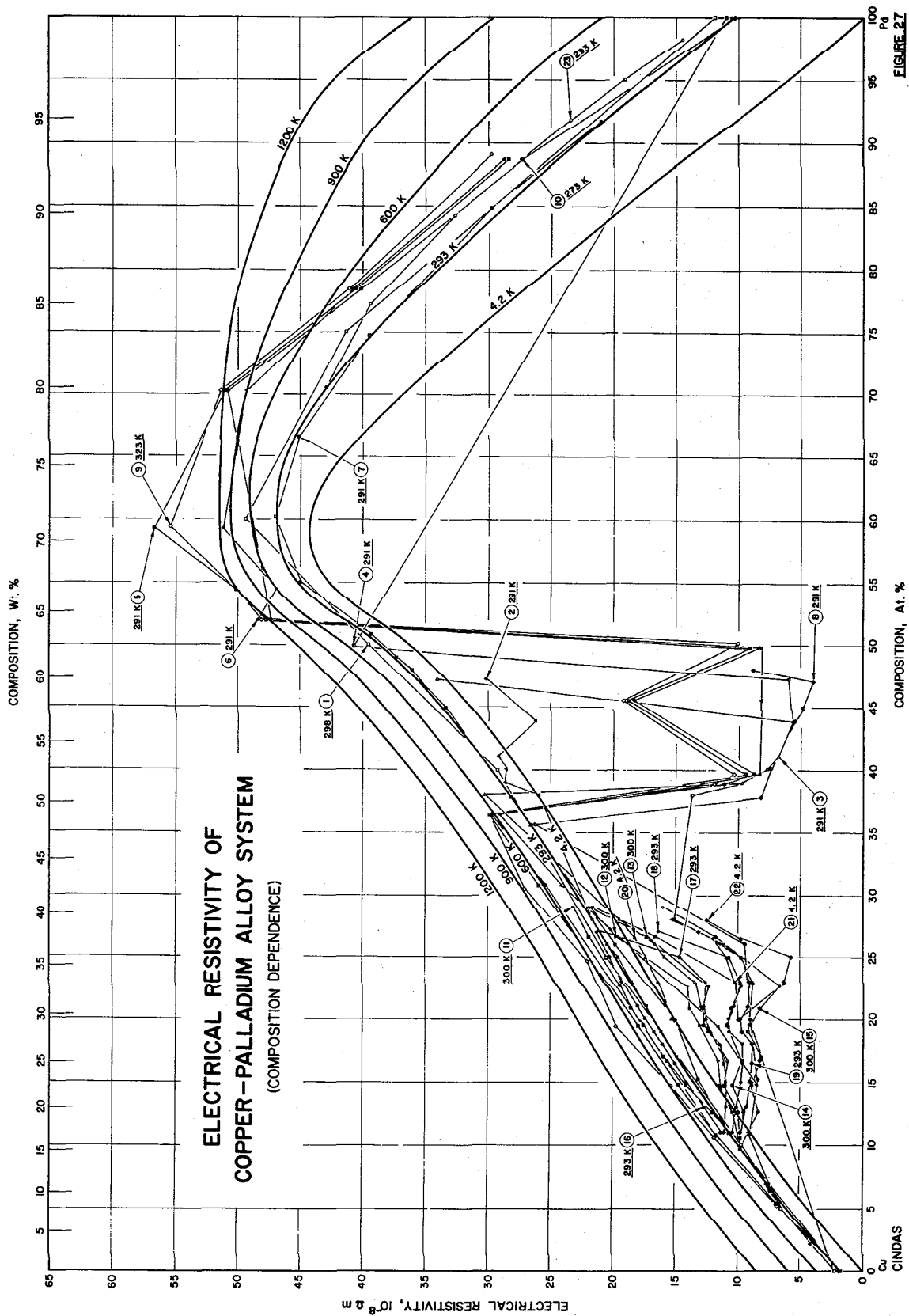


FIGURE 27

### 3.6. Copper-Zinc Alloy System

The copper-zinc alloy system does not constitute a continuous series of solid solutions. The maximum solid solubility of zinc in copper is 39.0 wt.% (38.3 at.%) at 727 K and the solubility decreases at higher and lower temperatures. At lower temperatures, the attainment of equilibrium becomes very slow and the solubility data are uncertain. Massalski and Kittl<sup>237</sup> analyzed the existing data and concluded that the boundary lies at about 34 at.% Zn at 473 K and it may lie at less than 30 at.% Zn at room temperature. Shinoda and Amano<sup>238</sup> reported a much greater reduction in solubility at room temperature. The maximum solid solubility of copper in zinc is 2.7 wt.% (2.77 at.%) at 697 K and it decreases to 0.3 wt.% (0.31 at.%) at 373 K.

There are 175 sets of experimental data available for this alloy system. These data sets are listed in Tables S-31, S-33, and S-35, tabulated in Tables S-32, S-34, and S-36, and shown partially in Figs. 29, 30, and 31. Most of the available data are for copper-rich alloys in the solid solution region. Due to the scarcity of data for zinc-rich alloys, the available data for Zn + Cu alloys are not evaluated and no recommendations are made in the present work.

For Cu + Zn alloys, Argent and Lee<sup>239</sup> (Cu + Zn data sets 31-50) reported the electrical resistivity for various compositions ranging from pure copper to 34.2 wt.% Zn at 77, 195, 273, and 373 K. Henry and Schroeder<sup>240</sup> (Cu + Zn data sets 57-65) reported the electrical resistivity of alloys with compositions ranging from 0.93 to 35.97 wt.% Zn at temperatures below room temperature. The values of Argent and Lee scatter more than those of Henry and Schroeder on a plot of resistivity versus composition.

Fairbank<sup>241</sup> (Cu + Zn data sets 12-30) has investigated the electrical resistivity of a full range of alloy compositions in the alpha-phase solid solution region in the temperature range 14.3 K to room temperature. Measurements were made on both annealed and hard-drawn specimens. His values for the annealed specimens are higher than those reported by other authors.

The data outside the region of solid solution are fragmentary and conflicting. In addition, beta-brass (46-48 wt.% Zn) forms ordered structures below about 735 K. For these reasons the data smoothing and synthesis was limited to the alpha-phase solid solution and was based mainly on the results of Henry and Schroeder<sup>240</sup> (Cu + Zn data sets 57-65), Smith<sup>242</sup> (Cu + Zn data sets 67-79), Smith and Palmer<sup>64</sup> (data set 80), and Kemp, Klemens, Tainsh, and White<sup>129,246,247</sup> (Cu + Zn data sets 81-94).

The resulting recommended electrical resistivity values for Cu, Zn, and for 9 Cu + Zn binary alloys are presented in Table 6 and shown in Figs. 28 and 31. No values were generated for alloys containing 35 to 99.5% Zn. The recommended values for Cu and for Zn are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Cu and Zn having residual electrical resistivities as given at 1 K in Table 6. The alloys for which the recommended values are generated are not ordered and have not been quenched or cold-worked severely. The recommended values cover the temperature range from 1 to 700 K. These values are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 6.

TABLE 6. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER-ZINC ALLOY SYSTEM†  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Cu: 100.00% (100.00 At.%) Zn: 0.00% ( 0.00 At.%)		Cu: 99.50% (99.51 At.%) Zn: 0.50% ( 0.49 At.%)		Cu: 99.00% (99.03 At.%) Zn: 1.00% ( 0.97 At.%)		Cu: 97.00% (97.08 At.%) Zn: 3.00% ( 2.92 At.%)		Cu: 95.00% (95.13 At.%) Zn: 5.00% ( 4.87 At.%)		Cu: 90.00% (90.25 At.%) Zn: 10.00% ( 9.75 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.00200	1	0.150*	1	0.270	1	0.710	1	1.09	1	1.84
4	0.00200	4	0.150	4	0.270	4	0.710	4	1.09	4	1.84
7	0.00200	7	0.150	7	0.270	7	0.710	7	1.09	7	1.84
10	0.00202	10	0.150	10	0.270	10	0.710	10	1.09	10	1.84
15	0.00218	15	0.150	15	0.271	15	0.710	15	1.09	15	1.85
20	0.00280	20	0.151	20	0.279	20	0.710	20	1.10	20	1.86
25	0.00450	25	0.159	25	0.289	25	0.711	25	1.11	25	1.87
30	0.00830	30	0.172	30	0.302	30	0.719	30	1.13	30	1.88
40	0.0240	40	0.207	40	0.338	40	0.748	40	1.16	40	1.91
50	0.0520	50	0.243	50	0.381	50	0.794	50	1.20	50	1.96
60	0.0974	60	0.288	60	0.431	60	0.856	60	1.26	60	2.02
70	0.154	70	0.341	70	0.489	70	0.924	70	1.33	70	2.10
80	0.216	80	0.397	80	0.550	80	0.996	80	1.40	80	2.18
90	0.282	90	0.452	90	0.610	90	1.06	90	1.47	90	2.26
100	0.349	100	0.511	100	0.671	100	1.13	100	1.54	100	2.33
150	0.701	150	0.846	150	0.999	150	1.48	150	1.90	150	2.72
200	1.048	200	1.19	200	1.34	200	1.83	200	2.26	200	3.10
250	1.388	250	1.53	250	1.68	250	2.18	250	2.61	250	3.48
273	1.544	273	1.69	273	1.84	273	2.34	273	2.78	273	3.66
293	1.678	293	1.82	293	1.97	293	2.48	293	2.92	293	3.81
300	1.725	300	1.87	300	2.02	300	2.53	300	2.97	300	3.86
350	2.061	350	2.22	350	2.36	350	2.88	350	3.33	350	4.25
400	2.398	400	2.56	400	2.71	400	3.23	400	3.69	400	4.63
500	3.079	500	3.25*	500	3.40*	500	3.83*	500	4.41*	500	5.40*
600	3.771	600	3.94*	600	4.09*	600	4.63*	600	5.13*	600	6.17*
700	4.481	700	4.63*	700	4.78*	700	5.33*	700	5.85*	700	6.94*
800	5.213										
900	5.973										
1000	6.766										
1100	7.596										
1200	8.470										
1300	9.395										
1357.6	9.946(s)										
1358	21.01(t)										
1700	24.41										

† Uncertainties in the electrical resistivity values are as follows:

100.00 Cu- 0.00 Zn:  $\pm 3\%$  up to 100K,  $\pm 1\%$  above 100K to 250K,  $\pm 0.5\%$  above 250K to 350K,  $\pm 1\%$  above 350K to 500K,  $\pm 4\%$  above 500K to 1357.6K, and  $\pm 5\%$  above 1357.6K.  
 99.50 Cu- 0.50 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.  
 99.00 Cu- 1.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.  
 97.00 Cu- 3.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.  
 95.00 Cu- 5.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.  
 90.00 Cu- 10.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.

\* In temperature range where no experimental data are available.

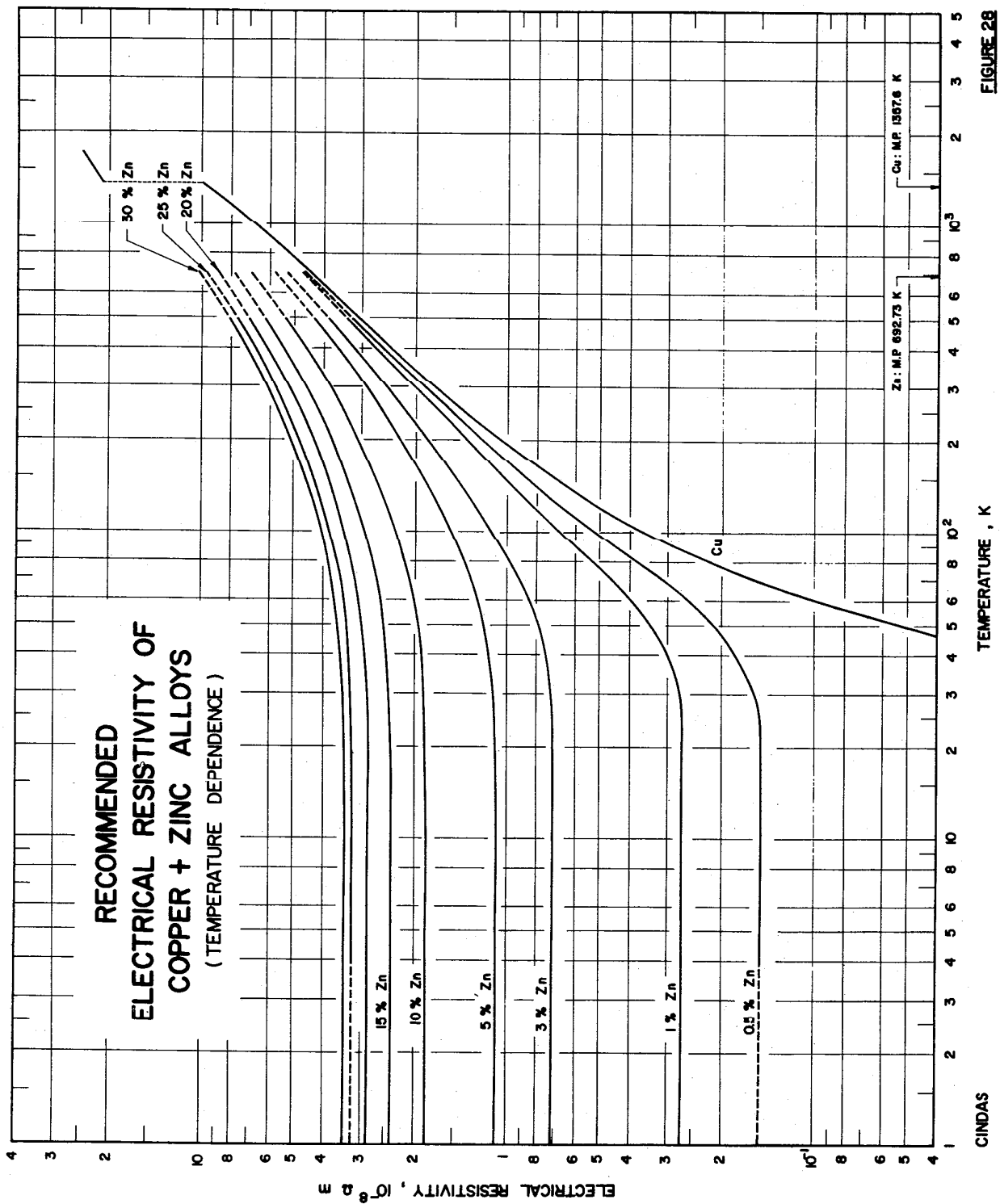
TABLE C. RECOMMENDED ELECTRICAL RESISTIVITY OF COPPER ZINC ALLOY SYSTEM† (continued)  
 (Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ )

Cu: 85.00% (85.36 At.%) Zn: 15.00% (14.64 At.%)		Cu: 80.00% (80.45 At.%) Zn: 20.00% (19.55 At.%)		Cu: 75.00% (75.53 At.%) Zn: 25.00% (24.47 At.%)		Cu: 70.00% (70.59 At.%) Zn: 30.00% (29.41 At.%)		Cu: 0.00% (0.00 At.%) Zn: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	2.38	1	2.84	1	3.20*	1	3.39	1	0.0100*
4	2.38	4	2.84	4	3.20	4	3.39	4	0.0100
7	2.38	7	2.84	7	3.20	7	3.39	7	0.0102
10	2.38	10	2.84	10	3.20	10	3.39	10	0.0112
15	2.39	15	2.85	15	3.21	15	3.40	15	0.0190
20	2.40	20	2.86	20	3.22	20	3.41	20	0.0387
25	2.42	25	2.87	25	3.23	25	3.43	25	0.0788
30	2.44	30	2.89	30	3.24	30	3.46	30	0.142
40	2.48	40	2.93	40	3.30	40	3.51	40	0.306
50	2.54	50	3.00	50	3.36	50	3.58	50	0.507
60	2.60	60	3.08	60	3.44	60	3.68	60	0.715
70	2.68	70	3.17	70	3.54	70	3.78	70	0.931
80	2.77	80	3.26	80	3.64	80	3.88	80	1.15
90	2.85	90	3.35	90	3.74	90	3.98	90	1.37
100	2.93	100	3.44	100	3.83	100	4.08	100	1.60
150	3.35	150	3.89	150	4.32	150	4.60	150	2.71
200	3.77	200	4.35	200	4.81	200	5.12	200	3.83
250	4.18	250	4.80	250	5.29	250	5.63	250	4.95
273	4.37	273	5.01	273	5.52	273	5.87	273	5.46
293	4.54	293	5.19	293	5.71	293	6.08	293	5.90
300	4.60	300	5.26	300	5.78	300	6.15	300	6.06
350	5.02	350	5.71	350	6.27	350	6.67	350	7.20
400	5.44	400	6.17	400	6.76	400	7.19	400	8.37
500	6.29*	500	7.08*	500	7.74*	500	8.23*	500	10.82
600	7.12*	600	7.99*	600	8.72*	600	9.27*	600	13.49
700	7.95*	700	8.90*	700	9.70*	700	10.31*	692.73	16.23*

† Uncertainties in the electrical resistivity values are as follows:

- 85.00 Cu - 15.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.
- 80.00 Cu - 20.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.
- 75.00 Cu - 25.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.
- 70.00 Cu - 30.00 Zn:  $\pm 3\%$  below 500 K and  $\pm 5\%$  from 500 to 700 K.
- 0.00 Cu - 100.00 Zn:  $\pm 5\%$  below 50 K,  $\pm 3\%$  from 50 to 400 K, and  $\pm 4\%$  above 400 K.

\* In temperature range where no experimental data are available.





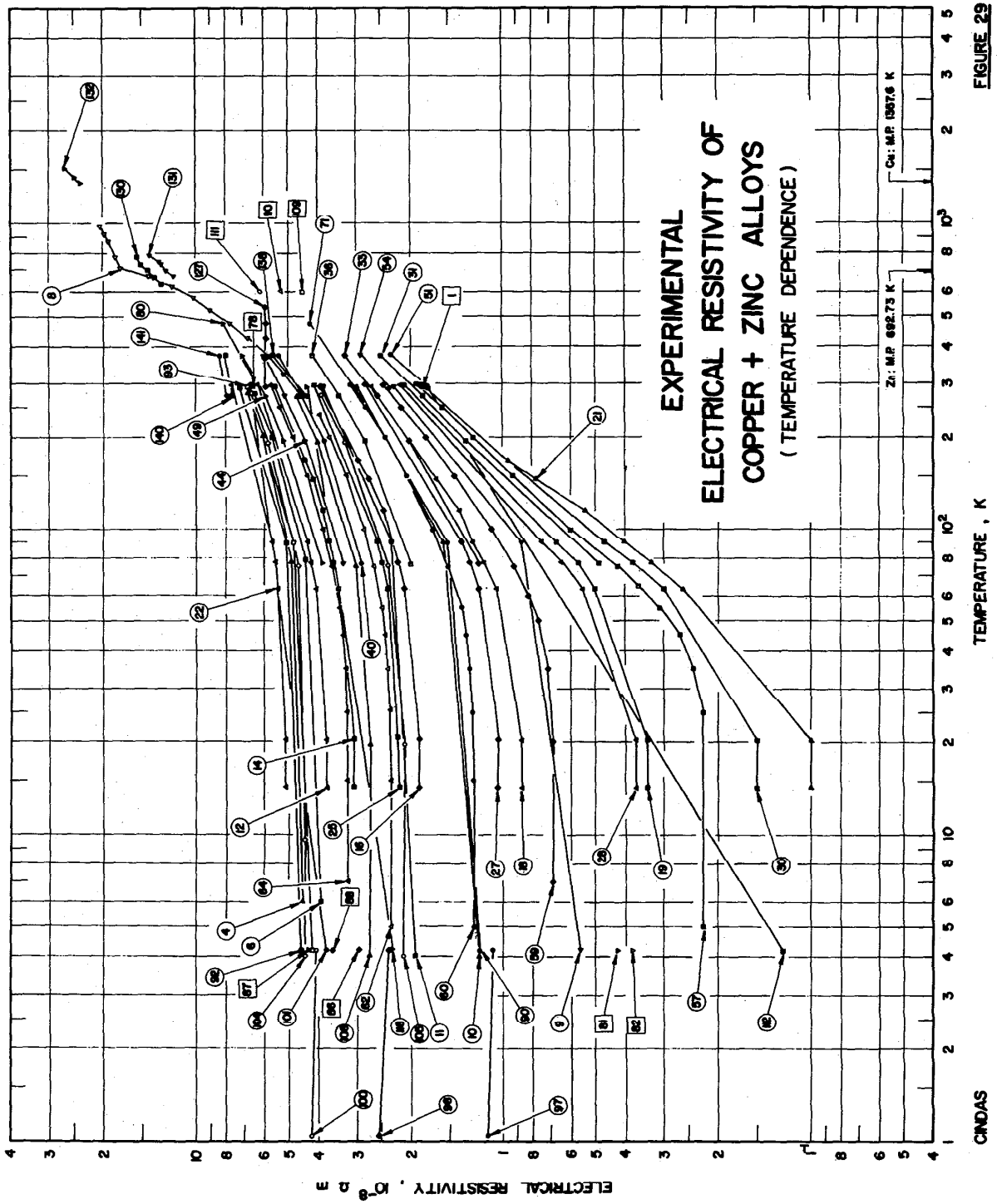
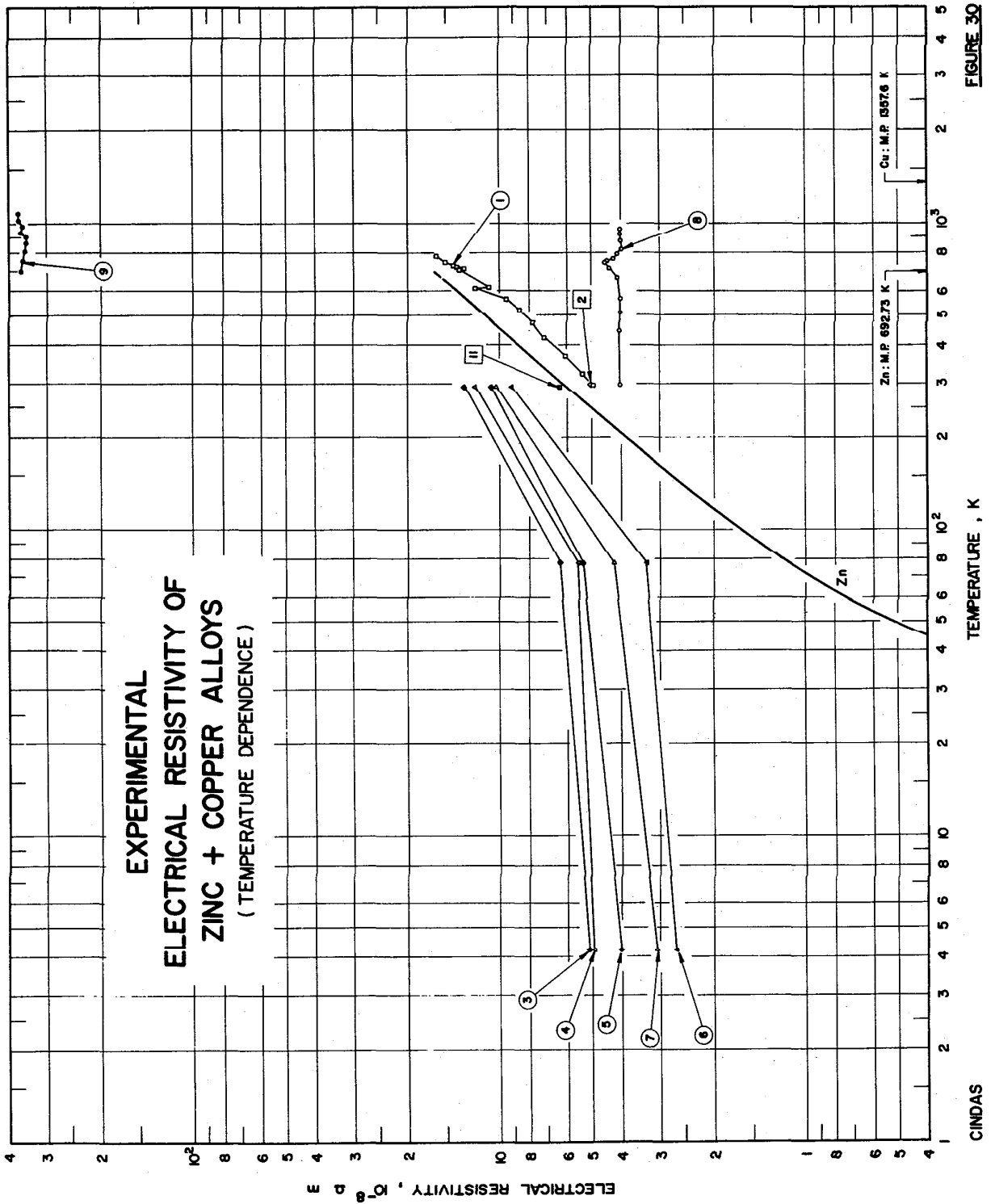
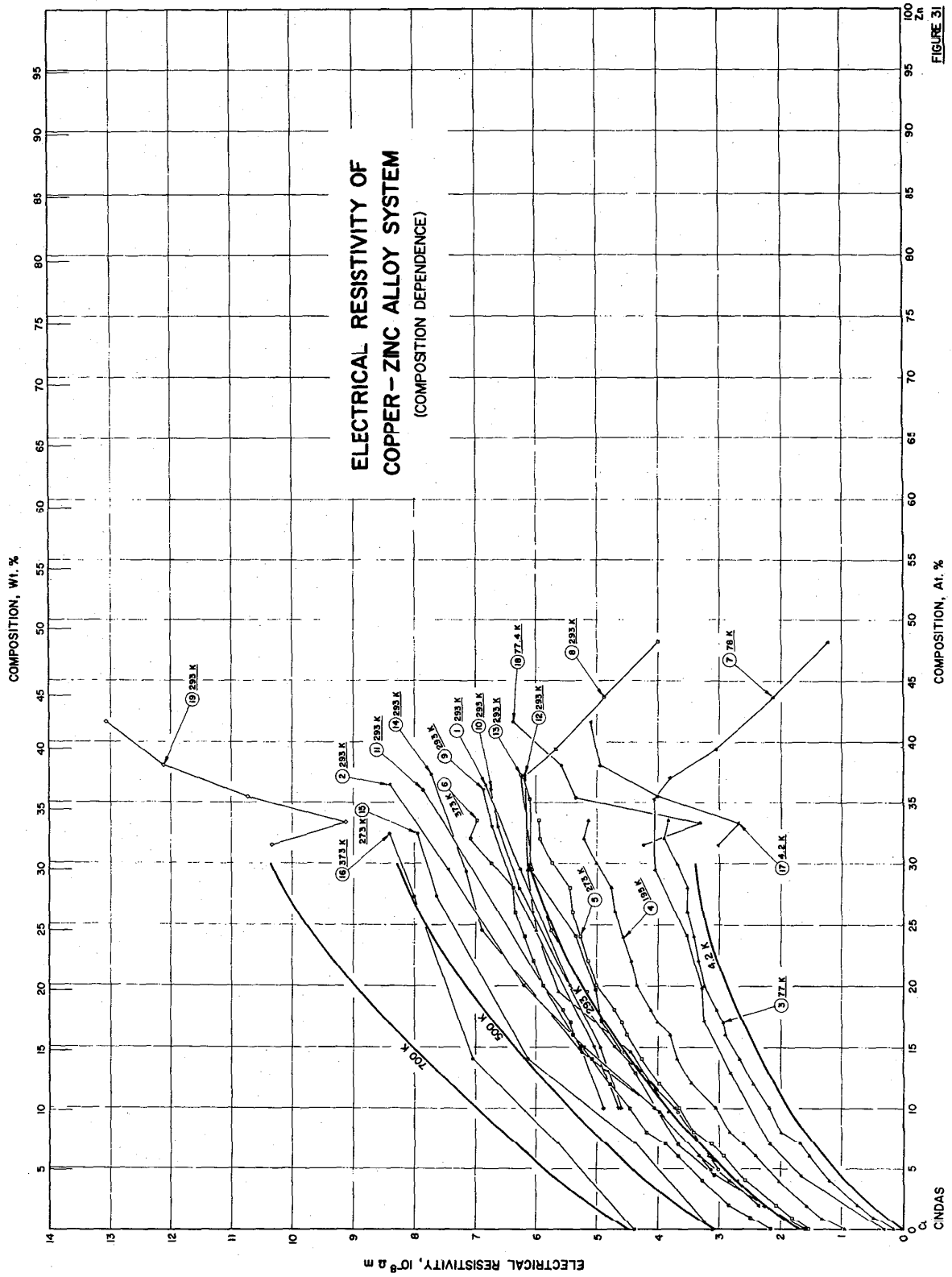


FIGURE 29





### 3.7. Gold-Palladium Alloy System

Twenty data-source references are available for the electrical resistivity of the Au-Pd alloy system. From these references, a total of 93 data sets, six of which are merely single data points, have been extracted along with specimen characterization and measurement information. Forty-three of the data sets are for Au + Pd alloys covering the temperature range from 1.2 to 1400 K, 15 of the data sets are for Pd + Au alloys covering the temperature range from 4 to 1400 K, and 35 of the data sets are isotherms of the electrical resistivity as a function of composition. These experimental data sets are listed in Tables S-37, S-39, and S-41 which provide information on specimen characterization and measurement conditions, tabulated in Tables S-38, S-40, and S-42, and shown partially in Figs. 34, 35, and 37. In order to show both functional dependencies of the electrical resistivity, a few of the data sets have been presented in the tables and figures both for temperature dependence and for composition dependence.

Since the electrical resistivity of a specimen depends on the arrangement of its constituent atoms such as ordering, the crystal structure of Au-Pd alloys is briefly discussed here first. The preponderance of data indicates that the Au-Pd alloy system forms a continuous series of solid solutions.<sup>264</sup> However, electron diffraction analyses of thin film specimens by Nagasawa *et al.*<sup>265</sup> have indicated the existence of long-range ordered structures in Au alloys with 15, 25, and 30 at.% Pd when annealed at temperatures below about 1123 K, the possible existence of such structures near the stoichiometric composition AuPd<sub>3</sub>, and the absence of such structures in alloys with 10 at.% Pd or 35 to 60 at.% Pd. The authors suggest that the reason why x-ray diffraction studies of bulk specimens have not shown similar evidence of superlattice structure may be that the time required for homogenization of the alloys is much greater for the bulk specimens than for the thin films.

The existence of short-range order in the Au-Pd alloy system has been established through diffuse x ray scattering studies of an alloy with 40 at.% Pd by Copeland and Nicholson,<sup>266</sup> of alloys with 40, 50, and 60 at.% Pd by Iveronova and Katsnel'son,<sup>267,268</sup> and of an alloy with 40 at.% Pd by Lin *et al.*<sup>269</sup> These studies further indicated that (1) cold-worked samples can exhibit short-range order, (2) subsequent annealing of cold-worked samples at temperatures from about 373 to 773 K, when followed by quenching, tends to increase the degree of short-range order, (3) subsequent annealing at temperatures of about 1073 K, when followed by quenching, tends to decrease the degree of short-range order, and (4) subsequent annealing at about 1073 K, when followed by slow cooling, may produce a greater degree of short-range order than any of the other described treatments of cold-worked samples. Devi *et al.*<sup>270</sup> carried out x-ray investigations of the temperature dependence of the lattice parameter of a 41% Pd alloy, but no deviation from linearity was found up to 873 K, and the authors concluded that measurements of the lattice parameter may not be sensitive to the presence of short-range order in Au-Pd alloys.

The effects of plastic deformation on the electrical resistivity of Au-Pd alloys have been studied by Köster and Hal-

pern,<sup>271</sup> Logie *et al.*,<sup>272</sup> and Kim and Flanagan.<sup>232</sup> Normally, the effect of deformation is to increase the electrical resistivity, due to increased scattering from crystal defects introduced by the deformation. However, each of the above studies provided evidence for an anomalous decrease occurs for a wide range of compositions, but it is a maximum for specimens with about 40 at.% Pd. Such specimens, when deformed by about 40% reduction in area, may show a resistivity decrease of nearly 6%. Kim and Flanagan,<sup>232</sup> in this consideration of alternative explanations for the anomaly, concluded that cold-work reduces the degree of short-range order present in the specimen. This conclusion, together with the knowledge<sup>232</sup> that short-range ordering causes an increase in the resistivity of Au-Pd alloys, explains the anomaly. Although deformation does produce defects which tend to increase the resistivity, the destruction of short-range order (and the consequent resistivity decrease) overshadows the effect of the defects and results in a net decrease in resistivity.

Studies of the recovery kinetics of cold-worked or quenched specimens upon annealing by Kim and Flanagan,<sup>273</sup> Haas and Lücke,<sup>274</sup> and Lücke *et al.*<sup>275</sup> have given further insight into the processes and mechanisms of short-range ordering in Au-Pd alloys. The picture of short-range ordering derived from these studies and ones mentioned earlier is as follows. Above a certain high temperature, short-range ordering does not occur. Below this temperature, the degree of short-range order present at equilibrium increases with decreasing temperature. The formation of short-range order is dependent on the presence of crystal defects (such as vacancies, interstitials, etc.) which allow local atomic ordering via their migration through the crystal. Such defects may be produced by plastic deformation, quenching, or irradiation. Kim and Flanagan studied the formation of short-range ordering via defects produced by cold-working while Lücke and co-workers primarily studied ordering via defects produced by quenching. As discussed before, the cold-working of annealed specimens may destroy short-range order while at the same time introducing defects which, upon subsequent annealing, may allow the formation of a greater degree of short-range order than was originally present in the annealed specimen. Not only does the formation of short-range order depend on the presence of defects, but the rate of ordering depends on the concentration of defects. The rate of ordering tends to increase with increasing defect concentration and with increasing temperature. In addition, different types of defects may come into play in ordering at different temperatures. Kim and Flanagan, based upon their analysis of ordering rates, described distinct stages of ordering which differ according to the mechanism of ordering and the types of defects involved at different temperatures.

The final state of short-range order achieved at a given temperature may depend on the thermal history of the specimen. For example, Lücke *et al.*<sup>275</sup> found that equilibrium values of short-range order may be difficult to attain. At low temperatures, the rate of diffusion may be too slow to attain equilibrium. This difficulty may in part be overcome by quenching the specimen from high temperatures, where the vacancy concentration is high, prior to annealing at a lower temperature. The surplus concentration of vacancies frozen-

in by the quench then serves to enhance the rate of ordering. In other cases, the excess vacancies may be annealed out before the equilibrium degree of short-range order is attained. With the resultant negligible vacancy concentration, no further ordering can occur and the final degree of short-range order is less than the equilibrium value. A constant resistivity value is thus reached, but it is lower than the resistivity value characteristic of the equilibrium state of short-range order.

The effect of short-range ordering on the magnitude of the electrical resistivity can be sizeable. In their studies of the anomalous decrease in resistivity of annealed alloys upon deformation, Kim and Flanagan<sup>232</sup> found that short-range ordering, even when opposed by the effects of cold-work, may contribute as much as 3% to the electrical resistivity of 25 at.% Pd alloys, 5% to 40 at.% Pd alloys, and 2% to 65 at.% Pd alloys. Similarly, in their studies of the increase of resistivity upon annealing cold-worked specimens, Kim and Flanagan<sup>273</sup> found that short-range ordering may contribute as much as 4% or 5% to the electrical resistivity of 25, 30, and 40 at.% Pd alloys, even when opposed by the effect of the annealing out of crystal defects. Further information was contributed by Lücke *et al.*<sup>275</sup> who found that the electrical resistivities of specimens in different states of short-range order may differ by as much as 8% for 50 at.% Pd alloys and 1% for 10 at.% Pd alloys.

Lücke *et al.*<sup>275</sup> (Au + Pd data sets 42 and 43) also investigated the effects of short-range order of the temperature dependence of the electrical resistivity. Using specimens with 50 at.% Pd, they quenched from 1273 K and then annealed at 513 K for different times to establish different degrees of short-range order. The resistivities of the specimens with different degrees of order were then measured from 73 to 473 K. The results showed differences in the magnitude of the resistivity of up to 8% and differences in the temperature derivative of the resistivity (at 273 K) of up to about 3% for the different degrees of short-range order. Rowland *et al.*<sup>276</sup> (Au + Pd data sets 26–32, Pd + Au data sets 13–15, and Au–Pd data sets 13–28) speculated that a temperature dependence of short-range ordering might be a possible explanation of a very shallow minimum observed around 700 K for alloys with 30 to 60 at.% Pd).

The first step in the generation of recommended electrical resistivity values for this alloy system was the simultaneous examination of the residual resistivity ( $\rho_0$ ), the resistivity at 300 K ( $\rho_{300\text{K}}$ ), and the difference between the two, in a manner similar to that used in the analysis of the electrical resistivity of the Ag–Pd alloy system. Only three research documents have reported the residual resistivity of Au–Pd alloys over a wide range of compositions. One of the three documents, by Kim<sup>277</sup> (Au–Pd data set 34), was a thesis unavailable in its original form, so the data were extracted as reported by Kim and Flanagan<sup>278</sup> without specimen characterization or measurement information. Of the three, only Hau<sup>279</sup> (Au + Pd data sets 9–14, Pd + Au data sets 1–3, and Au–Pd data sets 4–6) and Rowland *et al.*<sup>276</sup> reported the resistivities at 4.2 K and near room temperature. The 1% inaccuracy in the measured resistivities, as reported by Hau, was about 4% better than the inaccuracy reported by Rowland *et al.*, whose measurement of the specimen dimensions

was uncertain. Consequently, the values of Hau were followed rather closely in generating recommended values for the residual resistivity.

The residual resistivities of Hau<sup>279</sup> (Au–Pd data set 4) and Rowland *et al.*<sup>276</sup> (Au–Pd data set 13) show reasonable agreement over much of the composition range, but the values of Rowland *et al.* are lower than those of Hau by as much as  $1.3 \times 10^{-8} \Omega\text{m}$  in the 35 to 55 at.% Pd range. As mentioned above, this is the region where short-range ordering is known to have its maximum effect on the resistivity, with greater degrees of short-range order producing greater residual resistivities. The immediate question of whether the discrepancy between the two sets of data is due to a difference in the degree of short-range order present in the respective specimens is difficult to answer conclusively with the known information. The heat treatment of the specimens of Rowland *et al.*, heating at 1073 K followed by slow cooling, could conceivably produce a significant degree of short-range order, as could the heat treatment of the specimens of Hau which consisted of heating at 973 K followed, presumably, by slow cooling. Unfortunately, Rowland *et al.* had insufficient knowledge of the structural details of their specimens to be certain of the degree of short-range ordering present and Hau reported that short-range order could not be detected in his experiment. Comparison of the data of Hau with the room-temperature resistivities reported by Köster and Halpern<sup>271</sup> (Au–Pd data sets 1–3) and Lücke *et al.*<sup>275</sup> (Au + Pd data sets 42–43) for alloys with 40 and 50 at.% Pd show that the resistivities reported by Hau are in all cases lower than the resistivities reported by the other authors. Since the specimens of Köster and Halpern and of Lücke *et al.* were known to possess some degree of short-range order, this information is consistent with the conclusion that the specimens of Hau possessed less short-range ordering than even the least specimens of these other authors. However, the explanation of the discrepancy between the residual resistivity data of Rowland *et al.* and of Hau is still unclear.

The discrepancy between the residual resistivity data of Hau and of Rowland *et al.* raises immediate problems for the generation of recommended values of the electrical resistivity at high temperatures. Rowland *et al.* are the only investigators to report resistivities at high temperatures for a wide range of compositions. Given the discrepancy in residual resistivities, the low temperature data of Hau, which were followed closely in generating recommended values, cannot simply or easily be joined with the higher temperature data of Rowland *et al.* This problem is diminished by an examination of  $(\rho_{300\text{K}} - \rho_0)$ , the temperature-dependent part of the resistivity at 300 K. While the residual resistivities of Hau and Rowland *et al.* differ by as much as  $1.3 \times 10^{-8} \Omega\text{m}$  in the 35 to 55 at.% Pd range, it was found that the temperature-dependent part of their resistivities differed by less than  $0.1 \times 10^{-8} \Omega\text{m}$  at 300 K in this composition range. Apparently, the difference in the specimens of Rowland *et al.* and Hau is such that only the residual resistivity is affected, and the temperature-dependent part of the resistivity remains largely unaffected. Thus, it becomes possible to synthesize the data of Rowland *et al.* and Hau if the analysis is carried out primarily in terms of the temperature-dependent part of the resistivity,  $(\rho - \rho_0)$ . This procedure assumes that any dif-

ferences in the degree of short-range order present in the two sets of specimens have negligible effect on the temperature-dependent parts of the resistivities at all temperatures.

Accordingly, the temperature-dependent part of the resistivity was separated out in all cases where  $\rho_0$  was reported by the authors. In some cases, the authors did not report the residual resistivity, but it still seemed reasonable to estimate  $\rho_0$  for the specimen by using the recommended residual resistivity for the composition in question. In one case, the authors reported the temperature-dependent part of the resistivity directly. Kim and Flanagan<sup>278</sup> reported thermal resistivities based on values of the residual resistivity which were obtained "by extrapolation to the temperature at which the resistivities of pure metals over the same temperature range extrapolate to zero," and not by direct measurement. Comparison of the extrapolations with direct measurements was not possible because neither the extrapolated values nor the total resistivities were reported. Although the gross features of the thermal resistivity as reported by Kim and Flanagan, Hau, and Rowland *et al.* are similar, the magnitudes of the data of Kim and Flanagan are sometimes inconsistent with the more complete data reported by others. Consequently, the temperature-dependent resistivity data reported by Kim and Flanagan were given little weight in the generation of recommended values.

Smoothed isotherms of the temperature-dependent resistivity as a function of composition were generated by a cross-plotting procedure involving successive smoothings of the temperature-dependent resistivity as a function of both temperature and composition. The final results for selected temperatures are shown in Fig. 36. For compositions from 0 to 17 at. % Pd, there is a gradual decrease in the temperature-dependent resistivity from its value for pure gold. This downward slope is supported at low temperatures by the data of Hau and, for dilute alloys up to 700 K by the data of Otter<sup>226</sup> (Au + Pd data sets 1-4). At high temperatures, the data of Rowland *et al.* also show a negative slope, but one of

less magnitude than shown in Fig. 37. This is because the final smoothed values of the temperature-dependent resistivity pass below the data of Rowland *et al.* for their 10.5 at. % Pd. These deviations are not inconsistent with an error in sample dimensions, which was suggested as possible by Rowland *et al.*, and result in deviations from the total resistivity reported by Rowland *et al.* which lie within their experimental inaccuracy of 5%. From a minimum at around 17 at. % Pd, the temperature-dependent resistivity at high temperatures rises to a maximum at about 40 at. % Pd, falls again to a minimum at about 50 at. % Pd, and then rises rapidly to the values for pure palladium.

The final total electrical resistivity values were obtained by adding the residual resistivities to the temperature-dependent resistivities for the selected compositions. The resulting recommended values for Au, Pd, and for 25 Au-Pd binary alloys are presented in Table 7 and shown in Figs. 32 and 33. The recommended values are also shown in Fig. 37 as a function of composition together with some experimental data. The divergence of the data of Rowland *et al.* from the recommended values results primarily from differences in the residual resistivity, as discussed above. The recommended values for Au and for Pd are for well-annealed, high-purity specimens, but those values for temperatures below about 100 K are applicable only to Au and Pd having residual electrical resistivities as given at 1 K in Table 7. The alloys for which the recommended values are generated have at most a low degree of short-range order and have not been quenched or cold-worked severely. The recommended values cover the temperature range from 1 to 1400 K and are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 7. A few of the values for dilute gold-rich alloys are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

TABLE 7. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-PALLADIUM ALLOY SYSTEM †  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Au: 100.00% (100.00 At.%) Pd: 0.00% (0.00 At.%)		Au: 99.50% (99.08 At.%) Pd: 0.50% (0.92 At.%)		Au: 99.00% (98.16 At.%) Pd: 1.00% (1.84 At.%)		Au: 97.00% (94.58 At.%) Pd: 3.00% (5.42 At.%)		Au: 95.00% (91.12 At.%) Pd: 5.00% (8.88 At.%)		Au: 90.00% (82.94 At.%) Pd: 10.00% (17.06 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.0220	1	0.35*	1	0.69*	1	2.02*	1	3.31	1	6.17*
4	0.0220	4	0.35	4	0.69	4	2.02	4	3.31	4	6.17
7	0.0221	7	0.35*	7	0.69*	7	2.02	7	3.31	7	6.17
10	0.0226	10	0.35*	10	0.69*	10	2.02	10	3.31	10	6.17
15	0.0258	15	0.35**	15	0.70**	15	2.03	15	3.32	15	6.17
20	0.0346†	20	0.36**	20	0.71**	20	2.04	20	3.33	20	6.18
25	0.0503†	25	0.37**	25	0.73**	25	2.05	25	3.34	25	6.19
30	0.0727†	30	0.40**	30	0.75**	30	2.07	30	3.36	30	6.21
40	0.141†	40	0.46**	40	0.80**	40	2.13	40	3.41	40	6.26
50	0.222	50	0.54**	50	0.88**	50	2.21	50	3.49	50	6.33
60	0.309	60	0.63**	60	0.97**	60	2.29	60	3.57	60	6.41
70	0.396	70	0.72**	70	1.05**	70	2.37	70	3.65	70	6.49
80	0.482	80	0.80†	80	1.14†	80	2.46	80	3.72	80	6.56
90	0.567	90	0.89†	90	1.23†	90	2.54	90	3.80	90	6.63
100	0.652	100	0.97†	100	1.31†	100	2.61	100	3.88	100	6.70
150	1.063	150	1.38	150	1.71	150	2.99	150	4.25	150	7.07
200	1.464	200	1.78	200	2.10	200	3.38	200	4.63	200	7.45
250	1.865	250	2.20	250	2.51	250	3.80	250	5.04	250	7.84
273	2.052	273	2.38	273	2.69	273	3.99	273	5.21	273	8.01
293	2.214	293	2.54	293	2.86	293	4.14	293	5.35	293	8.17
300	2.271	300	2.59	300	2.91	300	4.20	300	5.41	300	8.22
350	2.683	350	3.00	350	3.32	350	4.58	350	5.79	350	8.56
400	3.102	400	3.41	400	3.73	400	4.97	400	6.17	400	8.93
500	3.962	500	4.24	500	4.55	500	5.75	500	6.93	500	9.69
600	4.853	600	5.11	600	5.41	600	6.55	600	7.71	600	10.47
700	5.780	700	6.02	700	6.31	700	7.40	700	8.53	700	11.30
800	6.755	800	6.99*	800	7.25*	800	8.31*	800	9.43	800	12.19
900	7.787	900	8.01*	900	8.26*	900	9.29*	900	10.40	900	13.11
1000	8.884	1000	9.13*	1000	9.36*	1000	10.36*	1000	11.43	1000	14.08
1100	10.057	1100	10.28*	1100	10.52*	1100	11.51*	1100	12.53	1100	15.14
1200	11.312	1200	11.53*	1200	11.75*	1200	11.75*	1200	13.72	1200	16.31
1300	12.632	1300	12.83*	1300	13.07*	1300	13.07*	1300	14.99*	1300	17.58
1337.58	13.146(s)	1348	13.53*	1355	13.87*	1355	13.87*	1355	15.20*	1355	18.96
1338	31.08(t)										
1700	36.26										

† Uncertainties in the electrical resistivity values are as follows:

- 100.00 Au - 0.00 Pd:  $\pm 1\%$  up to 10 K,  $\pm 2.5\%$  above 10 K to 15 K,  $\pm 6\%$  above 15 K to 40 K,  $\pm 3\%$  above 40 K to 80 K,  $\pm 1\%$  above 80 K to 500 K, and  $\pm 2.5\%$  above 500 K.  
 99.50 Au - 0.50 Pd:  $\pm 5\%$  up to 10 K,  $\pm 9\%$  above 10 K to 100 K, and  $\pm 5\%$  above 100 K.  
 99.00 Au - 1.00 Pd:  $\pm 5\%$  up to 10 K,  $\pm 7\%$  above 10 K to 100 K, and  $\pm 5\%$  above 100 K.  
 97.00 Au - 3.00 Pd:  $\pm 5\%$   
 95.00 Au - 5.00 Pd:  $\pm 5\%$   
 90.00 Au - 10.00 Pd:  $\pm 4\%$

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 7. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-PALLADIUM ALLOY SYSTEM† (continued)

Au: 85.00% (75.38 At.%) Pd: 15.00% (24.62 At.%)		Au: 80.00% (68.36 At.%) Pd: 20.00% (31.64 At.%)		Au: 75.00% (61.84 At.%) Pd: 25.00% (38.16 At.%)		Au: 70.00% (55.76 At.%) Pd: 30.00% (44.24 At.%)		Au: 65.00% (50.08 At.%) Pd: 35.00% (49.92 At.%)		Au: 60.00% (44.76 At.%) Pd: 40.00% (55.24 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	8.57*	1	10.61*	1	12.49	1	15.68*	1	20.57*	1	23.54*
4	8.57*	4	10.61	4	12.49	4	15.68	4	20.57	4	23.54
7	8.57*	7	10.61	7	12.49	7	15.68	7	20.57	7	23.54
10	8.57*	10	10.62	10	12.49	10	15.68	10	20.57	10	23.54
15	8.58*	15	10.63	15	12.51	15	15.69	15	20.58	15	23.56
20	8.59*	20	10.64	20	12.53	20	15.70	20	20.60	20	23.58
25	8.61*	25	10.66	25	12.55	25	15.73	25	20.63	25	23.61
30	8.62*	30	10.68	30	12.57	30	15.76	30	20.67	30	23.65
40	8.67*	40	10.74	40	12.63	40	15.83	40	20.75	40	23.75
50	8.75*	50	10.82	50	12.73	50	15.93	50	20.85	50	23.88
60	8.83*	60	10.91	60	12.82	60	16.03	60	20.97	60	24.03
70	8.91*	70	10.99	70	12.92	70	16.14	70	21.10	70	24.19
80	8.99	80	11.07	80	13.00	80	16.24	80	21.22	80	24.34
90	9.06*	90	11.15	90	13.09	90	16.35	90	21.34	90	24.49
100	9.14*	100	11.23	100	13.19	100	16.44	100	21.45	100	24.64
150	9.52*	150	11.66	150	13.66	150	16.93	150	21.98	150	25.27
200	9.91*	200	12.11	200	14.14	200	17.44	200	22.54	200	25.84
250	10.31*	250	12.55	250	14.65	250	17.97	250	23.07	250	26.42
273	10.50*	273	12.75	273	14.89	273	18.23	273	23.32	273	26.70
293	10.66	293	12.93	293	15.09	293	18.46	293	23.53	293	26.94
300	10.72*	300	12.99	300	15.16	300	18.54	300	23.61	300	27.02
350	11.10*	350	13.45	350	15.73	350	19.10	350	24.14	350	27.63*
400	11.48*	400	13.93	400	16.29	400	19.67	400	24.67	400	28.23*
500	12.28*	500	14.91	500	17.43	500	20.83	500	25.73	500	29.38*
600	13.14*	600	15.91	600	18.61	600	21.92	600	26.74	600	30.41*
700	14.02*	700	16.90	700	19.77	700	22.92	700	27.61	700	31.31*
800	14.93*	800	17.87	800	20.85	800	23.84	800	28.38	800	32.17*
900	15.86*	900	18.87	900	21.88	900	24.75	900	29.17	900	33.05*
1000	16.85*	1000	19.94	1000	22.96	1000	25.69	1000	30.08	1000	34.01*
1100	17.96*	1100	21.12	1100	24.13	1100	26.72	1100	31.13	1100	35.06*
1200	19.19*	1200	22.39	1200	25.38	1200	27.89	1200	32.31	1200	36.20*
1300	20.51*	1300	23.71	1300	26.67	1300	29.16	1300	33.57	1300	37.43*
1400	21.88*	1400	25.02	1400	28.00	1400	30.49	1400	34.84	1400	38.72*

† Uncertainties in the electrical resistivity data are as follows:

85.00 Au - 15.00 Pd:  $\pm 3\%$  up to 400 K and  $\pm 4\%$  above 400 K.80.00 Au - 20.00 Pd:  $\pm 5\%$ 75.00 Au - 25.00 Pd:  $\pm 4\%$ 70.00 Au - 30.00 Pd:  $\pm 5\%$ 65.00 Au - 35.00 Pd:  $\pm 5\%$ 60.00 Au - 40.00 Pd:  $\pm 3\%$  up to 400 K and  $\pm 4\%$  above 400 K.

\* In temperature range where no experimental data are available.



TABLE 7. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-PALLADIUM ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Au: 55.00% (39.77 At.%) Pd: 45.00% (60.23 At.%)		Au: 50.00% (35.07 At.%) Pd: 50.00% (64.93 At.%)		Au: 45.00% (30.65 At.%) Pd: 55.00% (69.35 At.%)		Au: 40.00% (26.43 At.%) Pd: 60.00% (73.57 At.%)		Au: 35.00% (22.53 At.%) Pd: 65.00% (77.47 At.%)		Au: 30.00% (18.80 At.%) Pd: 70.00% (81.20 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	23.18*	1	21.50*	1	19.57*	1	17.41*	1	15.03*	1	12.59*
4	23.18	4	21.50	4	19.57	4	17.41*	4	15.03*	4	12.59
7	23.18	7	21.50	7	19.57	7	17.41*	7	15.03*	7	12.59
10	23.18	10	21.50	10	19.57	10	17.41*	10	15.03*	10	12.59
15	23.19	15	21.51	15	19.59	15	17.42*	15	15.06*	15	12.61
20	23.21	20	21.53	20	19.63	20	17.45*	20	15.09*	20	12.65
25	23.25	25	21.57	25	19.67	25	17.49*	25	15.13*	25	12.69
30	23.30	30	21.62	30	19.72	30	17.54*	30	15.19*	30	12.75
40	23.41	40	21.75	40	19.84	40	17.70*	40	15.34*	40	12.93
50	23.56	50	21.92	50	20.03	50	17.91*	50	15.57*	50	13.18
60	23.74	60	22.13	60	20.27	60	18.17*	60	15.86*	60	13.48
70	23.94	70	22.37	70	20.54	70	18.47*	70	16.19*	70	13.84
80	24.14	80	22.60	80	20.81	80	18.77	80	16.52*	80	14.21
90	24.34	90	22.85	90	21.09	90	19.09	90	16.87*	90	14.58
100	24.54	100	23.09	100	21.36	100	19.40	100	17.21*	100	14.94
150	25.49	150	24.32	150	22.75	150	20.94	150	18.89*	150	16.74
200	26.41	200	25.55	200	24.14	200	22.47	200	20.51*	200	18.45
250	27.24	250	26.74	250	25.49	250	23.98	250	22.08*	250	20.07
273	27.61	273	27.23	273	26.10	273	24.65	273	22.81*	273	20.82
293	27.93	293	27.63	293	26.61	293	25.23	293	23.44*	293	21.49
300	28.04	300	27.76	300	26.79	300	25.42	300	23.66*	300	21.72
350	28.75	350	28.64*	350	27.91	350	26.74	350	25.15*	350	23.35
400	29.41	400	29.42*	400	28.90	400	27.95	400	26.56*	400	24.92
500	30.62	500	30.81*	500	30.63	500	30.08	500	29.09*	500	27.79
600	31.76	600	32.12*	600	32.16	600	31.94	600	31.30*	600	30.32
700	32.84	700	33.38*	700	33.59	700	33.64	700	33.28*	700	32.58
800	33.88	800	34.59*	800	34.95	800	35.19	800	35.06*	800	34.60
900	35.88	900	35.74*	900	36.25	900	36.62	900	36.67*	900	36.45
1000	35.88	1000	36.83*	1000	37.46	1000	37.94	1000	38.19*	1000	38.22
1100	36.91	1100	37.90*	1100	38.63	1100	39.22	1100	39.67*	1100	39.96
1200	38.00	1200	39.01*	1200	39.81	1200	40.49	1200	41.12*	1200	41.65
1300	38.16	1300	40.16*	1300	41.01	1300	41.75*	1300	42.53*	1300	43.22
1400	41.40	1400	41.31*	1400	42.15	1400	43.10*	1400	43.88*	1400	44.63

† Uncertainties in the electrical resistivity data are as follows:

- 55.00 Au - 45.00 Pd:  $\pm 2\%$  up to 600 K and  $\pm 3\%$  above 600 K.
- 50.00 Au - 50.00 Pd:  $\pm 2\%$
- 45.00 Au - 55.00 Pd:  $\pm 2\%$
- 40.00 Au - 60.00 Pd:  $\pm 2\%$
- 35.00 Au - 65.00 Pd:  $\pm 2\%$
- 30.00 Au - 70.00 Pd:  $\pm 3\%$

\* In temperature range where no experimental data are available.

TABLE 7. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-PALLADIUM ALLOY SYSTEM† (continued)

(Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ )

Au: 25.00% (15.26 At.%) Pd: 75.00% (84.74 At.%)		Au: 20.00% (11.90 At.%) Pd: 80.00% (88.10 At.%)		Au: 15.00% (8.70 At.%) Pd: 85.00% (91.30 At.%)		Au: 10.00% (5.66 At.%) Pd: 90.00% (94.34 At.%)		Au: 5.00% (2.76 At.%) Pd: 95.00% (97.24 At.%)		Au: 3.00% (1.64 At.%) Pd: 97.00% (98.36 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	10.23*	1	7.97*	1	5.83*	1	3.79*	1	1.85*	1	1.10*
4	10.22	4	7.97*	4	5.83	4	3.79	4	1.85*	4	1.10
7	10.23	7	7.97*	7	5.83	7	3.79	7	1.85*	7	1.10*
10	10.24	10	7.97*	10	5.85	10	3.80	10	1.86*	10	1.10*
15	10.26	15	8.00*	15	5.87	15	3.83	15	1.88*	15	1.12*
20	10.30	20	8.04*	20	5.91	20	3.87	20	1.93*	20	1.15*
25	10.34	25	8.09*	25	5.96	25	3.92	25	1.98*	25	1.20*
30	10.40	30	8.15*	30	6.03	30	4.00	30	2.05*	30	1.26*
40	10.58	40	8.35*	40	6.22*	40	4.18	40	2.23*	40	1.46*
50	10.84	50	8.62*	50	6.49	50	4.46	50	2.50*	50	1.73*
60	11.16	60	8.95*	60	6.84	60	4.82	60	2.85*	60	2.08*
70	11.54	70	9.34*	70	7.24	70	5.22	70	3.28*	70	2.48*
80	11.94	80	9.76*	80	7.66	80	5.65	80	3.69*	80	2.92*
90	12.34	90	10.19*	90	8.11	90	6.09	90	4.12*	90	3.34*
100	12.72	100	10.60*	100	8.54	100	6.54	100	4.58*	100	3.80*
150	14.62	150	12.61*	150	10.65	150	8.68	150	6.72*	150	5.94*
200	16.42	200	14.45*	200	12.56	200	10.65	200	8.75*	200	7.98*
250	18.10	250	16.15*	250	14.30	250	12.45	250	10.65*	250	9.89*
273	18.86	273	16.82	273	15.08	273	13.25	273	11.49*	273	10.75
293	19.53	293	17.60	293	15.77	293	13.95	293	12.21	293	11.51
300	19.77	300	17.85	300	16.01	300	14.20*	300	12.46*	300	11.77*
350	21.51	350	19.64*	350	17.80	350	16.00*	350	14.24*	350	13.67*
400	23.19	400	21.41*	400	19.61	400	17.81*	400	16.07*	400	15.49*
500	26.27	500	24.72*	500	23.05	500	21.31*	500	19.58*	500	18.93*
600	29.08	600	27.72*	600	26.18	600	24.52*	600	22.84*	600	22.14*
700	31.60	700	30.42*	700	28.99	700	27.43*	700	25.82*	700	25.12*
800	33.86	800	32.85*	800	31.56	800	30.09*	800	28.54*	800	27.87*
900	35.94	900	35.12*	900	33.95	900	32.56*	900	31.07*	900	30.43*
1000	37.97	1000	37.31*	1000	36.24	1000	34.88*	1000	33.43*	1000	32.83*
1100	39.95	1100	39.40*	1100	38.41	1100	37.05*	1100	35.64*	1100	35.06*
1200	41.78	1200	41.82*	1200	40.39	1200	39.05*	1200	37.68*	1200	37.12*
1300	43.42	1300	43.02*	1300	42.14	1300	40.85*	1300	39.52*	1300	38.98*
1400	44.89	1400	44.51*	1400	43.65	1400	42.44*	1400	41.15*	1400	40.60*

† Uncertainties in the electrical resistivity values are as follows:

- 25.00 Au - 75.00 Pd:  $\pm 3\%$
- 20.00 Au - 80.00 Pd:  $\pm 4\%$  up to 100 K and  $\pm 2\%$  above 100 K,
- 15.00 Au - 85.00 Pd:  $\pm 4\%$  up to 100 K and  $\pm 2\%$  above 100 K,
- 10.00 Au - 90.00 Pd:  $\pm 4\%$  up to 100 K and  $\pm 2\%$  above 100 K,
- 5.00 Au - 95.00 Pd:  $\pm 3\%$  up to 10 K,  $\pm 4\%$  above 10 K to 100 K, and  $\pm 2\%$  above 100 K,
- 3.00 Au - 97.00 Pd:  $\pm 3\%$  up to 10 K,  $\pm 5\%$  above 10 K to 100 K, and  $\pm 2\%$  above 100 K.

\* In temperature range where no experimental data are available.

TABLE 7. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-PALLADIUM ALLOY SYSTEM† (continued)

(Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ )

Au: 1.00% (0.54 At.%) Pd: 99.00% (99.46 At.%)		Au: 0.50% (0.27 At.%) Pd: 99.50% (99.73 At.%)		Au: 0.00% (0.00 At.%) Pd: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	0.36*	1	0.18*	1	0.0200
4	0.36	4	0.18	4	0.0205
7	0.36*	7	0.18*	7	0.0217
10	0.36*	10	0.18*	10	0.0242
15	0.37*	15	0.21*	15	0.0346
20	0.41*	20	0.24*	20	0.0564
25	0.46*	25	0.29*	25	0.0938
30	0.52*	30	0.35*	30	0.151
40	0.70*	40	0.51*	40	0.335
50	0.96*	50	0.78*	50	0.607
60	1.30*	60	1.11*	60	0.940
70	1.70*	70	1.50*	70	1.32
80	2.13*	80	1.93*	80	1.75
90	2.56*	90	2.36*	90	2.19
100	3.01*	100	2.81*	100	2.63
150	5.17*	150	4.98*	150	4.81
200	7.20*	200	7.02*	200	6.89
250	9.17*	250	9.00*	250	8.88
273	10.07	273	9.89	273	9.78
293	10.85*	293	10.67*	293	10.54
300	11.12*	300	10.93*	300	10.80
350	12.99*	350	12.78*	350	12.66
400	14.80*	400	14.59*	400	14.46
500	18.22*	500	18.06*	500	17.89
600	21.43*	600	21.26*	600	21.10
700	24.42*	700	24.25*	700	24.10
800	27.21*	800	27.04*	800	26.89
900	29.79*	900	29.64*	900	29.50
1000	32.19*	1000	32.04*	1000	31.92
1100	34.43*	1100	34.27*	1200	36.21
1200	36.49*	1200	36.34*	1400	39.80
1300	38.37*	1300	38.22*	1600	42.70
1400	40.04*	1400	39.91*	1827	45.14( $\epsilon$ )
				1830	83.0( $t$ )
				2000	83.0

† Uncertainties in the electrical resistivity values are as follows:

1.00 Au - 99.00 Pd:  $\pm 3\%$  up to 10 K,  $\pm 5\%$  above 10 K to 100 K, and  $\pm 2\%$  above 100 K.0.50 Au - 99.50 Pd:  $\pm 3\%$  up to 10 K,  $\pm 5\%$  above 10 K to 100 K, and  $\pm 2\%$  above 100 K.0.00 Au - 100.00 Pd:  $\pm 2\%$  up to 40 K,  $\pm 1\%$  above 40 K to 350 K,  $\pm 2\%$  above 350 K to 1600 K,  $\pm 2.5\%$  above 1600 K to 1827 K, and  $\pm 9\%$  above 1827 K.

\* In temperature range where no experimental data are available.

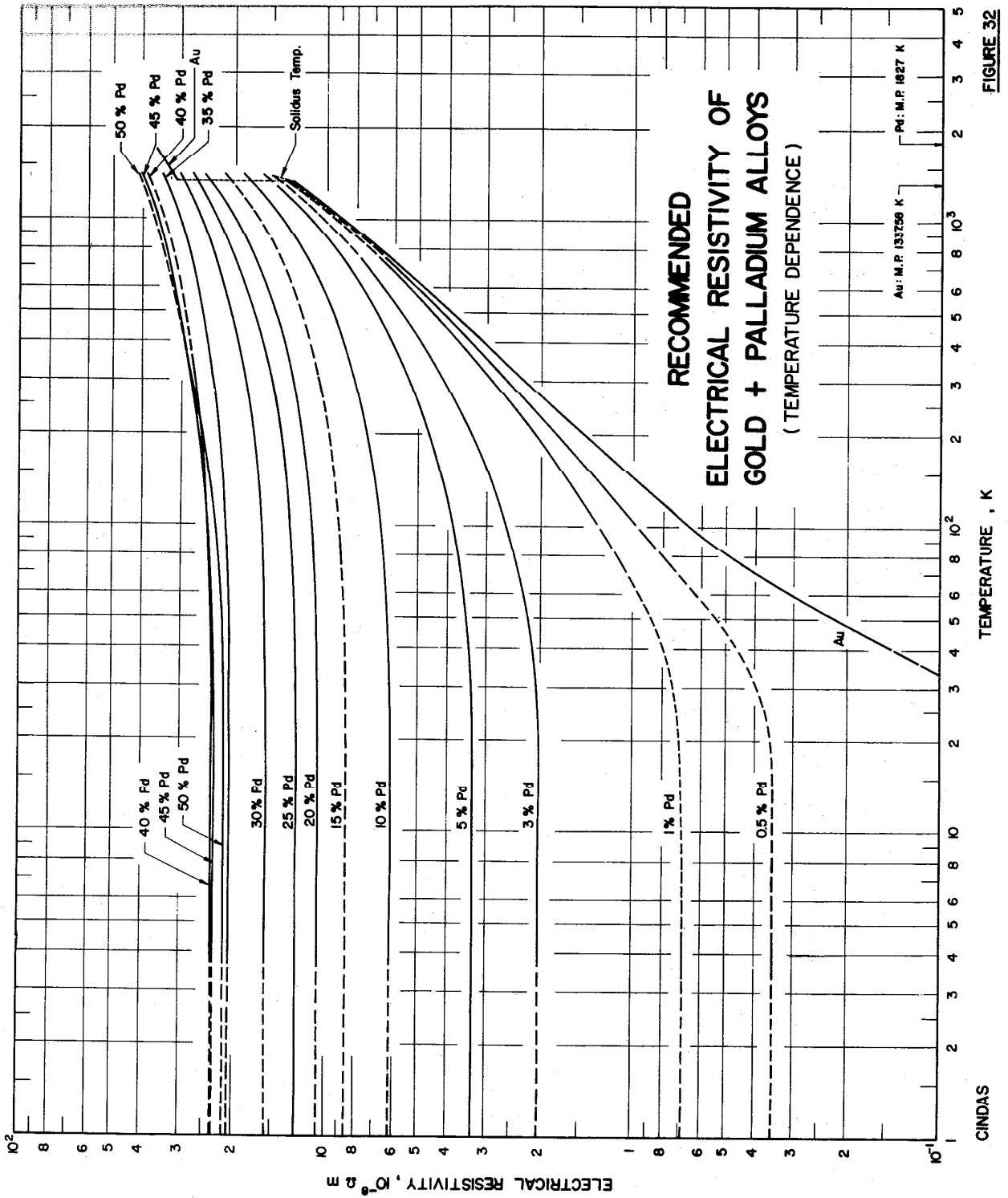


FIGURE 32

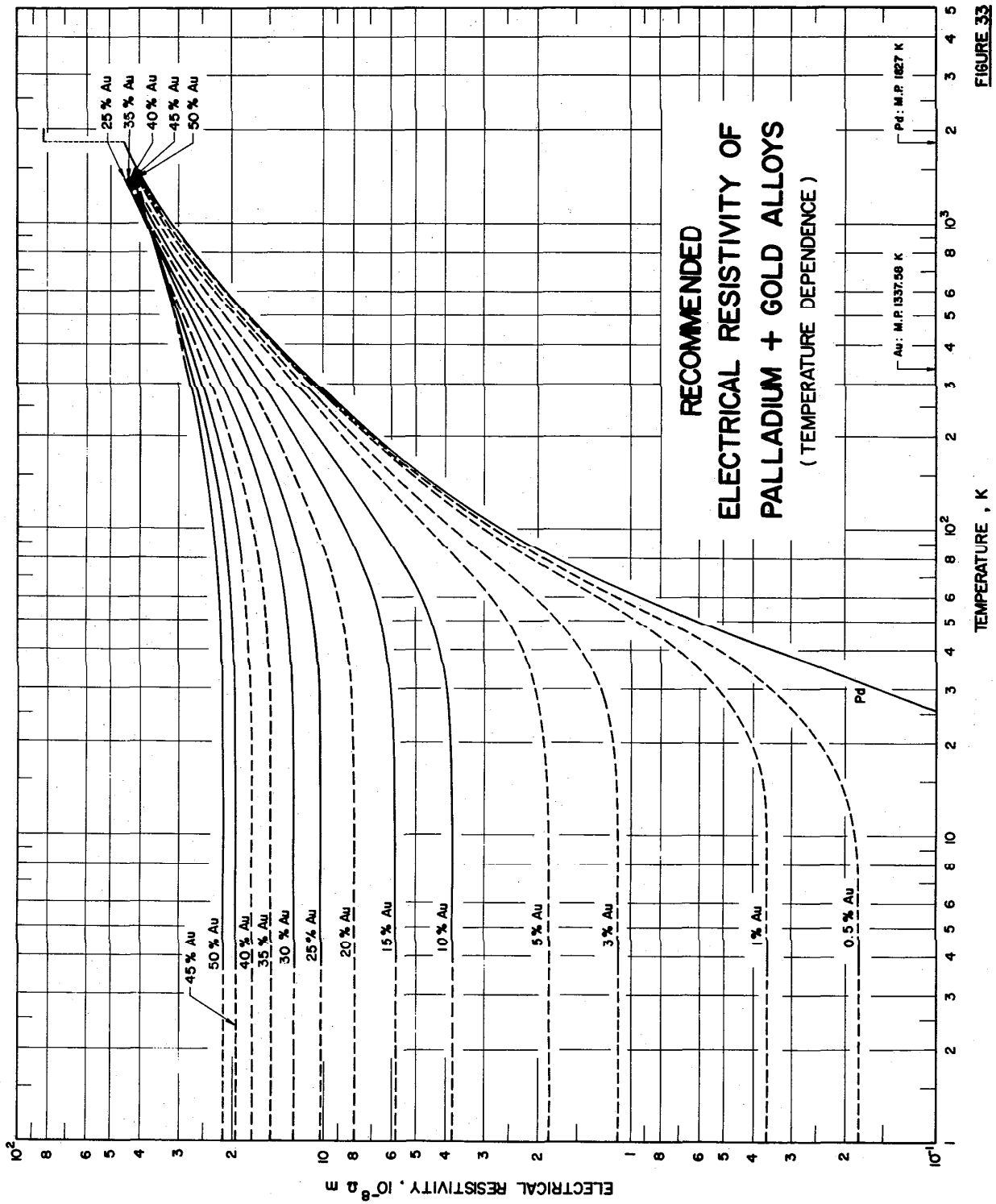


FIGURE 33

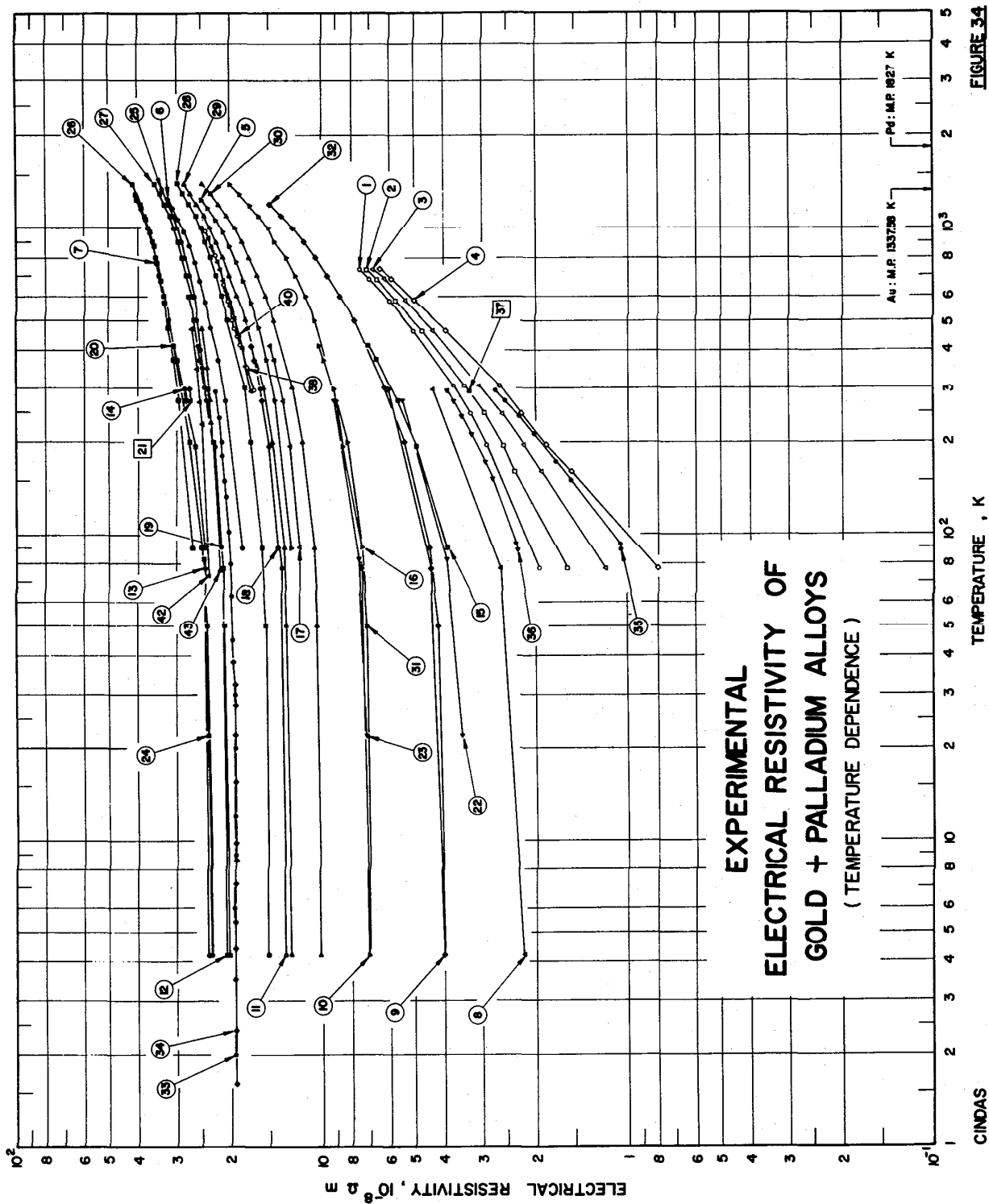
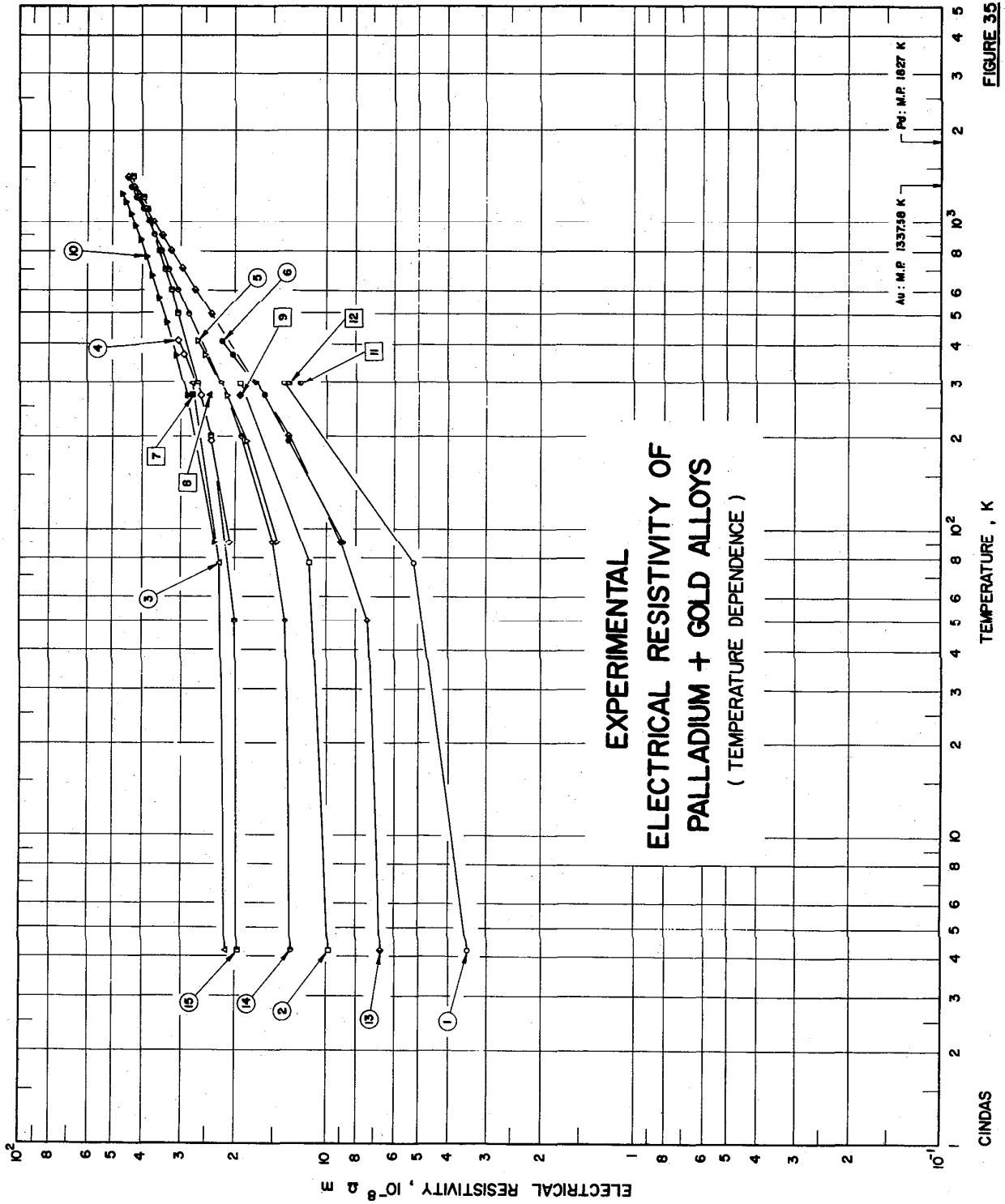
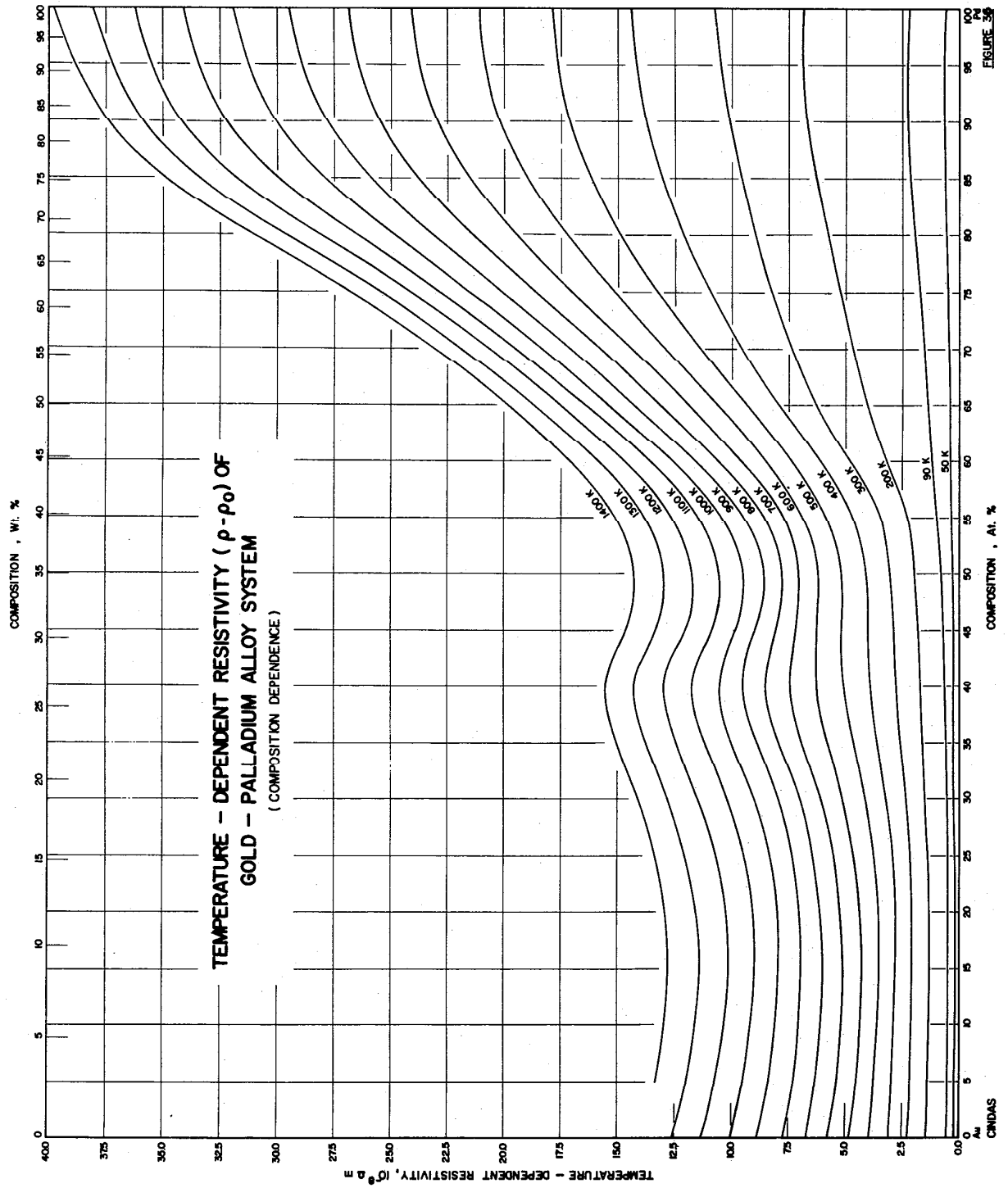


FIGURE 34







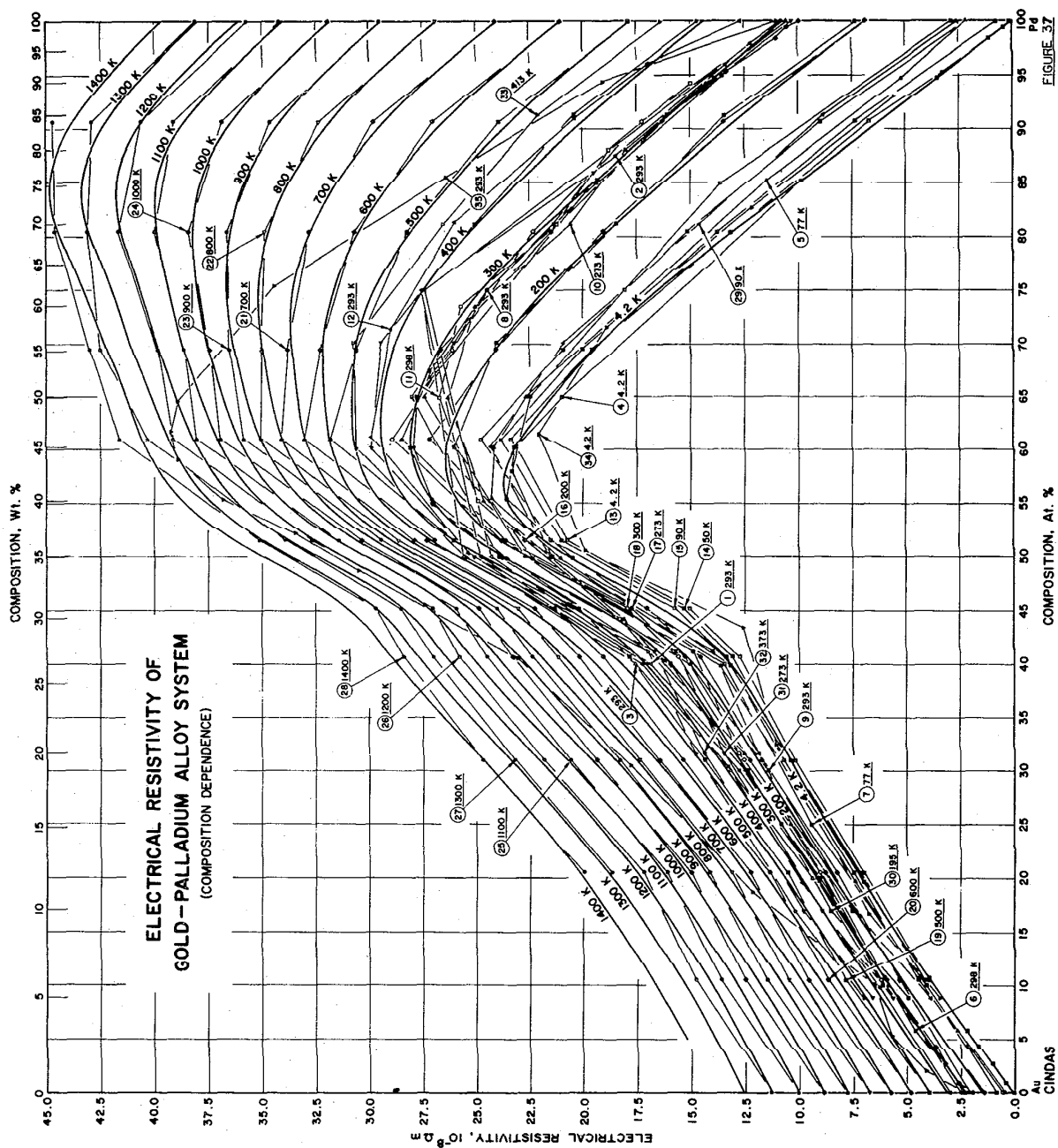


FIGURE 37

### 3.8. Gold–Silver Alloy System

Most of the evidence<sup>264,289</sup> indicates that the gold–silver alloy system forms a continuous series of solid solutions. Grum–Grzhimailo<sup>290</sup> has reported measurements on the electrical resistance, Hall effect, and lattice parameter which indicate the formation of intermetallic compounds  $\text{Ag}_3\text{Au}$ ,  $\text{Ag}_3\text{Au}_3$ , and  $\text{AgAu}_3$ , but this work has been discounted in the present analysis.

The existence of short-range ordering in the gold–silver alloy system is well recognized, though the mechanism of the ordering process and the effects of short-range order on the resistivity are disputed. Lücke and co-workers<sup>291–293,275</sup> have performed isothermal and isochronal annealing investigations of a wide range of silver–gold alloys and have concluded that an increase in the degree of short-range order is associated with an increase in the electrical resistivity and that the short-range order is of the conventional type described by Cowley.<sup>294</sup> On the contrary, Schüle and co-workers<sup>295,296</sup> have reported measurements on specimens very nearly identical with those of Lücke *et al.* which indicate that an increase in the degree of short-range order is associated with a decrease in the electrical resistivity under certain conditions and that the formation of short-range order proceeds in a nonhomogeneous manner via the growth of localized regions of high order, the boundaries of which can cause additional electron scattering and the consequent resistivity increase observed by Lücke *et al.* The change in the resistivity of quenched gold–silver alloy specimens upon annealing and the formation of short-range order can be as much as 2%.

There are 183 sets of experimental data available for the electrical resistivity of this alloy system, with 17 sets being single data points. These data sets are listed in Tables S-43, S-45, and S-47 which provide information on specimen characterization and measurement conditions, tabulated in Tables S-44, S-46, and S-48, and shown partially in Figs. 40, 41, and 42. In order to show both functional dependences of the electrical resistivity, a few of the data sets have been presented in the tables and figures both for temperature dependence and for composition dependence.

In the analysis and synthesis of experimental data to generate recommended values, the dependence of residual resistivity on alloy composition was determined using the abundant data from measurements at 4.2 K and below. A curve representing the totality of the data was tested and smoothed by examination of second differences. It shows a region of relatively low curvature for atomic fraction  $c$  of silver between 0.65 and 0.85 (between 65 and 85 at. % Ag); the reality of this feature seems to be supported by analysis of the alloy resistivities at higher temperatures.

The analysis of alloy resistivity was based on a study of the quantity  $\Delta(c, T)$ , as given by Eq. (26), derived from total resistivity values by subtracting from them the residual resistivity for the given  $c$  and the atomic-fraction-weighted average of the pure metal resistivities for the given  $T$ . The quantity  $\Delta$  is only a few percent of the total resistivity, and varies smoothly with  $c$  except for very dilute alloys. The analysis is described in some detail in Appendix 5.1; here a very few comments will suffice.

Examination of  $\Delta$  values makes very evident the presence of relatively large and erratic errors in much of the older data, probably due to inadequate control of the composition and purity of the alloy samples. The analysis began with a study of the data for  $T < 300$  K obtained using samples for which the resistivity was also measured at 4.2 K or below, since knowledge of the latter quantity helped to eliminate or diminish several sources of error. The data of Giauque and Stout<sup>297</sup> (Au + Ag data sets 23–26, Ag + Au data sets 21, 22, and Au–Ag data sets 16–20), Crisp and Rungis<sup>298</sup> (Au + Ag data sets 38–44, Ag + Au data sets 30–39, and Au + Ag data sets 9, 10), Davis and Rayne<sup>299</sup> (Au + Ag data sets 51–57, Ag + Au data sets 48–51, and Au–Ag data sets 11–13), Bocs *et al.*<sup>300</sup> (Au + Ag data sets 6–11, Ag + Au data sets 5–10, and Au–Ag data sets 2, 3), and Huray *et al.*<sup>135</sup> (Au + Ag data sets 45, 46, and Ag + Au data sets 40, 41) were plotted and cross-plotted to arrive at acceptable smoothed values of  $\Delta$  and  $\Delta/T$  from 100 to 300 K. The values of  $\Delta$  could be extrapolated to lower temperatures and to more dilute alloys guided by values derived from the data of Stewart and Huebener<sup>301</sup> (Au + Ag data sets 58–60 and Au–Ag data set 14) and of Dugdale and Basinski<sup>29</sup> (Au + Ag data set 15), who studied deviations from Matthiessen's Rule in alloys with less than 1 at. % solute. The analysis was then extended to higher temperatures by using the data of Iyer and Asimow<sup>302</sup> (Au + Ag data sets 2–5, Ag + Au data sets 11–13, and Au–Ag data set 46) on alloys with 5, 10, 30, 50, 70, 90 and 95 at. % silver. These data were smoothed and then partially corrected for errors that have a systematic effect on a plot of  $\Delta$  against  $T$  for a single sample (errors in solute concentration, in sample dimensions, and in the residual resistivity curve) by comparison with the more accurate low-temperature data. The reasonableness of the corrections was checked, and the values were interpolated and extrapolated to other solute concentrations by use of cross-plots. Finally, the recommended values of the resistivity were derived from the values of  $\Delta$ ,  $\rho_0$ , and the pure-metal resistivities.

The most reliable results were obtained for concentrated alloys (20 to 80 at. % solute), for which extrapolation of  $\Delta$  to low temperature and of  $\Delta/T$  to high temperatures was most reliable. At low temperatures and low solute concentrations the uncertainty (in percent) rises along with the estimated uncertainty in the residual resistance. At high temperatures and low solute concentrations the uncertainty in the extrapolation of  $\Delta$  combines with the uncertainty in the resistivity of the pure metals to produce the estimated  $\pm 4\%$  uncertainty in the result. It is unfortunate that there seem to be no resistivity data on Ag–Au alloys with less than 5 at. % of solute, for  $T > 400$  K.

The resulting recommended electrical resistivity values for Au, Ag, and for 25 Au–Ag binary alloys are presented in Table 8 and shown in Figs. 38, 39, and 42. The recommended values for Au and for Ag are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Au and Ag having residual electrical resistivities as given at 1 K in Table 8. As discussed in the beginning of this section, the electrical resistivity of Au–Ag alloys can be varied by changes in their short-range order produced by thermal treatment. This can amount to as

TABLE 8. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-SILVER ALLOY SYSTEM†  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Au: 100.00% (100.00 At.%) Ag: 0.00% ( 0.00 At.%)		Au: 99.50% (99.09 At.%) Ag: 0.50% ( 0.91 At.%)		Au: 99.00% (98.19 At.%) Ag: 1.00% ( 1.81 At.%)		Au: 97.00% (94.65 At.%) Ag: 3.00% ( 5.35 At.%)		Au: 95.00% (91.23 At.%) Ag: 5.00% ( 8.77 At.%)		Au: 90.00% (83.13 At.%) Ag: 10.00% (16.87 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.0220	1	0.272*	1	0.536*	1	1.55*	1	2.47*	1	4.48*
4	0.0220	4	0.272	4	0.536	4	1.55	4	2.47	4	4.48
7	0.0221	7	0.272*	7	0.537	7	1.55	7	2.48	7	4.48
10	0.0226	10	0.274*	10	0.539	10	1.55	10	2.48	10	4.49
15	0.0258	15	0.280*	15	0.545	15	1.55	15	2.48	15	4.49
20	0.0346†	20	0.292	20	0.557	20	1.57	20	2.50	20	4.50
25	0.0503†	25	0.312	25	0.577	25	1.59	25	2.52	25	4.52
30	0.0727†	30	0.340	30	0.606	30	1.61	30	2.54	30	4.55
40	0.141†	40	0.414	40	0.681	40	1.69	40	2.62	40	4.62
50	0.222	50	0.498	50	0.766	50	1.78	50	2.70	50	4.71
60	0.309	60	0.583	60	0.855	60	1.87	60	2.80	60	4.80
70	0.396	70	0.669	70	0.944	70	1.96	70	2.89	70	4.89
80	0.482	80	0.754	80	1.03	80	2.05	80	2.98	80	4.98
90	0.567	90	0.838	90	1.12	90	2.14	90	3.07	90	5.07
100	0.652	100	0.921	100	1.20	100	2.23	100	3.16	100	5.16
150	1.063	150	1.33	150	1.61	150	2.66	150	3.60	150	5.59
200	1.464	200	1.73	200	2.00	200	3.07	200	4.00	200	5.99
250	1.865	250	2.13	250	2.40	250	3.46	250	4.40	250	6.39
273	2.052	273	2.31	273	2.58	273	3.64	273	4.58	273	6.57
293	2.214	293	2.47	293	2.75	293	3.80	293	4.74	293	6.73
300	2.271	300	2.53*	300	2.80*	300	3.86	300	4.79	300	6.78
350	2.683	350	2.94*	350	3.22*	350	4.26	350	5.19	350	7.19
400	3.102	400	3.36*	400	3.63*	400	4.66	400	5.59	400	7.58
500	3.962	500	4.21*	500	4.47*	500	5.48	500	6.40	500	8.39
600	4.853	600	5.08*	600	5.33*	600	6.32	600	7.25	600	9.23
700	5.780	700	5.99*	700	6.23*	700	7.20	700	8.14	700	10.12
800	6.755	800	6.94*	800	7.16*	800	8.13	800	9.09	800	11.06
900	7.787	900	7.95*	900	8.16*	900	9.13	900	10.09	900	12.05
1000	8.884	1000	9.04*	1000	9.24*	1000	10.20	1000	11.16	1000	13.10
1100	10.057	1100	10.19*	1100	10.39*	1100	11.33*	1100	12.30	1100	14.22
1200	11.312	1200	11.43*	1200	11.61*	1200	12.55*	1200	13.52	1200	15.42
1300	12.632										
1337.58	13.146 (s)										
1338	31.08 (t)										
1700	35.26										

† Uncertainties in the electrical resistivity values are as follows:

100.00 Au - 0.00 Ag:  $\pm 1\%$  up to 10 K,  $\pm 2.5\%$  above 10 K to 15 K,  $\pm 6\%$  above 15 K to 40 K,  $\pm 3\%$  above 40 K to 80 K,  $\pm 1\%$  above 80 K to 500 K, and  $\pm 2.5\%$  above 500 K.  
 99.50 Au - 0.50 Ag:  $\pm 4\%$  below 80 K,  $\pm 3\%$  from 80 to 600 K, and  $\pm 4\%$  above 600 K.  
 99.00 Au - 1.00 Ag:  $\pm 4\%$  below 80 K,  $\pm 3\%$  from 80 to 600 K, and  $\pm 4\%$  above 600 K.  
 97.00 Au - 3.00 Ag:  $\pm 4\%$  below 80 K,  $\pm 3\%$  from 80 to 600 K, and  $\pm 2\%$  above 600 K.  
 95.00 Au - 5.00 Ag:  $\pm 2\%$  up to 600 K and  $\pm 1\%$  above 600 K.  
 90.00 Au - 10.00 Ag:  $\pm 1\%$

‡ Provisional value.

\* In temperature range where no experimental data are available.

TABLE 8. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-SILVER ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Au: 85.00% (75.63 At.%) Ag: 15.00% (24.37 At.%)		Au: 80.00% (68.66 At.%) Ag: 20.00% (31.34 At.%)		Au: 75.00% (62.16 At.%) Ag: 25.00% (37.84 At.%)		Au: 70.00% (56.10 At.%) Ag: 30.00% (43.90 At.%)		Au: 65.00% (50.43 At.%) Ag: 35.00% (49.58 At.%)		Au: 60.00% (45.10 At.%) Ag: 40.00% (54.90 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	6.08*	1	7.30*	1	8.18*	1	8.73*	1	9.00*	1	9.01*
4	6.08	4	7.30	4	8.18	4	8.73*	4	9.00*	4	9.01*
7	6.08	7	7.30	7	8.18*	7	8.73*	7	9.00	7	9.01*
10	6.09	10	7.31	10	8.18*	10	8.73*	10	9.00	10	9.01*
15	6.09	15	7.31	15	8.18*	15	8.74*	15	9.00	15	9.02*
20	6.10	20	7.32	20	8.19*	20	8.75*	20	9.01	20	9.03*
25	6.12	25	7.34	25	8.21*	25	8.76*	25	9.03	25	9.04*
30	6.15	30	7.36	30	8.23*	30	8.78*	30	9.05	30	9.06*
40	6.22	40	7.43	40	8.30*	40	8.85*	40	9.11	40	9.12*
50	6.30	50	7.52	50	8.38*	50	8.93*	50	9.19	50	9.20*
60	6.39	60	7.60	60	8.47*	60	9.01*	60	9.28	60	9.28*
70	6.48	70	7.69	70	8.56*	70	9.10*	70	9.36	70	9.36*
80	6.57	80	7.78	80	8.64	80	9.19*	80	9.45	80	9.45*
90	6.66	90	7.87	90	8.73*	90	9.27*	90	9.53	90	9.53*
100	6.75	100	7.96	100	8.82*	100	9.36*	100	9.61	100	9.61*
150	7.17	150	8.37	150	9.23*	150	9.76*	150	10.01	150	10.01*
200	7.57	200	8.77	200	9.62*	200	10.15*	200	10.39	200	10.38*
250	7.96	250	9.16	250	10.00*	250	10.53*	250	10.77	250	10.75*
273	8.14	273	9.34	273	10.18	273	10.70	273	10.94	273	10.92
293	8.30	293	9.50	293	10.34*	293	10.86	293	11.09	293	11.07
300	8.36*	300	9.55	300	10.39*	300	10.91	300	11.14	300	11.12
350	8.75*	350	9.94	350	10.78	350	11.29	350	11.52	350	11.50
400	9.15*	400	10.33	400	11.17*	400	11.68*	400	11.90	400	11.87*
500	9.95*	500	11.13	500	11.95*	500	12.45*	500	12.67	500	12.62*
600	10.78*	600	11.95	600	12.76*	600	13.24*	600	13.44	600	13.39*
700	11.66*	700	12.81	700	13.60*	700	14.07*	700	14.26	700	14.19*
800	12.58*	800	13.71	800	14.49*	800	14.94*	800	15.11	800	15.02*
900	13.55*	900	14.67	900	15.42*	900	15.86*	900	16.01	900	15.90*
1000	14.58*	1000	15.68	1000	16.41*	1000	16.82*	1000	16.95	1000	16.82*
1100	15.68*	1100	16.76	1100	17.47*	1100	17.86*	1100	17.96	1100	17.81*
1200	16.86*	1200	17.90*	1200	18.59*	1200	18.96*	1200	19.04*	1200	18.86*

† Uncertainties in the electrical resistivity values are as follows:

- 85.00 Au - 15.00 Ag:  $\pm 1\%$ .
- 80.00 Au - 20.00 Ag:  $\pm 1\%$ .
- 75.00 Au - 25.00 Ag:  $\pm 1\%$ .
- 70.00 Au - 30.00 Ag:  $\pm 1\%$ .
- 65.00 Au - 35.00 Ag:  $\pm 1\%$ .
- 60.00 Au - 40.00 Ag:  $\pm 1\%$ .

\* In temperature range where no experimental data are available.

TABLE 8. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-SILVER ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Au: 55.00% (40.10 At. %) Ag: 45.00% (59.90 At. %)		Au: 50.00% (35.39 At. %) Ag: 50.00% (64.61 At. %)		Au: 45.00% (30.94 At. %) Ag: 55.00% (69.06 At. %)		Au: 40.00% (26.75 At. %) Ag: 60.00% (73.25 At. %)		Au: 35.00% (22.77 At. %) Ag: 65.00% (77.23 At. %)		Au: 30.00% (19.01 At. %) Ag: 70.00% (80.99 At. %)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	8.73*	1	8.37*	1	7.80*	1	7.13*	1	6.40*	1	5.61
4	8.79	4	8.37*	4	7.80	4	7.13	4	6.40*	4	5.61
7	8.79*	7	8.38*	7	7.80	7	7.14	7	6.40*	7	5.61
10	8.79*	10	8.38*	10	7.81	10	7.14	10	6.40*	10	5.61
15	8.80*	15	8.38*	15	7.81	15	7.14	15	6.41*	15	5.61
20	8.81*	20	8.39	20	7.82	20	7.15	20	6.41*	20	5.62
25	8.82*	25	8.40	25	7.83	25	7.16	25	6.43*	25	5.63
30	8.84*	30	8.42	30	7.85	30	7.18	30	6.44*	30	5.65
40	8.90*	40	8.48	40	7.91	40	7.24	40	6.50*	40	5.70
50	8.98*	50	8.55	50	7.98	50	7.30	50	6.56*	50	5.77
60	9.06*	60	8.63	60	8.06	60	7.38	60	6.64*	60	5.84
70	9.14*	70	8.72	70	8.14	70	7.46	70	6.72*	70	5.92
80	9.22	80	8.80	80	8.22	80	7.54	80	6.80*	80	5.99
90	9.31*	90	8.88	90	8.30	90	7.62	90	6.87*	90	6.07
100	9.39*	100	8.96	100	8.37	100	7.69	100	6.95*	100	6.15
150	9.77*	150	9.34	150	8.75	150	8.06	150	7.31*	150	6.50
200	10.14*	200	9.70	200	9.11	200	8.42	200	7.66*	200	6.85
250	10.51*	250	10.06	250	9.46	250	8.76	250	8.00*	250	7.18
273	10.68	273	10.23	273	9.62	273	8.92	273	8.16*	273	7.34
293	10.82	293	10.37	293	9.76	293	9.06	293	8.29	293	7.47
300	10.87	300	10.42	300	9.81	300	9.11	300	8.34	300	7.52
350	11.23	350	10.78	350	10.16	350	9.46*	350	8.68*	350	7.85
400	11.60*	400	11.14*	400	10.52	400	9.81*	400	9.03*	400	8.19*
500	12.34*	500	11.87*	500	11.24	500	10.52*	500	9.73*	500	8.88*
600	13.10*	600	12.62*	600	11.98	600	11.24*	600	10.44*	600	9.58*
700	13.89*	700	13.39*	700	12.74	700	11.99*	700	11.18*	700	10.30*
800	14.71*	800	14.20*	800	13.53	800	12.77*	800	11.94*	800	11.05*
900	15.57*	900	15.03*	900	14.35	900	13.57*	900	12.73*	900	11.85*
1000	16.47*	1000	15.91*	1000	15.21	1000	14.41*	1000	13.55*	1000	12.63*
1100	17.44*	1100	16.86*	1100	16.13	1100	15.31*	1100	14.42*	1100	13.48*
1200	18.47*	1200	17.86*	1200	17.10	1200	16.25*	1200	15.34*	1200	14.38*

† Uncertainties in the electrical resistivity values are as follows:

- 55.00 Au - 45.00 Ag:  $\pm 1\%$ ,
- 50.00 Au - 50.00 Ag:  $\pm 1\%$ ,
- 45.00 Au - 55.00 Ag:  $\pm 1\%$ ,
- 40.00 Au - 60.00 Ag:  $\pm 1\%$ ,
- 35.00 Au - 65.00 Ag:  $\pm 1\%$ ,
- 30.00 Au - 70.00 Ag:  $\pm 2\%$  up to 400 K and  $\pm 1\%$  above 400 K.

\* In temperature range where no experimental data are available.

TABLE 8. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-SILVER ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Au: 25.00% (15.44 At. %) Ag: 75.00% (84.56 At. %)		Au: 20.00% (12.04 At. %) Ag: 80.00% (87.96 At. %)		Au: 15.00% (8.81 At. %) Ag: 85.00% (91.19 At. %)		Au: 10.00% (5.74 At. %) Ag: 90.00% (94.26 At. %)		Au: 5.00% (2.80 At. %) Ag: 95.00% (97.20 At. %)		Au: 3.00% (1.67 At. %) Ag: 97.00% (98.33 At. %)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	4.75*	1	3.85*	1	2.90*	1	1.94*	1	0.964*	1	0.577*
4	4.75*	4	3.85	4	2.90	4	1.94	4	0.964	4	0.577
7	4.76*	7	3.85*	7	2.91	7	1.94*	7	0.965*	7	0.578
10	4.76*	10	3.85*	10	2.91	10	1.94*	10	0.966*	10	0.579
15	4.76*	15	3.86*	15	2.91	15	1.94*	15	0.970*	15	0.583
20	4.77*	20	3.86*	20	2.92	20	1.95*	20	0.976*	20	0.588
25	4.78*	25	3.87*	25	2.93	25	1.96*	25	0.985*	25	0.589
30	4.80*	30	3.89*	30	2.94	30	1.98*	30	1.00*	30	0.614
40	4.85*	40	3.94*	40	2.99	40	2.02*	40	1.05*	40	0.659
50	4.91*	50	4.00*	50	3.05	50	2.08*	50	1.11*	50	0.716
60	4.98*	60	4.07*	60	3.12	60	2.15*	60	1.17*	60	0.779
70	5.06*	70	4.15*	70	3.19	70	2.22*	70	1.24*	70	0.845
80	5.14	80	4.23*	80	3.27	80	2.29*	80	1.31*	80	0.911
90	5.21*	90	4.30*	90	3.34	90	2.37*	90	1.38*	90	0.977
100	5.29*	100	4.37*	100	3.42	100	2.44*	100	1.44	100	1.04
150	5.64*	150	4.72*	150	3.76	150	2.77*	150	1.76	150	1.35
200	5.98*	200	5.05*	200	4.08	200	3.09*	200	2.08	200	1.66
250	6.31*	250	5.37*	250	4.40	250	3.40*	250	2.38	250	1.96
273	6.46	273	5.52	273	4.55	273	3.54	273	2.52	273	2.08
293	6.59	293	5.65*	293	4.67	293	3.66	293	2.64*	293	2.20
300	6.63	300	5.70*	300	4.72	300	3.71	300	2.68*	300	2.24*
350	6.96	350	6.02*	350	5.03	350	4.00	350	2.96*	350	2.52*
400	7.30*	400	6.34*	400	5.34	400	4.31	400	3.25*	400	2.82*
500	7.97*	500	7.00*	500	5.99	500	4.93	500	3.86*	500	3.43*
600	8.66*	600	7.68*	600	6.65	600	5.57	600	4.49*	600	4.07*
700	9.37*	700	8.37*	700	7.32	700	6.24	700	5.15*	700	4.73*
800	10.10*	800	9.09*	800	8.02	800	6.93	800	5.83*	800	5.41*
900	10.85*	900	9.83*	900	8.74	900	7.64	900	6.54*	900	6.11*
1000	11.64*	1000	10.59*	1000	9.50	1000	8.39	1000	7.27*	1000	6.84*
1100	12.47*	1100	11.41*	1100	10.31	1100	9.19	1100	8.06*	1100	7.64*
1200	13.36*	1200	12.28*	1200	11.17*	1200	10.04*	1200	8.90*	1200	8.55*

† Uncertainties in the electrical resistivity values are as follows:

25.00 Au - 75.00 Ag:  $\pm 2\%$  up to 400 K and  $\pm 1\%$  above 400 K.20.00 Au - 80.00 Ag:  $\pm 2\%$ .15.00 Au - 85.00 Ag:  $\pm 2\%$ .10.00 Au - 90.00 Ag:  $\pm 3\%$  up to 200 K and  $\pm 2\%$  above 200 K.5.00 Au - 95.00 Ag:  $\pm 4\%$ .3.00 Au - 97.00 Ag:  $\pm 4\%$  up to 200 K and  $\pm 3\%$  above 200 K.

\* In temperature range where no experimental data are available.

TABLE 8. RECOMMENDED ELECTRICAL RESISTIVITY OF GOLD-SILVER ALLOY SYSTEM† (continued)

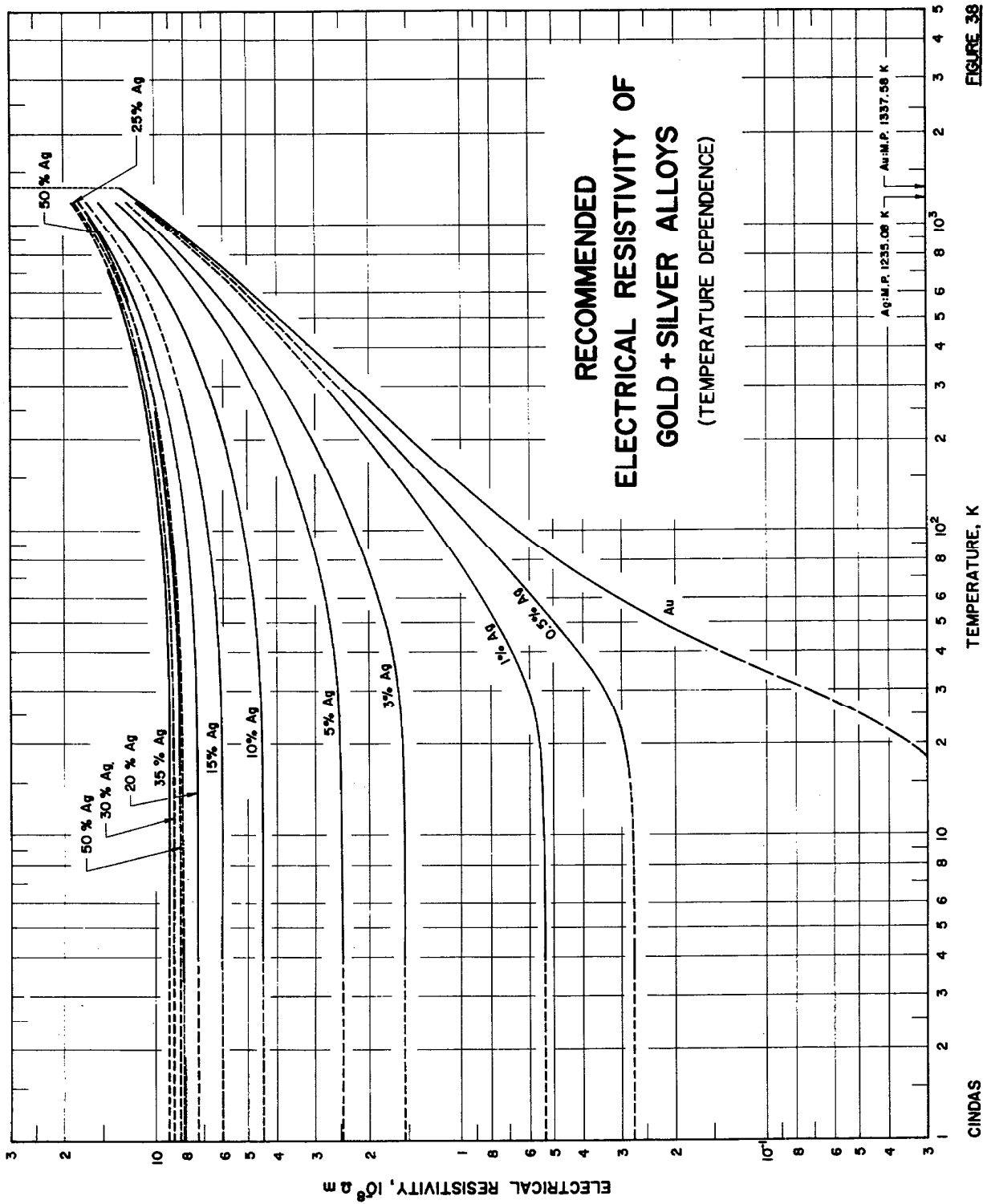
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-4} \Omega \text{ m}$ ]

Au: 1.00% (0.55 At.%) Ag: 99.00% (99.45 At.%)		Au: 0.50% (0.27 At.%) Ag: 99.50% (99.73 At.%)		Au: 0.00% (0.00 At.%) Ag: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	0.198*	1	0.097	1	0.00100
4	0.193	4	0.097	4	0.00100
7	0.194	7	0.098	7	0.00103
10	0.196	10	0.099	10	0.00115
15	0.199	15	0.102	15	0.00190
20	0.205	20	0.107	20	0.00423
25	0.216	25	0.115	25	0.00959
30	0.230	30	0.126	30	0.0195
40	0.269	40	0.162	40	0.0541
50	0.318	50	0.210	50	0.104
60	0.377	60	0.269	60	0.163
70	0.440	70	0.332	70	0.226
80	0.508	80	0.395	80	0.290
90	0.566	90	0.458	90	0.355
100	0.627	100	0.521	100	0.419
150	0.935	150	0.834	150	0.728
200	1.25	200	1.15	200	1.031
250	1.56	250	1.45	250	1.330
273	1.69	273	1.58	273	1.468
293	1.80	293	1.69	293	1.587
300	1.84*	300	1.73*	300	1.629
350	2.12*	350	2.02*	350	1.930
400	2.49*	400	2.33*	400	2.236
500	3.04*	500	2.93*	500	2.863
600	3.69*	600	3.60*	600	3.509
700	4.35*	700	4.26*	700	4.174
800	5.03*	800	4.94*	800	4.860
900	5.73*	900	5.65*	900	5.565
1000	6.47*	1000	6.40*	1000	6.297
1100	7.28*	1100	7.19*	1100	7.085
1200	8.13*	1200	8.03*	1200	7.922
				1235.08	8.233 (s)
				1236	17.31 (t)
				1400	18.69
				1600	20.38

† Uncertainties in the electrical resistivity values are as follows:

1.00 Au - 99.00 Ag:  $\pm 4\%$  up to 100 K and  $\pm 3\%$  above 100 K.0.50 Au - 99.50 Ag:  $\pm 4\%$  up to 100 K and  $\pm 3\%$  above 100 K.0.00 Au - 100.00 Ag:  $\pm 1\%$  up to 10 K,  $\pm 5\%$  above 10 K to 30 K,  $\pm 2\%$  above 30 K to 70 K,  $\pm 1\%$  above 70 K to 400 K,  $\pm 2\%$  above 400 K to 1235.08 K, and  $\pm 4\%$  above 1235.08 K.

\* In temperature range where no experimental data are available.





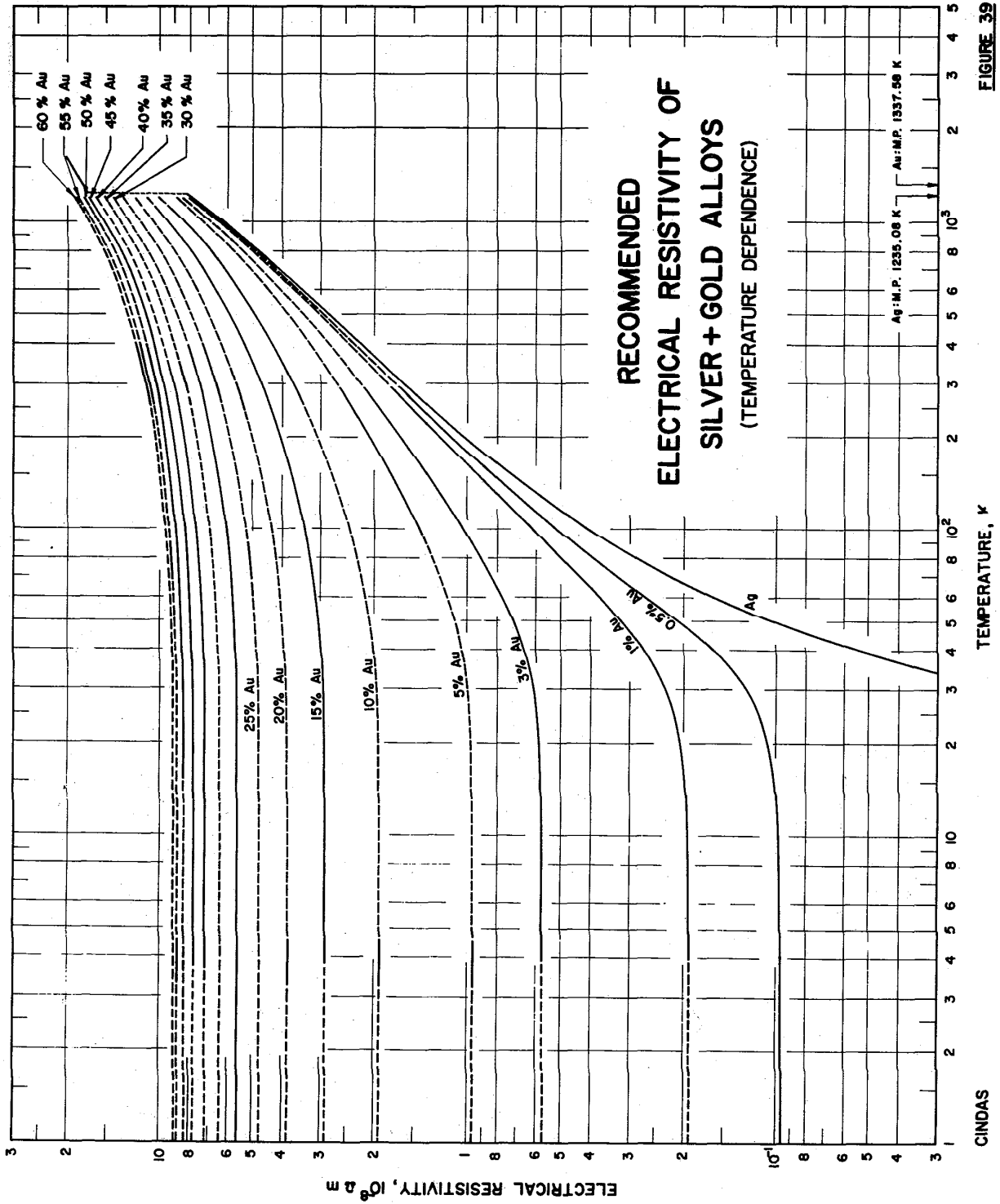
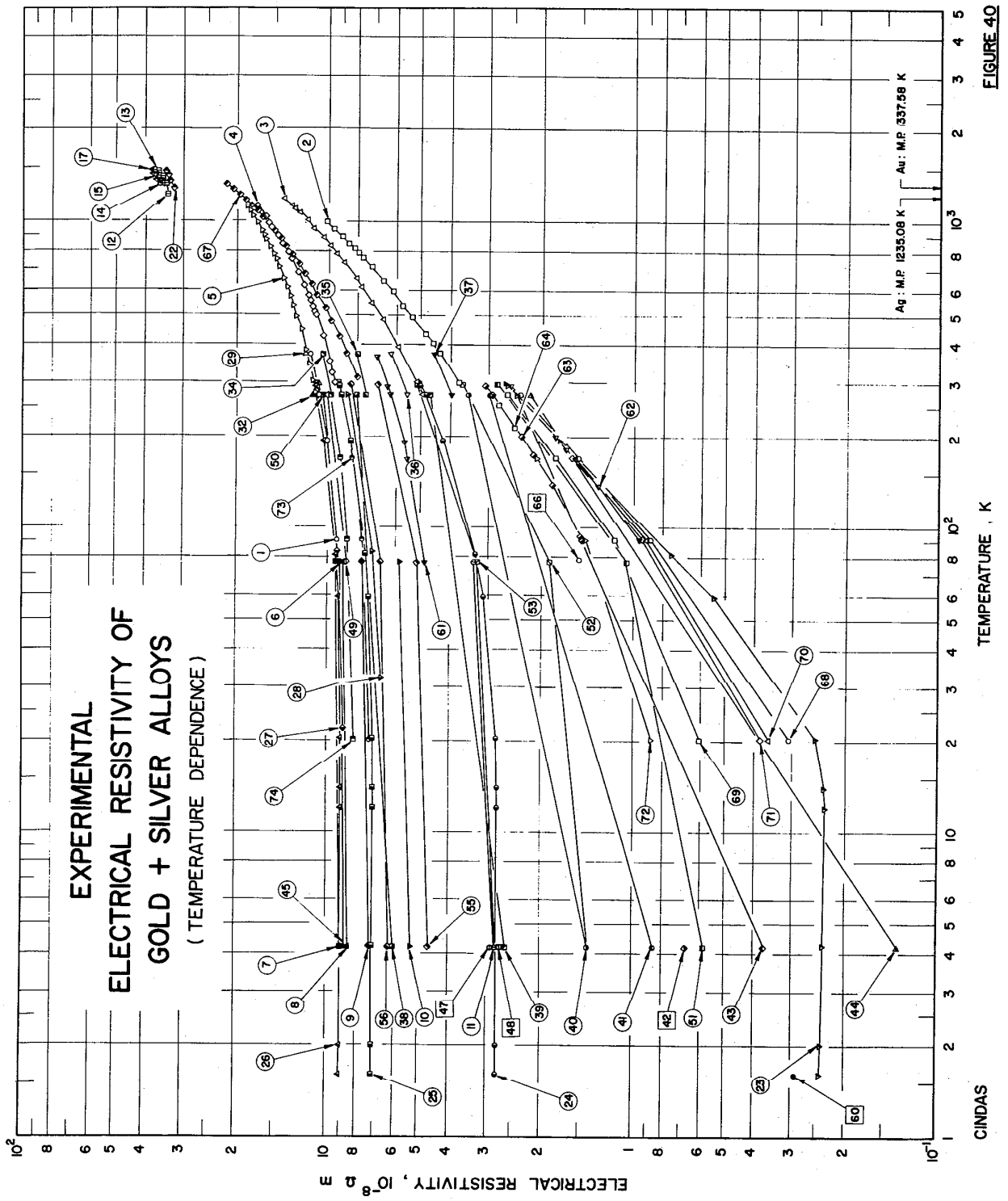


FIGURE 39



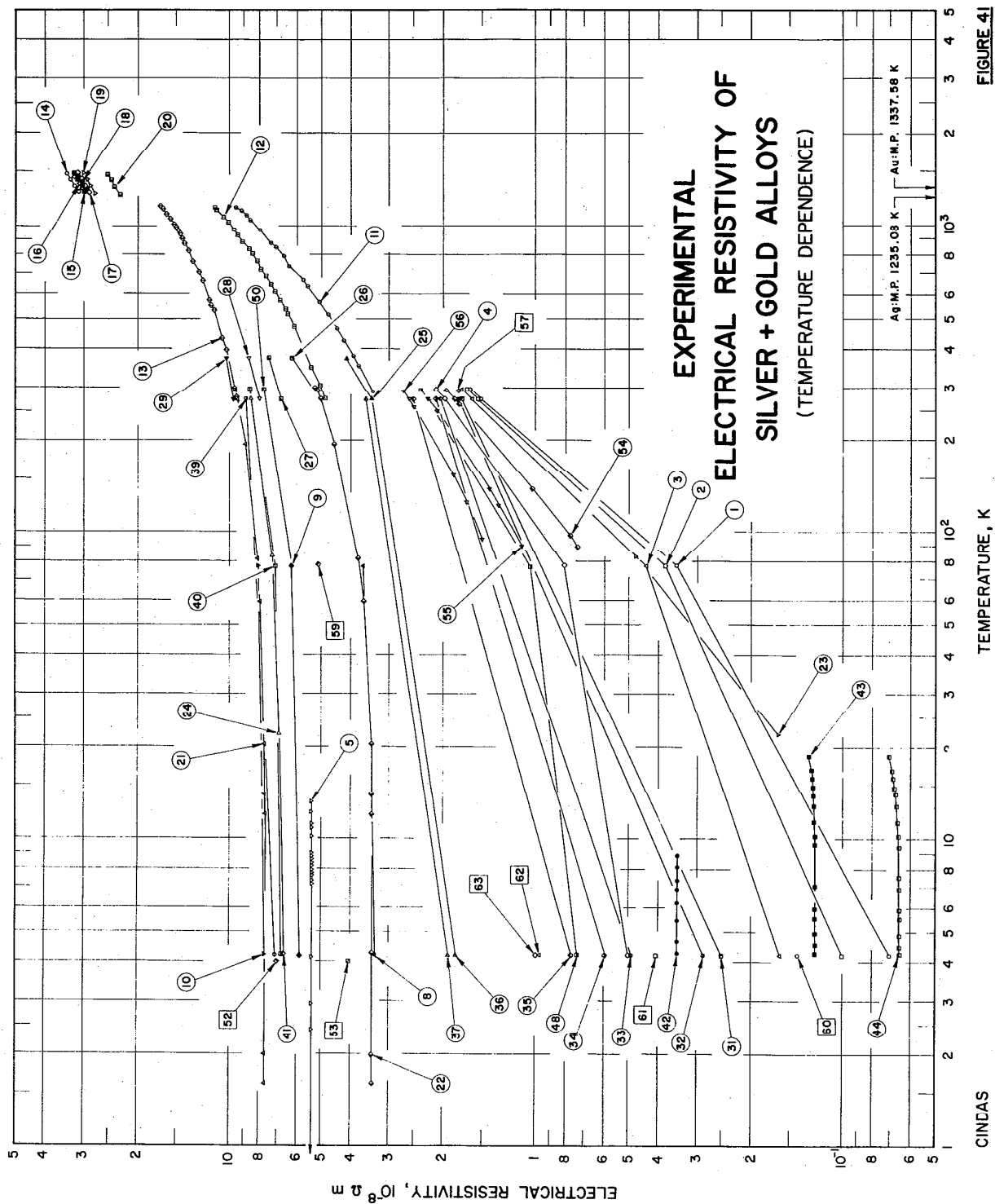


FIGURE 41

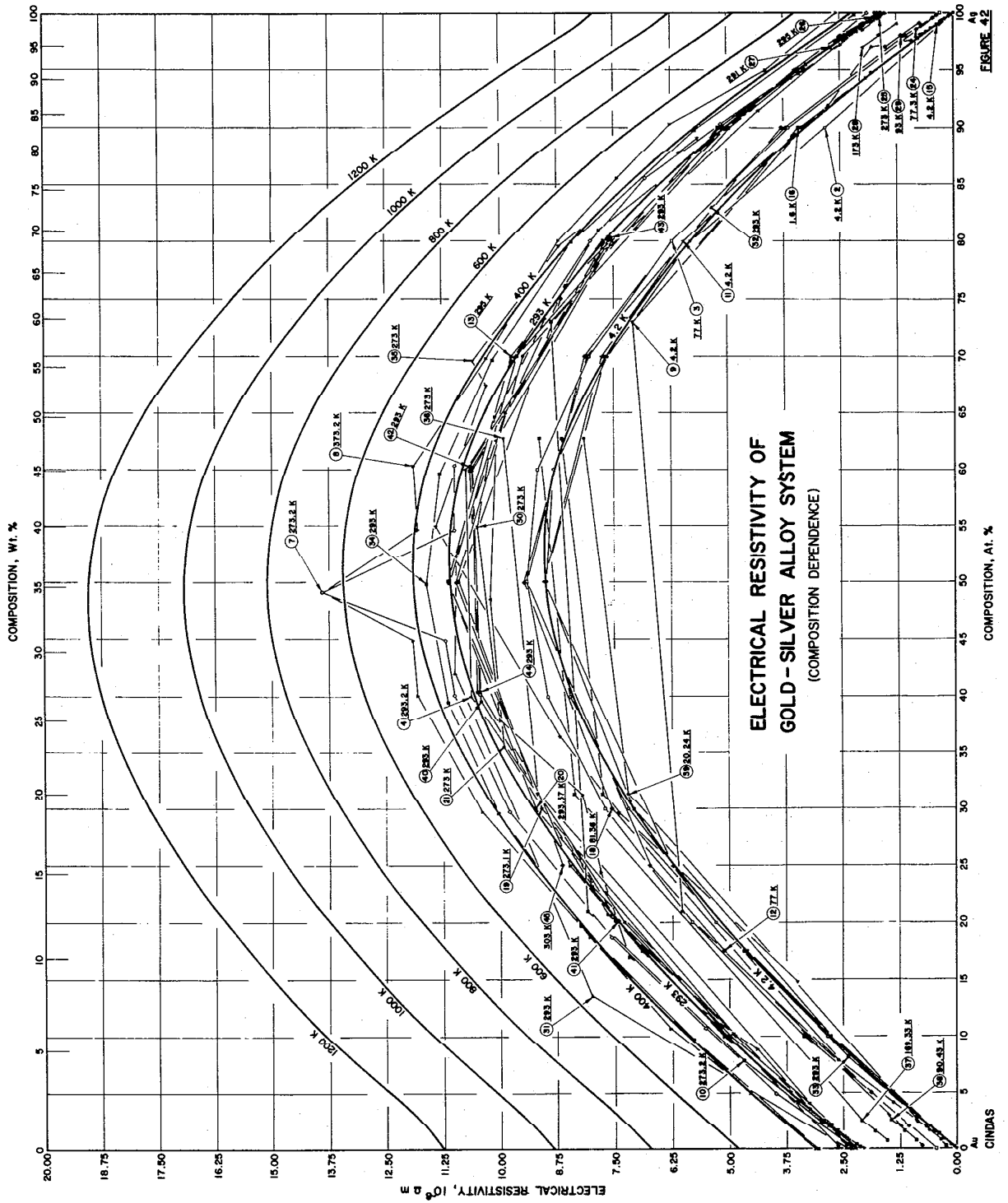


FIGURE 42

much as 2% in the case of concentrated alloys subjected to extremes of quenching and annealing. The data analyzed here were obtained with samples not deliberately subjected to such treatment, and the recommended values may be regarded as applicable to alloys which have not been quenched or cold-worked severely and have the equilibrium degree of short-range order at each temperature. The recommended values cover the temperature range from 1 to 1200 K and are not corrected for the thermal expansion of the material. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 8.

### 3.9. Iron-Nickel Alloy System

The electrical resistivity of the iron-nickel alloy system has received a considerable amount of attention, no doubt due in large measure to both elements being present in a large number of technologically important alloys. There are 45 data-source references available in the literature on the electrical resistivity of Fe-Ni alloys. From these references, 198 sets of experimental data were obtained spanning a temperature range 0.4 to 1995 K. These experimental data sets are listed in Tables S-49, S-51, and S-53 which provide information on specimen characterization and measurement conditions, tabulated in Tables S-50, S-52, and S-54, and shown partially in Figs. 47, 48, and 50.

The iron-nickel alloy system does not form a continuous series of solid solutions at low and moderate temperature (below 1183 K). The maximum solid solubility of nickel in iron is 6.81 wt.% (6.5 at.%) at 618 K and the solubility decreases at higher and lower temperatures.<sup>321</sup> For nickel-rich alloys the solubility of iron in nickel is uncertain due to the formation of FeNi<sub>3</sub> ordered structure; it may be below 3 wt.% around room temperature. In addition, there is a martensitic transformation from metastable austenite in alloys containing up to 30 wt.% Ni resulting in a metastable  $\alpha_2$  phase. The phase diagram is further complicated by magnetic transitions; at about 1040 K in the  $\alpha$  phase, at about 673 K in the  $\alpha + \gamma$  equilibrium phase mixture, and on a curve reaching a maximum of about 885 K at about 66 wt.% Ni in the  $\gamma$  phase.<sup>264</sup> Finally, there is an order-disorder transformation due to the formation of FeNi<sub>3</sub>, covering a wide range of composition, from perhaps 50 to 85 wt.% Ni, which has a maximum transition temperature of about 776 K.

Regarding the metastable states in the iron-rich region, early work identified the transformation of metastable austenite as being of the diffusionless, martensitic type.<sup>322</sup> Later, effects of strain and grain size upon martensite formation were studied from changes in the electrical resistivity.<sup>323-324</sup> The results indicate that the transformation is essentially independent of heating/cooling rate, the transformation may occur over an interval of temperatures spanning perhaps 100 deg for a 30% Ni alloy, and the amount of martensite formed upon cooling depends upon specimen history.

The electrical resistivity of dilute alloys with either iron or nickel as base metal has been measured during investigations of the deviations from Matthiessen's rule. At the lowest temperatures the deviations follow a roughly  $T^2$  behavior attributed to spin-mixing as reported by Fert and Camp-

bell<sup>325</sup> (Fe + Ni data set 93) for 1% or 2% Ni in Fe and by Farrell and Greig<sup>326</sup> (Ni + Fe data sets 3-5) for up to 5% Fe in Ni. Further, the variation with composition is quite weak at these temperatures. Near room temperature the rapidly rising deviations have leveled off as observed by Farrell and Greig,<sup>326</sup> Schwerer and Conroy<sup>327</sup> (Ni + Fe data sets 47-51), and Schwerer and Cuddy<sup>328</sup> (Fe + Ni data set 94). Above 300 K Schwerer and Cuddy<sup>329</sup> (Fe + Ni data sets 95, 96 and Ni + Fe data sets 64, 65) find evidence for spin-disorder resistivity in the generally decreasing temperature dependence of the deviations for both 1% Ni in Fe and 1% Fe in Ni at temperatures up to the Curie point.

Electrical resistivity of alloys with compositions in the  $\leq 30\%$  Ni region is well documented. The extensive measurements of Shirakawa<sup>330</sup> (Fe + Ni data sets 65-76) from 78 to 1123 K map out the temperature hysteresis loops for alloys with compositions between 4% and 30% Ni. It is unfortunate that the resistivity data reported on the lower Ni content specimens are atypically small in value, increasingly so at elevated temperatures; this is perhaps the result of problems inherent with a two-probe measurement technique. These findings were confirmed by the work of Ascher<sup>331</sup> (Fe + Ni data sets 90, 91) in which a 30% Ni specimen had been chilled in liquid air prior to measurement. The specimen was subsequently subjected to a complete temperature cycle with the resulting electrical resistivity in both martensitic and austenitic states being in close agreement with that of Shirakawa.<sup>330</sup> The change in electrical resistivity upon transforming the austenite to martensite is quite striking for this composition, amounting to a reduction of about 60%. A number of alloy compositions had previously been measured by Ingersoll<sup>332</sup> (Fe + Ni data sets 1-8) at these temperatures, but with only heating curves reported. In retrospect it may be noted that these smoothed data apparently do show the onset of the inverse transformation at higher temperatures. Recent work by Reed *et al.*<sup>333</sup> (Fe + Ni data sets 36-39) on an alloy with 29% Ni show the effects of a low-temperature anneal upon the electrical resistivity. The findings include the following: annealing of point defects affects only the residual resistivity such that the observed  $3.1 \times 10^{-8} \Omega\text{m}$  residual resistivity recovery corresponds to an estimated 0.5 at.% in point defect concentration, the reduction in electrical resistivity which accompanies the martensitic transformation amounts to an average of  $0.46 \times 10^{-8} \Omega\text{m}/\%$  martensite at 293 K, and the effect of dislocations upon electrical resistivity is negligible at room temperature, with estimates being down at the  $0.1 \times 10^{-8} \Omega\text{m}$  level. The findings of Livingston and Mukherjee<sup>334</sup> (Fe + Ni data set 42) on a slow-cooled specimen with 29.7 at.% Ni also show a very rapid onset to the decrease in resistivity at the transformation temperature.

The Invar composition range of about 35% to 50% Ni has received recent attention. The residual resistivity is found to increase sharply with increasing iron content. An explanation in terms of a weak ferromagnet model was suggested both by Armstrong and Fletcher<sup>335</sup> and by Gautier and Loegel.<sup>336</sup> Further, the temperature-dependent resistivity is found to increase with temperature as  $T^n$ , where  $n$  is reported as  $n = 2$  below 60 K<sup>336</sup> and  $n = 1.8$  to 2.0 up to 120 K.<sup>335</sup> Generally, the residual resistivity data from Ref. 335

(Fe-Ni data set 34) along with those of Mikhailova<sup>337</sup> (Fe + Ni data set 48) and Clark *et al.*<sup>103</sup> (Fe + Ni data sets 31, 32, and Ni + Fe data set 32) are for commercial grade materials. Consequently, these data lie somewhat above those from Ref. 336 (Fe + Ni data sets 50–56), of Larikov *et al.*<sup>338</sup> (Fe-Ni data set 27), and of Kondorskii and Sedov<sup>339</sup> (Fe-Ni data set 26). Near room temperature are the data of Jellinghaus and Andrés<sup>340</sup> (Fe-Ni data set 30), Kalinin *et al.*<sup>341</sup> (Fe-Ni data set 25), and Window<sup>342</sup> (Fe-Ni data set 29), all of which are in reasonably good agreement. At higher temperatures are the data of Larikov *et al.*<sup>338</sup> (Fe + Ni data sets 80–83 and Ni + Fe data set 61) up to 1300 K and of Somura<sup>343</sup> (Fe + Ni data sets 84–89) up to about 800 K. Both of them reported a concentration dependence that varies rapidly, but diminishes toward the highest temperatures, and perhaps even disappears above 700 K.<sup>343</sup> Also in this connection are the weakly concentration-dependent data reported by Window<sup>342</sup> (Fe-Ni data set 28) at 873 K. If, as has been suggested, alloys in the Invar range are describable in terms of a mixed phase model (see, for instance, Ref. 344), then specimen thermal history becomes very important. For instance, the cooling data reported by Larikov *et al.*<sup>338</sup> deviate toward slightly smaller resistivity values, but only below the Curie temperature. This may indicate that some phase segregation is taking place.

In the nickel-rich portion of the Fe-Ni system, the formation of ordering associated with FeNi<sub>3</sub> has been intensively studied. Basically two techniques have been reported to achieve the order. Following the initial high-temperature annealing a sequence of anneals below the critical temperature may be carried out. Or, a constant cooling rate may be applied. The first method was used in the early work of Källback<sup>345</sup> who reported electrical resistivity of the disordered (quenched) state (Ni + Fe data set 29) and also of states with partial, but undetermined amounts of order (Ni + Fe data set 28). Recently Moore *et al.*<sup>346</sup> (Ni + Fe data sets 39–42) subjected an alloy to a series of extended anneals designed to achieve essentially complete ordering. The electrical resistivity was reduced some 35% for temperatures between 4.2 K and 400 K by this procedure. The second method of producing order was reported by Wakelin and Yates<sup>347</sup> (Ni + Fe data sets 9–27) who applied cooling rates from 100 deg h<sup>-1</sup> to 0.1 deg h<sup>-1</sup> on alloys containing 50%–80% Ni. The essentially linear nature of the cooling curves at the slower cooling rates suggested that the fully ordered state was achieved. However, the cooling curves for the slower rates were relatively displaced, perhaps indicating that an extra resistivity mechanism was present. This was tentatively identified with dislocations being frozen in during the rapid cooldowns. Overall, this method resulted in alloy specimens having varying degrees of order. Consequently, some ambiguities arise when making comparisons of the electrical resistivity data on these alloy specimens with other data.

Data which fall between the two preceding composition ranges are those reported by Szentirmay<sup>348</sup> (Ni + Fe data sets 62, 63) on alloys with 58% and 65% Ni. The data are for quenched alloys at temperatures between 150 and 350 K. The 58% Ni specimen was later subjected to an anneal following which the electrical resistivity was shown to be reduced by some 2%–5%.

The electrical resistivity of the molten alloys shows a linear temperature dependence as reported by Ono and Yagi<sup>349</sup> (Fe + Ni data sets 40, 41, and Ni + Fe data sets 34–36), by Baum *et al.*<sup>350</sup> (Fe + Ni data sets 57–64, Ni + Fe data sets 52–55, and Fe-Ni data set 24), and by Epin *et al.*<sup>351</sup> (Fe-Ni data set 33). The slope values reported in Refs. 349 and 351 agree rather well for the nickel-rich compositions while those from Ref. 350 are lower by a factor of ten. The ratio of resistivities, liquid to solid, for compositions throughout the alloy system was also reported in Ref. 351. An alloy with 75% Ni was reported by Ono and Yagi<sup>349</sup> to show an anomalously low resistivity. This was attributed to possible FeNi<sub>3</sub> clusters. Temperature hysteresis was reported by Baum *et al.*<sup>350</sup> upon cycling through the melting range. This may be an indication of the tendency for structures in the Fe-Ni system to be retained into the melting range as suggested by Filippov and Krestonikov.<sup>352</sup>

Much early work on the electrical resistivity of the iron-nickel system was devoted to mapping out the composition dependence. This information, usually obtained at or near room temperature, helped to form initial insights into the inner workings of this system. The early efforts of Burgess and Aston<sup>353</sup> (Fe-Ni data set 10) directed toward technical application were followed by the work of Honda<sup>354</sup> (Fe-Ni data sets 7, 8) showing the effects of cold-chilling on alloys having  $\leq 30\%$  Ni, by the combined composition and temperature dependence measurements of Ingersoll<sup>352</sup> (Fe-Ni data sets 14–22), and by the careful pressure dependence measurements of Bridgman<sup>355</sup> (Fe-Ni data set 12).

Each of the experimental areas discussed above formed the basis for a set of recommendations. These were subsequently merged smoothly together to form the recommendations for the entire Fe-Ni system.

Recommendations for the residual resistivity were based upon a number of low temperature data sets which generally included a value at 4.2 K. These are the data of Fert and Campbell,<sup>325</sup> Schwerer and Cuddy,<sup>329</sup> and Reed *et al.*<sup>333</sup> for low nickel compositions. Also included were the temperature-dependent data of Bäcklund<sup>350</sup> (Fe + Ni data sets 13, 14) and Soffer *et al.*<sup>357</sup> (Fe + Ni data sets 20–24), from which  $\rho_0$  was extracted. At higher nickel compositions the recommendations were based on the data of Cadeville and Loegel<sup>358</sup> (Fe-Ni data set 9), Larikov *et al.*<sup>338</sup> and Kondorskii and Sedov<sup>339</sup> for 35%–60% Ni, of Van Elst and Gorter<sup>220</sup> (Ni + Fe data set 6) and Moore *et al.*<sup>346</sup> (disordered state only) for 75% Ni, of Berger and Rivier<sup>359</sup> (Ni + Fe data set 2) for 85% Ni, and of Farrell and Greig,<sup>326</sup> Schwerer and Conroy,<sup>327</sup> Fert and Campbell,<sup>325</sup> and Schwerer and Cuddy<sup>329</sup> for  $\geq 95\%$  Ni.

At low temperatures, the temperature-dependent resistivity follows a  $T^2$  dependence. The scattering strength is quite strong in the Invar region, in which the recommendations follow the data of Gautier and Loegel,<sup>336</sup> and diminishes with increasing base metal compositions, for which the recommendations follow the data of Soffer *et al.*,<sup>357</sup> Fert and Campbell,<sup>325</sup> Schwerer and Cuddy,<sup>328</sup> Farrell and Greig,<sup>326</sup> and Schwerer and Conroy.<sup>327</sup>

At higher temperatures, a cross-correlation involving both temperature and composition was applied. The data used for this were those of Schwerer and Cuddy,<sup>328,329</sup> Soffer

TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF IRON-NICKEL ALLOY SYSTEM†

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-6} \Omega \text{ m}$ ]

Fe: 100.00% (100.00 At.%) Ni: 0.00% (0.00 At.%)		Fe: 99.50% (99.52 At.%) Ni: 0.50% (0.48 At.%)		Fe: 99.00% (99.05 At.%) Ni: 1.00% (0.95 At.%)		Fe: 97.00% (97.14 At.%) Ni: 3.00% (2.86 At.%)		Fe: 95.00% (95.23 At.%) Ni: 5.00% (4.77 At.%)		Fe: 90.00% (90.44 At.%) Ni: 10.00% (9.56 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho_M$	T	$\rho_M$	T	$\rho_M$
1	0.0225	1	0.95	1	1.90	1	5.60*	1	8.15**†	1	12.4**†
4	0.0227	4	0.95	4	1.90	4	5.60*	4	8.15**†	4	12.4**†
7	0.0231	7	0.95	7	1.90	7	5.60*	7	8.16**†	7	12.4**†
10	0.0238	10	0.95	10	1.91	10	5.61*	10	8.16**†	10	12.4**†
15	0.0257	15	0.96	15	1.91	15	5.62*	15	8.18**†	15	12.4**†
20	0.0287	20	0.96	20	1.92	20	5.64*	20	8.20**†	20	12.4**†
30	0.0421	30	0.98	30	1.95	30	5.68*	30	8.27**†	30	12.5**†
40	0.0758	40	1.03	40	2.00	40	5.76*	40	8.36**†	40	12.6**†
50	0.148	50	1.11	50	2.09	50	5.87*	50	8.49**†	50	12.8**†
60	0.271	60	1.23	60	2.23	60	6.04*	60	8.66**†	60	13.0**†
70	0.452	70	1.42	70	2.42	70	6.26*	70	8.91**†	70	13.3**†
80	0.693	80	1.67	80	2.67	80	6.54*	80	9.22**†	80	13.7**†
90	0.967	90	1.96	90	2.97	90	6.89	90	9.60**†	90	14.1**†
100	1.28	100	2.30	100	3.32	100	7.29	100	10.0	100	14.5
150	3.15	150	4.18	150	5.15	150	9.34	150	12.1	150	17.0
200	5.20	200	6.24	200	7.36	200	11.7	200	14.7	200	19.8
250	7.44	250	8.56	250	9.70	250	14.1	250	17.3	250	22.7
273	3.57	273	9.72	273	10.9	273	15.4	273	18.7	273	24.2
293	9.61	293	10.8	293	12.0	293	16.5	293	19.9	293	25.5
300	9.98	300	11.1	300	12.4	300	16.9	300	20.2	300	25.9
400	15.1	400	17.4	400	18.7	400	23.3	400	26.8	400	33.2
500	23.7	500	25.0	500	26.3	500	31.0	500	34.6	500	41.6
600	32.9	600	34.2	600	35.4	600	40.1	600	43.8	600	51.5
700	44.0	700	45.3	700	46.4	700	51.2	700	55.2	700	63.1
800	57.1	800	58.3	800	59.6	800	64.7	800	68.5	800	72.5
1000	90.8	900	73.7	900	75.1	900	80.5	900	84.7	800	77.1
1043	101.1	1000	91.9	1000	93.1	995	97.4*	925	88.9	900	92.6
1185	111.9( $\alpha$ )	1040	101.3	1037	101.6	1000	98.3*	1000	102.3	965	104.4
1185	111.0( $\gamma$ )	1100	107.4	1100	107.8	1075	108.0*	1035	107.4	1080	107.8
1400	117.9	1200	111.6*	1200	112.0	1200	113.2	1200	114.1	1200	115.9*
1667	124.4( $\gamma$ )	1400	118.2*	1400	118.6	1400	119.9	1400	120.8	1400	122.7*
1667	124.6( $\delta$ )	1600	123.4*	1600	123.8	1600	125.2	1600	126.3	1600	128.6*
1811	128.2( $s$ )	1808	128.3*( $s$ )	1803	128.4*( $s$ )	1791	129.5*( $s$ )	1782	130.7( $s$ )	1762	132.6*( $s$ )
1811	136.2( $t$ )	1810	135.4*( $t$ )	1808	135.6*( $t$ )	1800	136.4*( $t$ )	1793	137.4( $t$ )	1777	139.0*( $t$ )
2000	136.2	2000	138.4*	2000	138.6*	2000	139.7*	2000	140.6	2000	142.4*

† Uncertainties in the electrical resistivity values are as follows:  
 100.00 Fe - 0.00 Ni:  $\pm 5\%$  from 50 K to 100 K,  $\pm 3\%$  above 100 K to 200 K,  $\pm 2\%$  above 200 K to 1811 K, and  $\pm 5\%$  above 1811 K.  
 99.50 Fe - 0.50 Ni:  $\pm 5\%$  below 100 K,  $\pm 3\%$  from 100 K to 200 K,  $\pm 2\%$  above 200 K to 1808 K, and  $\pm 5\%$  above 1808 K.  
 99.00 Fe - 1.00 Ni:  $\pm 5\%$  below 100 K,  $\pm 3\%$  from 100 K to 200 K,  $\pm 2\%$  above 200 K to 1803 K, and  $\pm 5\%$  above 1803 K.  
 97.00 Fe - 3.00 Ni:  $\pm 5\%$  below 1075 K (martensite),  $\pm 3\%$  from 995 K to 1791 K (austenite), and  $\pm 5\%$  above 1791 K.  
 95.00 Fe - 5.00 Ni:  $\pm 7\%$  below 100 K,  $\pm 5\%$  from 100 K to 1035 K (martensite),  $\pm 3\%$  from 925 K to 1782 K (austenite), and  $\pm 5\%$  above 1782 K.  
 90.00 Fe - 10.00 Ni:  $\pm 7\%$  below 100 K,  $\pm 5\%$  from 100 K to 965 K (martensite),  $\pm 3\%$  from 770 K to 1762 K (austenite), and  $\pm 5\%$  above 1762 K.  
 $\rho_M, \rho_A$  Electrical resistivity for martensite, austenite respectively.  
 \* Provisional value.  
 † In temperature range where no experimental data are available.

TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF IRON-NICKEL ALLOY SYSTEM† (continued)  
 † Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8}$   $\Omega$  m]

Fe: 85.00% (85.33 At.%) Ni: 15.00% (14.37 At.%)		Fe: 80.00% (80.79 At.%) Ni: 20.00% (19.21 At.%)		Fe: 75.00% (75.93 At.%) Ni: 25.00% (24.07 At.%)		Fe: 70.00% (71.04 At.%) Ni: 30.00% (28.96 At.%)		Fe: 65.00% (66.13 At.%) Ni: 35.00% (33.87 At.%)		Fe: 60.00% (61.19 At.%) Ni: 40.00% (38.81 At.%)	
T	$\rho_M$	T	$\rho_M$	T	$\rho_M$	T	$\rho_M$	T	$\rho_M$	T	$\rho_M$
1	15.1*†	1	16.8*†	1	17.8*†	1	18.2*†	1	47.9*†	1	22.9*†
4	15.1*†	4	16.8*†	4	17.8	4	18.2	4	47.9*†	4	22.9*†
7	15.1*†	7	16.8*†	7	17.8	7	18.2	7	47.9*†	7	22.9*†
10	15.1*†	10	16.8*†	10	17.8	10	18.2	10	48.0*†	10	23.0*†
15	15.1*†	15	16.8*†	15	17.8	15	18.3	15	48.1*†	15	23.0*†
20	15.1*†	20	16.9*†	20	17.9	20	18.3	20	48.2*†	20	23.2*†
30	15.2*†	30	17.0*†	30	18.0	30	18.4	30	48.6*†	30	23.5*†
40	15.4*†	40	17.1*†	40	18.2	40	18.6	40	49.1*†	40	23.9*†
50	15.6*†	50	17.3*†	50	18.4	50	18.9	50	49.7*†	50	24.5*†
60	15.8*†	60	17.6*†	60	18.7	60	19.2	60	50.5*†	60	25.2*†
70	16.2*†	70	18.0*†	70	19.1	70	19.6	70	51.4*†	70	25.9*†
80	16.6*†	80	18.4*†	80	19.5	80	20.0	80	52.5*†	80	26.7*†
90	17.0*†	90	18.9*†	90	19.9	90	20.4	90	53.5*†	90	27.7*†
100	17.5	100	19.3	100	20.4	100	20.9	100	54.7*†	100	28.6*†
150	20.0	150	22.1	150	23.3	150	23.7	150	61.7*†	150	34.5*†
200	23.0	200	25.2	200	26.4	200	27.0	200	68.9*†	200	41.8
250	26.2	250	28.5	250	29.9	250	30.6	250	76.2*†	250	50.0
273	27.8	273	30.1	273	31.6	273	32.3	273	79.4*†	273	53.8
293	29.2	293	31.6	293	33.0	293	33.9	293	82.0*†	293	57.1
300	29.7	300	32.2	300	33.5	300	34.4	300	83.0	300	58.2
400	37.3	400	40.0	400	41.1	400	42.4	400	94.3	400	73.9
500	46.2	500	49.0	500	45.5	500	51.8	500	101.6	500	88.5
535	56.7	535	52.6	535	50.8	535	53.2	535	102.4	535	98.5
635	60.9	600	59.8	600	61.7	600	62.8	600	106.4	600	101.1
700	68.6	700	72.0	700	73.9	700	75.2	700	106.4	700	101.4
800	83.0	800	86.2	800	87.9	800	89.4	800	109.9	800	105.6
900	97.0	875	96.2	810	89.4	810	90.7	810	113.2	800	109.1
920	102.9	900	106.4	900	110.4	900	110.4	900	116.2	900	112.3
1000	109.7	1000	111.5	1000	113.7	1000	113.7	1000	119.1	1000	115.5
1200	116.9*	1200	118.3*	1200	119.9*	1200	119.9*	1200	121.8	1100	118.3
1400	123.5*	1400	124.7*	1400	125.7*	1400	125.7*	1400	124.3	1200	121.1
1600	129.7*	1600	130.5*	1600	131.0*	1600	131.0*	1600	128.5*	1400	126.0*
1748	133.8*(s)	1737	134.2*(s)	1728	134.2*(s)	1728	134.2*(s)	1715	132.0*	1600	130.2*
1763	140.1 (l)	1751	140.6 (l)	1741	140.8*(l)	1732	141.0(l)	1715	133.7*(s)	1710	132.4*(s)
2000	143.7	2000	144.3	2000	144.6*	2000	144.6*	2000	141.3*(l)	1718	140.6 (l)
								2000	145.0*	2000	144.9

† Uncertainties in the electrical resistivity are as follows:

- 85.00 Fe - 15.00 Ni:  $\pm 7\%$  below 100 K,  $\pm 5\%$  from 100 K to 920 K (martensite),  $\pm 3\%$  from 635 K to 1748 K (austenite), and  $\pm 5\%$  above 1748 K.
- 80.00 Fe - 20.00 Ni:  $\pm 7\%$  below 100 K,  $\pm 5\%$  from 100 K to 875 K (martensite),  $\pm 3\%$  from 395 K to 1728 K (austenite), and  $\pm 5\%$  above 1728 K.
- 75.00 Fe - 25.00 Ni:  $\pm 5\%$  below 810 K (martensite),  $\pm 3\%$  from 395 K to 1728 K (austenite), and  $\pm 5\%$  above 1728 K.
- 70.00 Fe - 30.00 Ni:  $\pm 3\%$  below 740 K (martensite),  $\pm 3\%$  from 250 K to 1720 K (austenite), and  $\pm 5\%$  above 1720 K.
- 65.00 Fe - 35.00 Ni:  $\pm 15\%$  below 150 K,  $\pm 10\%$  above 150 K to 300 K, and  $\pm 5\%$  above 300 K.
- 60.00 Fe - 40.00 Ni:  $\pm 10\%$  below 200 K,  $\pm 5\%$  from 200 K to 604 K,  $\pm 3\%$  above 600 K to 1710 K, and  $\pm 5\%$  above 1710 K.

$\rho_M$ ,  $\rho_A$  Electrical resistivity for martensite, austenite respectively.

\* Provisional value.

\* In temperature range where no experimental data are available.



TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF IRON-NICKEL ALLOY SYSTEM† (continued)

(Temperature, °K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ )

Fe: 55.00% (56.23 At.%) Ni: 45.00% (43.77 At.%)		Fe: 50.00% (51.25 At.%) Ni: 50.00% (48.75 At.%)		Fe: 45.00% (46.24 At.%) Ni: 55.00% (53.76 At.%)		Fe: 40.00% (41.21 At.%) Ni: 60.00% (58.79 At.%)		Fe: 35.00% (36.15 At.%) Ni: 65.00% (63.85 At.%)		Fe: 30.00% (31.06 At.%) Ni: 70.00% (68.94 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	13.1*†	1	8.93*†	1	7.00*†	1	5.74*†	1	4.93*†	1	4.46*
4	13.1†	4	8.94†	4	7.00†	4	5.74†	4	4.93*†	4	4.46*
7	13.1†	7	8.95†	7	7.01†	7	5.75†	7	4.94*†	7	4.47*
10	13.1†	10	8.96†	10	7.03†	10	5.76†	10	4.95*†	10	4.47*
15	13.2†	15	9.00†	15	7.06†	15	5.78†	15	4.97*†	15	4.49*
20	13.3†	20	9.06†	20	7.10†	20	5.82†	20	4.99*†	20	4.52*
30	13.5†	30	9.23†	30	7.23†	30	5.91†	30	5.07*†	30	4.59*
40	13.9†	40	9.46†	40	7.40†	40	6.05†	40	5.19*†	40	4.69*
50	14.3†	50	9.76†	50	7.63†	50	6.22†	50	5.34*†	50	4.83*
60	14.3†	60	10.1†	60	7.90†	60	6.43†	60	5.52*†	60	5.00*
70	15.4†	70	10.6†	70	8.25*†	70	6.69†	70	5.73*†	70	5.20*
80	16.1†	80	11.0†	80	8.65*†	80	6.99†	80	5.98*†	80	5.43
90	16.3†	90	11.6†	90	9.11*†	90	7.35†	90	6.28*†	90	5.69
100	17.3†	100	12.3†	100	9.63*†	100	7.73†	100	6.55*†	100	5.97
150	22.1†	150	16.2†	150	12.5*†	150	10.2†	150	8.49*†	150	7.71
200	27.8†	200	20.8†	200	16.3*†	200	13.3†	200	11.3†	200	10.2
250	33.7†	250	25.9†	250	21.0*†	250	17.4†	250	14.9†	250	13.5
273	36.8†	273	28.4†	273	23.4*†	273	19.6†	273	17.0†	273	15.3
293	39.2†	293	30.6†	293	25.6*†	293	21.6†	293	18.8†	293	17.1
300	40.2	300	31.4	300	26.4*	300	22.5	300	19.6	300	17.7
400	53.9	400	43.7	400	38.3*	400	34.0	400	30.4*	400	27.4
500	68.9	500	57.5	500	51.4*	500	46.6	500	42.3*	500	38.5
600	84.7	600	72.6	600	65.4*	600	60.2	600	55.6*	600	50.7
700	101.0	700	88.4	700	80.2*	700	74.7	700	69.6*	700	64.1
703	101.2	782	101.0	800	95.9*	800	90.1	800	84.7*	800	79.1
800	104.7	800	101.8	833	100.8*	859	100.0	871	96.2*	874	91.2
900	108.1	900	105.8	900	108.9*	900	102.0	900	98.1*	900	92.5
1000	111.3	1000	109.2	1000	107.6*	1000	105.6	1000	102.1*	1000	96.7
1100	114.3	1100	112.3	1100	110.9*	1100	109.0	1100	105.9*	1100	100.8
1200	117.2	1200	115.4	1200	114.1*	1200	112.3*	1200	109.5*	1200	104.7*
1400	122.7*	1400	121.1*	1400	120.1*	1400	118.7*	1400	116.4*	1400	112.5*
1600	127.6	1600	126.3*	1600	125.7*	1600	124.9*	1600	123.0	1600	120.1*
1706	130.0(s)	1704	128.7*(s)	1703	128.4*(s)	1702	127.9*(s)	1702	126.4(s)	1702	123.8*(s)
1713	138.5(t)	1708	138.4*(t)	1705	138.9*(t)	1703	139.7*(t)	1703	139.5*(t)	1704	138.7*(t)
2000	144.7	2000	144.5*	2000	144.2*†	2000	143.8†	2000	143.3†	2000	142.3*†

† Uncertainties in the electrical resistivity are as follows:

55.00 Fe - 45.00 Ni:  $\pm 7\%$  below 300 K,  $\pm 5\%$  from 300 K to 703 K,  $\pm 3\%$  above 703 K to 1706 K, and  $\pm 5\%$  above 1706 K.  
 50.00 Fe - 50.00 Ni:  $\pm 7\%$  below 300 K,  $\pm 5\%$  from 300 K to 782 K,  $\pm 3\%$  above 782 K to 1704 K, and  $\pm 5\%$  above 1704 K.  
 45.00 Fe - 55.00 Ni:  $\pm 7\%$  below 300 K,  $\pm 5\%$  from 300 K to 833 K,  $\pm 3\%$  above 833 K to 1703 K, and  $\pm 10\%$  above 1703 K.  
 40.00 Fe - 60.00 Ni:  $\pm 7\%$  below 300 K,  $\pm 5\%$  from 300 K to 859 K,  $\pm 3\%$  above 859 K to 1702 K, and  $\pm 10\%$  above 1702 K.  
 35.00 Fe - 65.00 Ni:  $\pm 7\%$  below 300 K,  $\pm 5\%$  from 300 K to 871 K,  $\pm 3\%$  above 871 K to 1702 K, and  $\pm 10\%$  above 1702 K.  
 30.00 Fe - 70.00 Ni:  $\pm 5\%$  below 1702 K and  $\pm 10\%$  above.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF IRON-NICKEL ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Fe: 25.00% (25.95 At.%) Ni: 75.00% (74.05 At.%)		Fe: 20.00% (20.81 At.%) Ni: 80.00% (79.19 At.%)		Fe: 15.00% (15.65 At.%) Ni: 85.00% (84.35 At.%)		Fe: 10.00% (10.46 At.%) Ni: 90.00% (89.54 At.%)		Fe: 5.00% (5.24 At.%) Ni: 95.00% (94.76 At.%)		Fe: 3.00% (3.15 At.%) Ni: 97.00% (96.85 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	4.26*	1	4.08*	1	3.71*	1	2.95*	1	1.73	1	1.10
4	4.26	4	4.08	4	3.71*	4	2.95*	4	1.73	4	1.10
7	4.27	7	4.09	7	3.72*	7	2.96*	7	1.74	7	1.11
10	4.27	10	4.09	10	3.72*	10	2.96*	10	1.74	10	1.11
15	4.29	15	4.11	15	3.74*	15	2.98*	15	1.76	15	1.13
20	4.31	20	4.13	20	3.76*	20	3.00*	20	1.78	20	1.15
30	4.39	30	4.20	30	3.83*	30	3.06*	30	1.84	30	1.21
40	4.49	40	4.29	40	3.92*	40	3.15*	40	1.94	40	1.30
50	4.61	50	4.42	50	4.03*	50	3.27*	50	2.06	50	1.44
60	4.77	60	4.56	60	4.17*	60	3.40*	60	2.27	60	1.61
70	4.94	70	4.73	70	4.33*	70	3.56*	70	2.50	70	1.82
80	5.14	80	4.92	80	4.52	80	3.74	80	2.76	80	2.05
90	5.37	90	5.14	90	4.64	90	3.95	90	3.04	90	2.31
100	5.62	100	5.39	100	4.97	100	4.20	100	3.34	100	2.59
150	7.30	150	7.05	150	6.59	150	5.79	150	4.93	150	4.09
200	9.71	200	9.27	200	8.64	200	7.77	200	6.66	200	5.78
250	12.8	250	12.1	250	11.2	250	10.3	250	8.65	250	7.64
273	14.3	273	13.6	273	12.6	273	11.4	273	9.66	273	8.53
293	15.9	293	14.9	293	13.8	293	12.5	293	10.6	293	9.32
300	16.4	300	15.4	300	14.2	300	12.9	300	10.9	300	9.59
400	25.1	400	23.1	400	21.1	400	18.9	400	16.1*	400	14.6*
500	35.1*	500	32.1	500	29.1	500	26.3	500	22.9*	500	20.9*
600	46.4*	600	42.3	600	38.6	600	35.4	600	31.6*	600	29.6*
700	59.0	700	54.3	700	50.5	700	47.1	700	40.6*	700	38.1*
800	73.2	800	68.7	800	63.6	800	51.7*	800	41.8*	800	38.1*
865	83.4	865	74.1	865	64.5	865	55.1*	865	45.6*	865	41.6*
900	85.3*	900	77.6	900	69.1	900	59.2*	900	49.2*	900	45.0*
1000	89.9*	1000	82.3	1000	73.5	1000	63.3*	1000	52.6*	1000	48.1*
1100	94.4*	1100	86.7	1100	77.8	1100	67.3*	1100	55.9*	1100	51.2*
1200	98.6*	1200	91.1*	1200	82.0*	1200	71.3*	1200	59.3*	1200	54.3*
1400	106.9*	1400	99.6*	1400	90.2*	1400	79.1*	1400	65.9*	1400	60.2*
1600	115.0*	1600	107.9*	1600	98.3	1600	86.6*	1600	72.3*	1600	66.1*
1703	119.1*(s)	1703	112.0*(s)	1703	102.5*(s)	1703	90.6*(s)	1703	76.0*(s)	1703	69.7*(s)
1706	136.1*(l)	1710	131.5*(l)	1715	124.3*(l)	1719	114.1*(l)	1724	99.7*(l)	1726	93.0*(l)
2000	139.7*	2000	135.0*	2000	127.6*	2000	117.3*	2000	102.8*	2000	96.0*

† Uncertainties in the electrical resistivity are as follows:

25.00 Fe - 75.00 Ni:  $\pm 5\%$  below 100 K,  $\pm 3\%$  from 100 K to 400 K,  $\pm 5\%$  above 400 K to 1703 K, and  $\pm 10\%$  above 1703 K.20.00 Fe - 80.00 Ni:  $\pm 5\%$  below 1705 K and  $\pm 10\%$  above.15.00 Fe - 85.00 Ni:  $\pm 5\%$  below 1707 K and  $\pm 10\%$  above.10.00 Fe - 90.00 Ni:  $\pm 5\%$  below 733 K,  $\pm 7\%$  from 733 K to 1710 K, and  $\pm 10\%$  above 1710 K.5.00 Fe - 95.00 Ni:  $\pm 5\%$  below 679 K,  $\pm 7\%$  from 679 K to 1716 K, and  $\pm 10\%$  above 1716 K.3.00 Fe - 97.00 Ni:  $\pm 5\%$  below 656 K,  $\pm 7\%$  from 656 K to 1720 K, and  $\pm 10\%$  above 1720 K.

\* Provisional value.

† In temperature range where no experimental data are available.

TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF IRON-NICKEL ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-3} \Omega \text{ m}$ ]

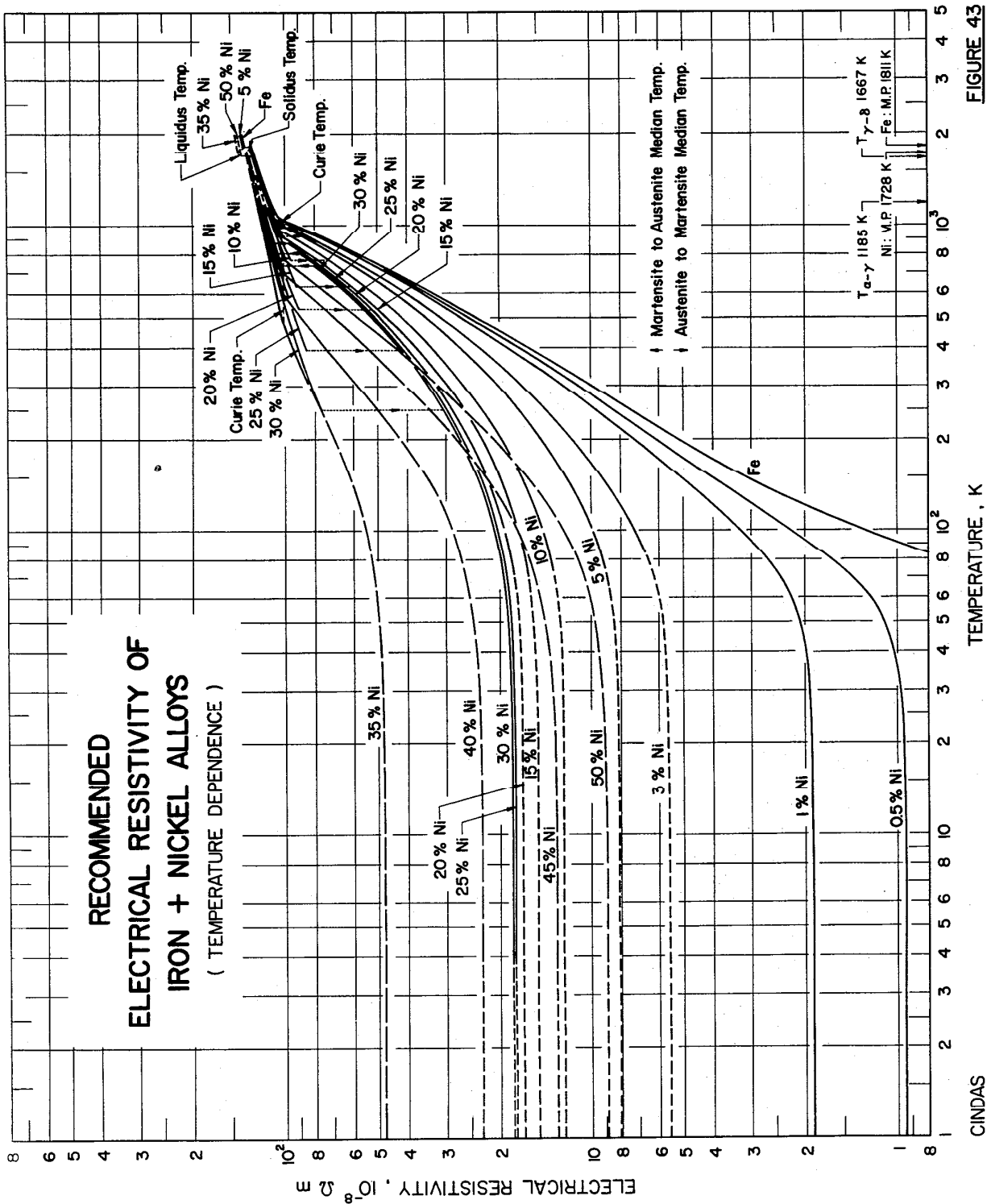
Fe: 1.00% (1.05 At.%) Ni: 99.00% (98.95 At.%)		Fe: 0.50% (0.53 At.%) Ni: 99.50% (99.47 At.%)		Fe: 0.00% (0.00 At.%) Ni: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	0.40*	1	0.21*	1	0.0032
4	0.40	4	0.21	4	0.0036
7	0.41	7	0.22	7	0.0044
10	0.41	10	0.22	10	0.0057
15	0.42	15	0.23	15	0.0090
20	0.44	20	0.24	20	0.0140
30	0.50	30	0.27	30	0.0317
40	0.58	40	0.33	40	0.0678
50	0.68	50	0.42	50	0.135
60	0.83	60	0.55	60	0.242
70	1.01	70	0.71	70	0.377
80	1.21	80	0.90	80	0.545
90	1.43	90	1.10	90	0.741
100	1.66	100	1.32	100	0.959
150	2.99	150	2.60	150	2.21
200	4.57	200	4.08	200	3.67
250	6.31	250	5.78	250	5.32
273	7.17	273	6.65	273	6.16
293	7.94	293	7.43	293	6.93
300	8.12	300	7.72	300	7.20
400	12.8	400	12.3	400	11.8
500	19.0	500	18.5	500	17.7
600	27.4	600	26.7	600	25.5
637	31.2	634	30.4	630	28.7
700	34.1	700	33.2	700	32.1
800	37.5	800	36.5	800	35.5
900	40.7	900	39.7	900	38.6
1000	43.7	1000	42.5	1000	41.4
1100	46.5*	1100	45.3*	1100	44.1
1200	49.2*	1200	48.0*	1200	46.6
1400	54.7*	1400	53.1*	1400	51.7
1600	60.1*	1600	58.5*	1600	56.9
1725	63.3*(s)	1727	61.8*(s)	1728	60.2*(s)
1727	85.8*(t)	1728	84.0*(t)	1728	82.2*(t)
2000	88.8*†	2000	87.0*†	2000	85.2*†

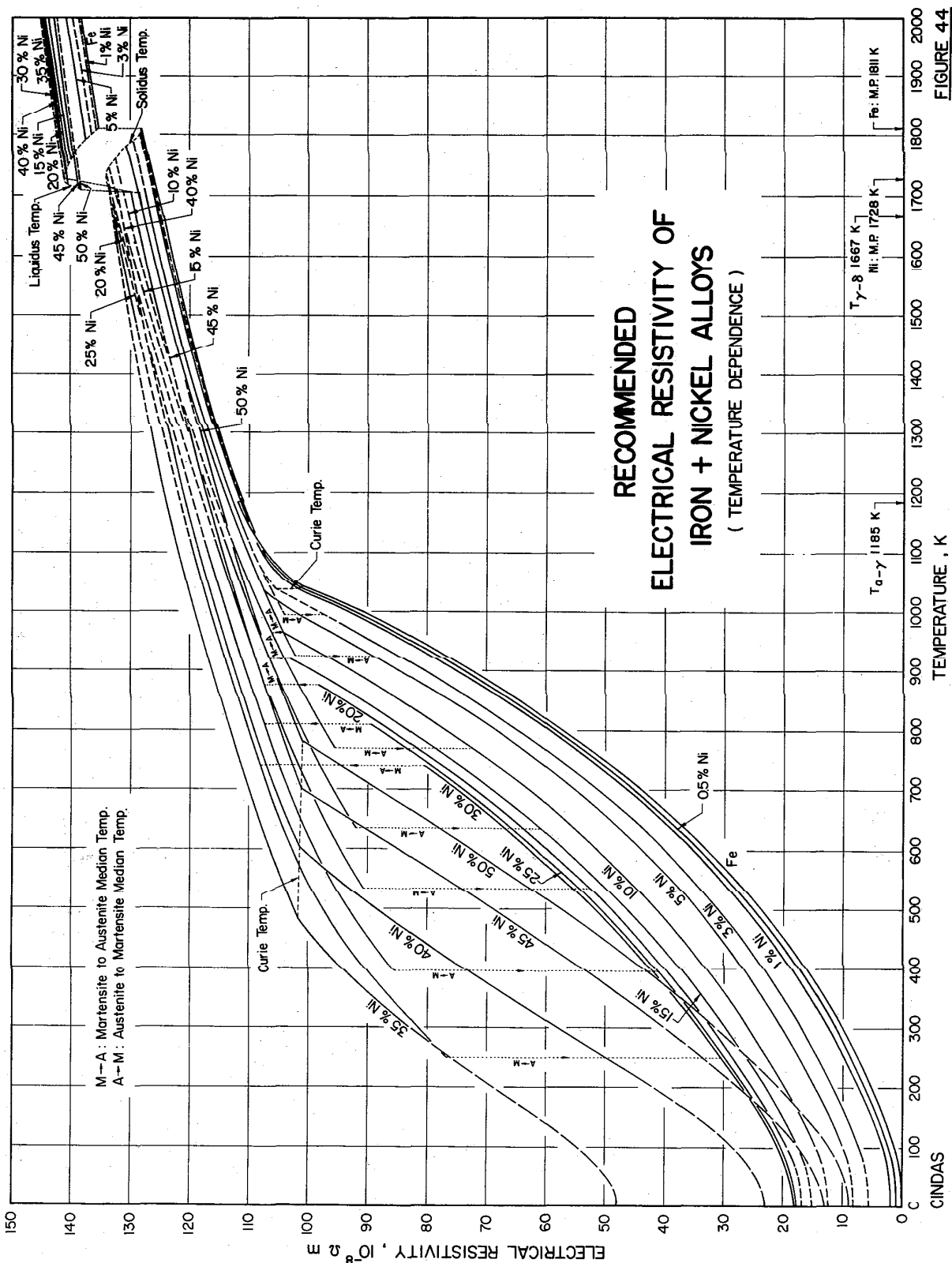
† Uncertainties in the electrical resistivity are as follows:

1.00 Fe - 99.00 Ni:  $\pm 5\%$  below 150 K,  $\pm 3\%$  from 150 K to 1000 K,  $\pm 5\%$  above 1000 K to 1725 K, and  $\pm 10\%$  above 1725 K.0.50 Fe - 99.50 Ni:  $\pm 5\%$  below 150 K,  $\pm 3\%$  from 150 K to 1000 K,  $\pm 5\%$  above 1000 K to 1727 K, and  $\pm 10\%$  above 1727 K.0.00 Fe - 100.00 Ni:  $\pm 5\%$  from 50 K to 150 K,  $\pm 3\%$  above 150 K to 1300 K,  $\pm 5\%$  above 1300 K to 1728 K, and  $\pm 10\%$  above 1728 K.

\* Provisional value.

† In temperature range where no experimental data are available.





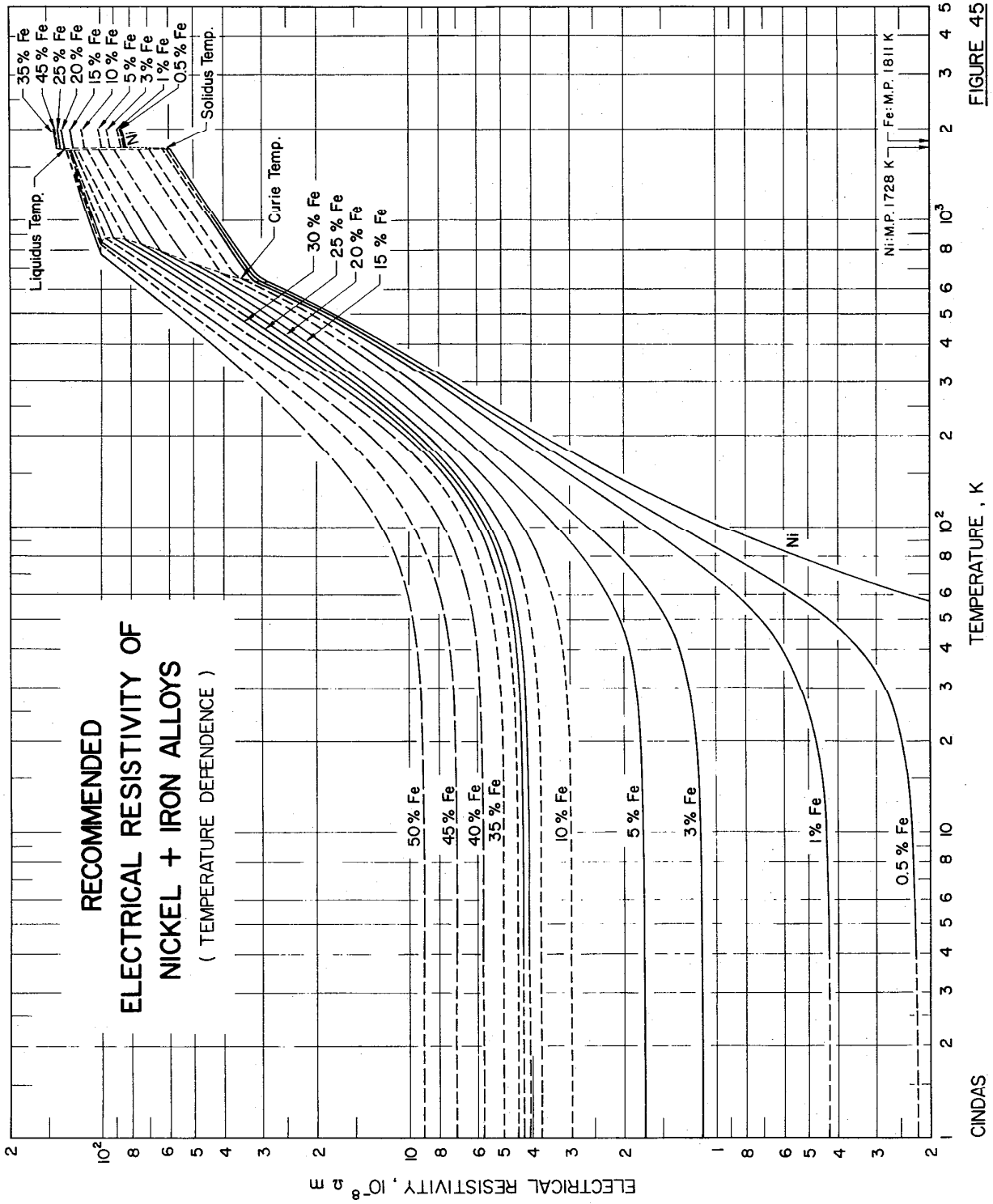


FIGURE 45

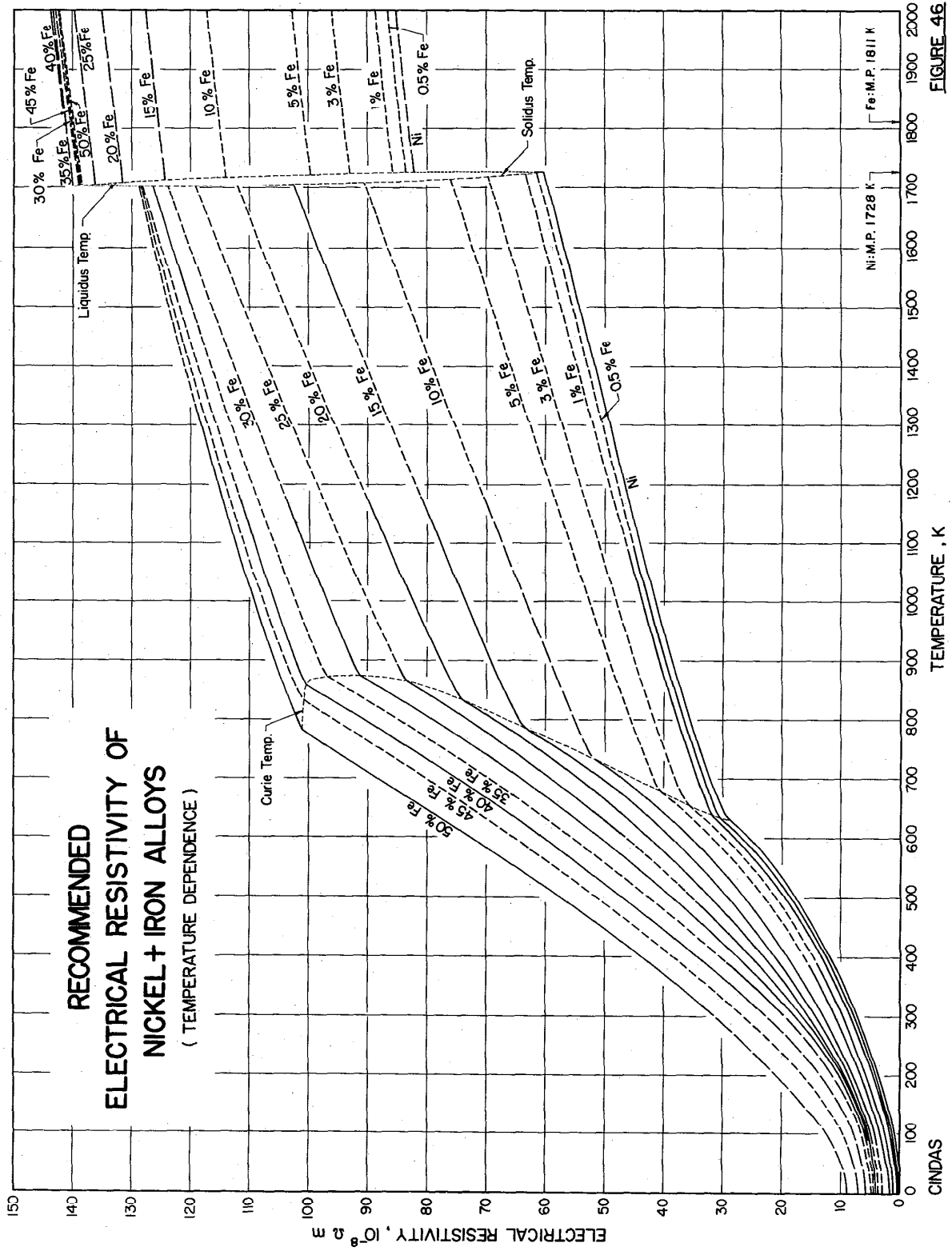


FIGURE 46

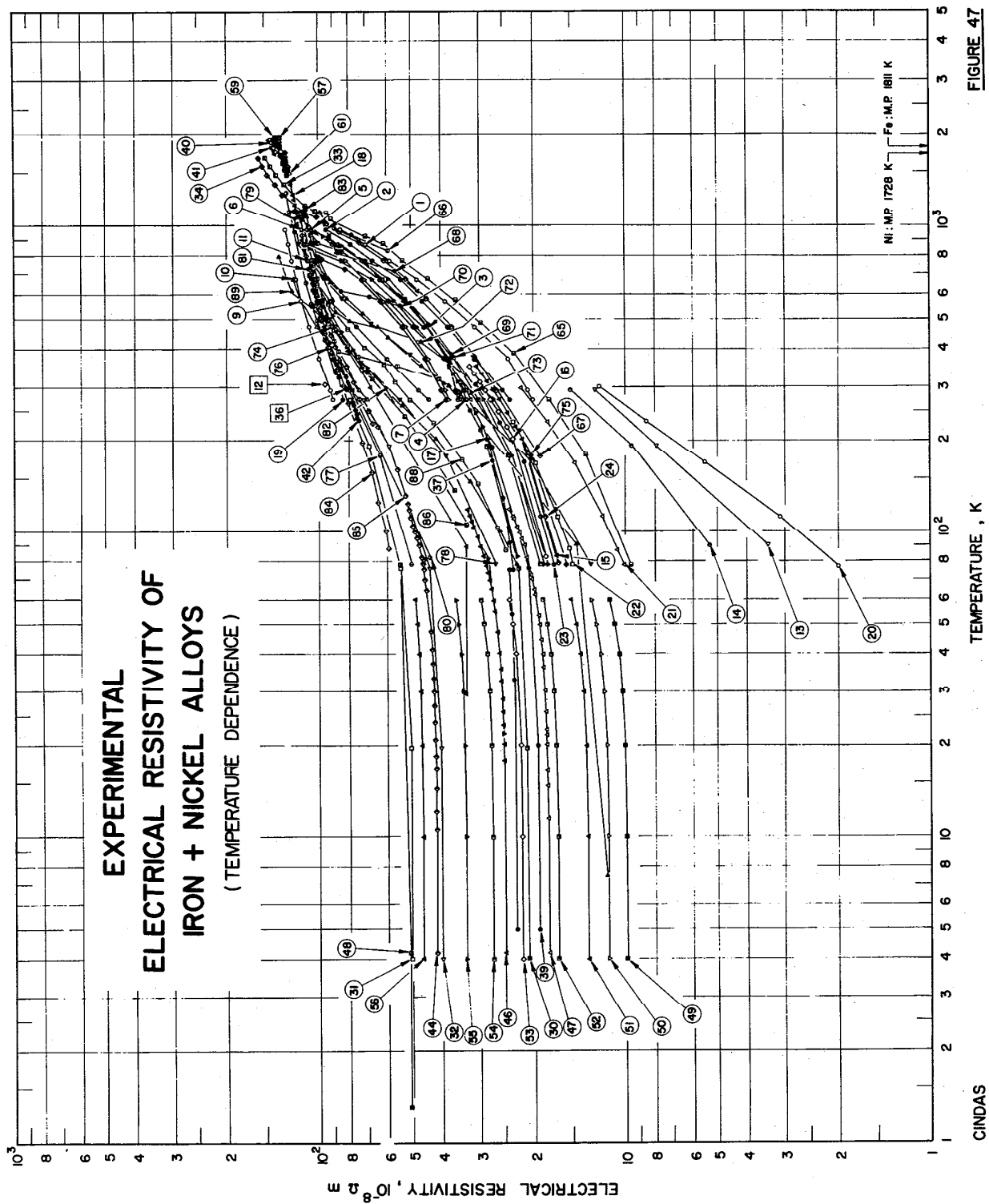
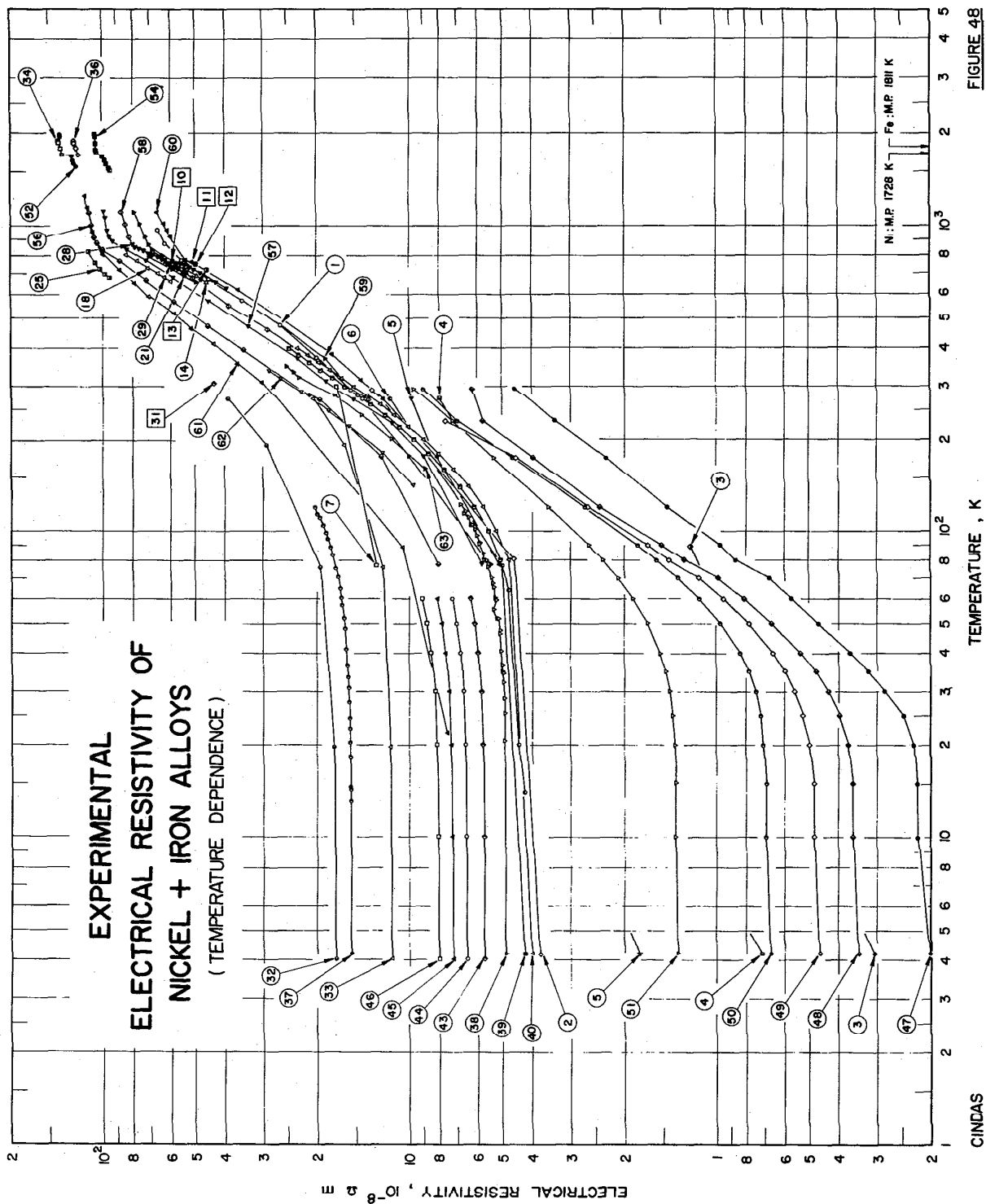


FIGURE 47





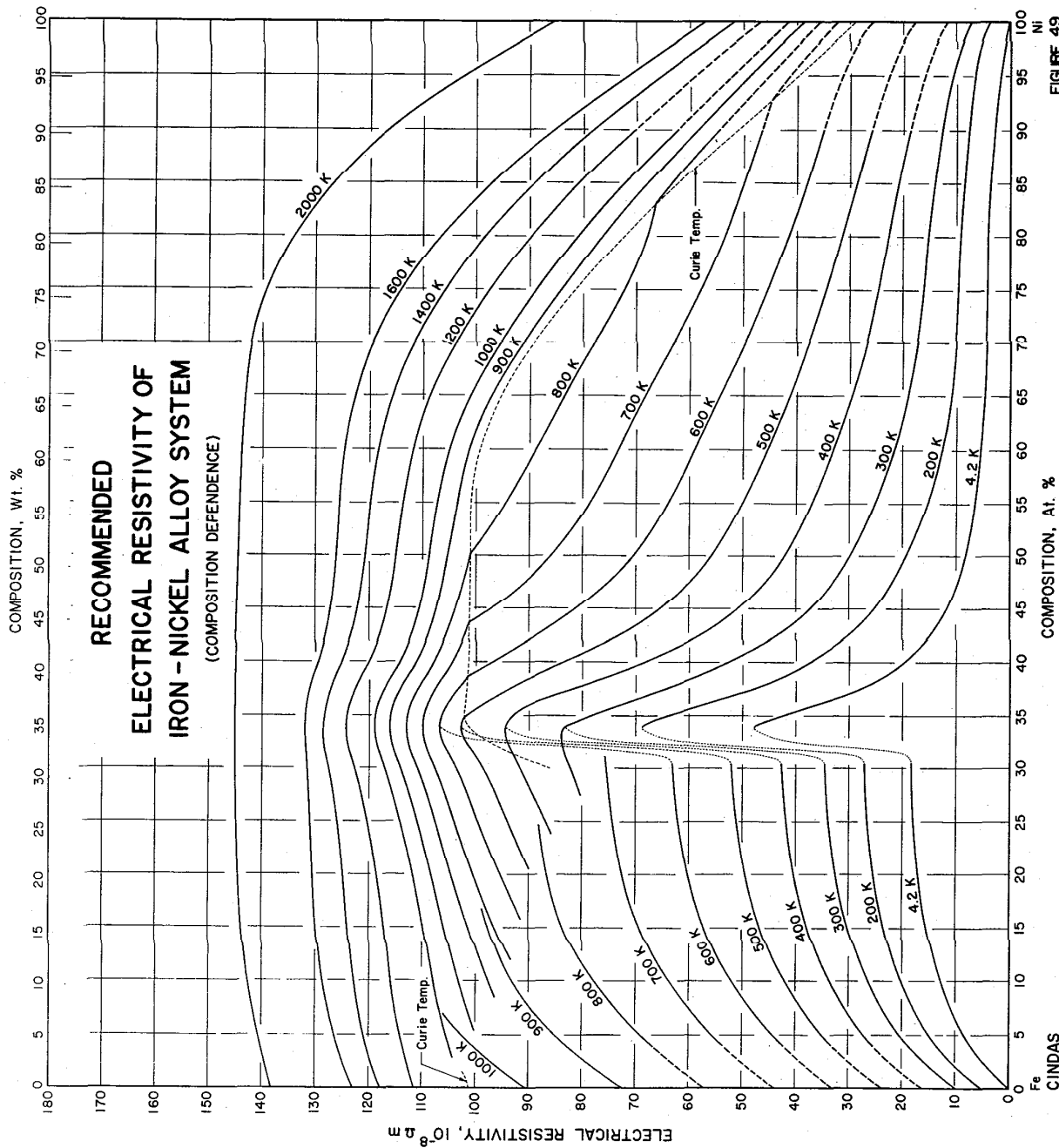


FIGURE 49

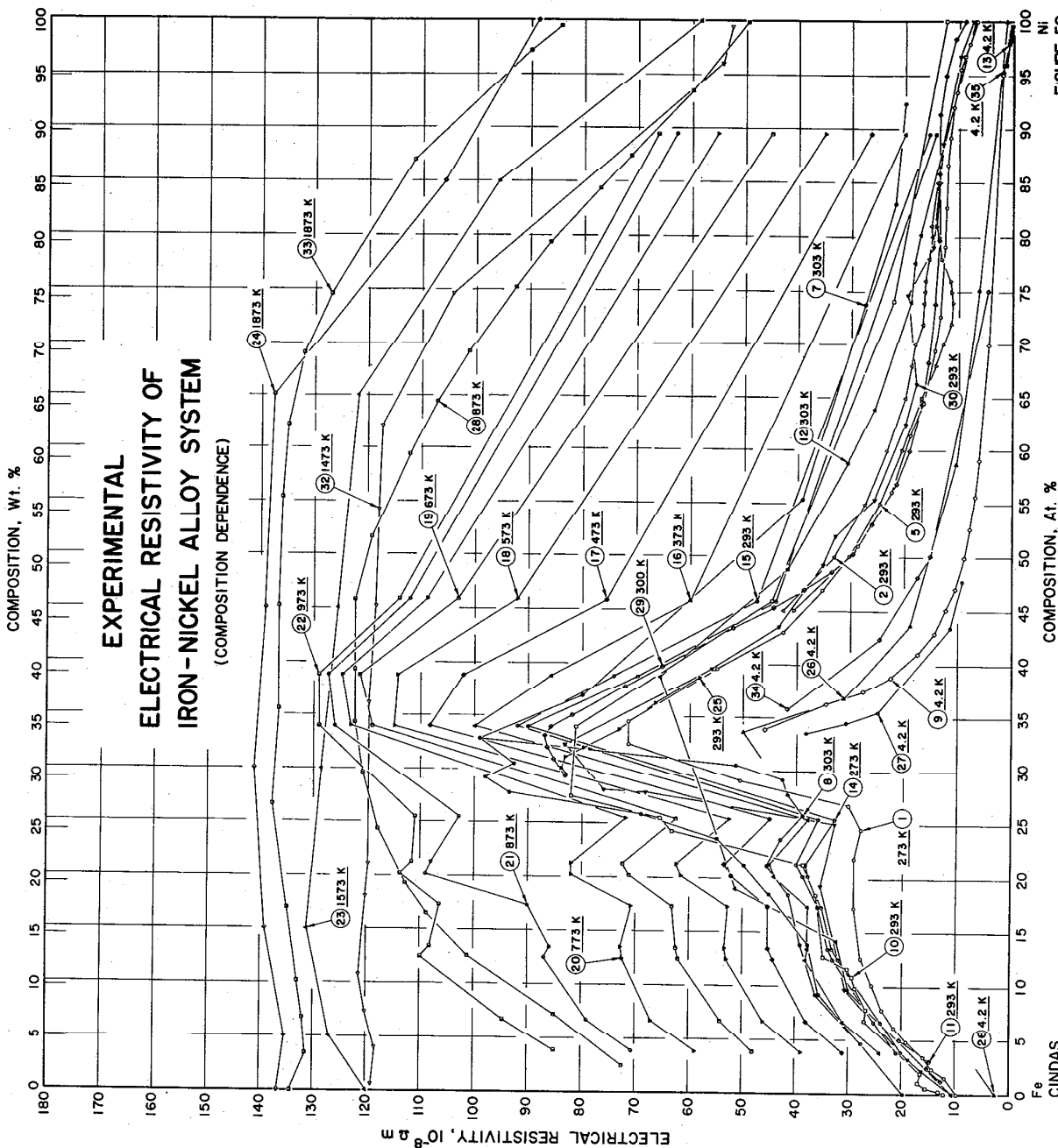


FIGURE 50

*et al.*,<sup>357</sup> Bäcklund,<sup>356</sup> Reed *et al.*,<sup>333</sup> Livingston and Mukherjee,<sup>334</sup> Ascher,<sup>331</sup> Shirakawa,<sup>330</sup> Ingersoll,<sup>332</sup> Larikov *et al.*,<sup>338</sup> Szentirmay,<sup>348</sup> Moore *et al.*,<sup>346</sup> Farrell and Greig,<sup>326</sup> and of Schwerer and Conroy.<sup>327</sup> Curie temperatures were taken from Hansen.<sup>264</sup>

For the martensitic and austenitic metastable states, recommendations are given for compositions between 3% and 30% Ni. The transformation temperatures are the median, 50% transformation completion, values from Hansen.<sup>264</sup> Values applicable to a 30% Ni composition follow the data of Reed *et al.*<sup>333</sup> and Livingston and Mukherjee<sup>334</sup> up to 300 K. The temperature hysteresis loops for all compositions are based upon the data of Ascher<sup>331</sup> and of Shirakawa.<sup>330</sup>

Recommendations at high temperatures include values for the liquid state. Solidus and liquidus temperatures are taken from Hansen.<sup>264</sup> Values for the solid state are based upon the data of Baum *et al.*,<sup>350</sup> and for the step-up resistivity increase across the melting range upon the  $\rho_l/\rho_s$  data from Epin *et al.*<sup>351</sup> The linear temperature dependence of the electrical resistivity in the molten region follows the slope values reported by Epin *et al.*,<sup>351</sup> and for nickel-rich compositions also follows the slope values reported by Ono and Yagi.<sup>349</sup>

It may be worthwhile to point out that the data from Refs. 349–351 were measured with a rotating field method. Since the electrical resistivity in this case is proportional to specimen volume (see, for instance, Ref. 349), a significant thermal expansion correction arises, amounting to 7%–8% for pure nickel or iron at the melting point. Therefore, inasmuch as Ref. 349 reports expansion corrections having been applied to the data, it is thought that actually all three references, 349–351, are reporting corrected data. As a result, the recommended values for alloys below 1300 K are not corrected for thermal expansion, while those at higher temperatures, up to and beyond the melting range, do in fact include the corrections.

The resulting recommended electrical resistivity values for Fe, Ni, and for 25 Fe–Ni binary alloys are presented in Table 9 and shown in Figs. 43–46, and 49. The recommended values for Fe and for Ni are for well-annealed high-purity specimens, but those values for temperatures below about 100 K are applicable only to Fe and Ni having residual electrical resistivities as given at 1 K in Table 9. The alloys for which the recommended values are generated are those having the stated compositions and being in the specified appropriate metallurgical state. The latter includes the fully martensitic or austenitic metastable states for 3% to 30% Ni and the completely disordered state for other compositions. The recommended values cover a full range of temperature from 1 to 2000 K and cover both solid and molten states. The estimated uncertainties in the values for the various alloys and for different temperature ranges are explicitly stated in a footnote to Table 9. Some of the values in Table 9 are indicated as provisional because their uncertainties are greater than  $\pm 5\%$ .

### 3.10. Silver–Palladium Alloy System

The preponderance of available evidence<sup>264,289,321</sup> suggests that the silver–palladium alloy system forms a continuous series of solid solutions without the formation of long-

range ordered structure. However, the results of electrical resistivity measurements by Savitskii and Pravoverov<sup>368,369</sup> have suggested to the contrary, which will be discussed later in detail as these bear directly on the evaluation of electrical resistivity data for these alloys.

Investigations of the effect of plastic deformation on the electrical resistivity of silver–palladium alloys have been undertaken by Aarts and Houston-MacMillan,<sup>370</sup> Rao,<sup>371</sup> Nicholson and co-workers,<sup>372–374</sup> and others and have shown an anomalous decrease of resistivity with increasing deformation. These investigations, together with isochromal and isothermal annealing studies of recovery processes and Hall constant measurements, have been interpreted (see, for example, Ref. 373) as showing the existence of short-range ordering in the silver–palladium alloy system. No x-ray evidence for the existence of short-range order in these alloys exists, probably because the scattering factors for silver and palladium atoms are nearly the same. In an x-ray investigation of a range of alloy compositions, Rao and Rao<sup>375</sup> found that the variation of lattice parameter with temperature deviates from a straight line, but concluded that their results could not be explained by the formation of short-range order.

There are 123 sets of data available for the electrical resistivity of this alloy system. These experimental data sets are listed in Tables S-55, S-57, and S-59 which provide information on specimen characterization and measurement conditions, tabulated in Tables S-56, S-58, and S-60, and shown partially in Figs. 53, 54, and 56.

Resistivity values reported for Ag–Pd alloys show striking discrepancies. Residual resistivities given for alloys with 50% silver differ by as much as 13%, and the room-temperature resistivities by 35%. Large differences occur even within the work of single authors; for instance, Kemp *et al.*<sup>376</sup> (Ag + Pd data sets 41 and 42) report for two samples with 60% silver (wire and rod, respectively) residual resistivities that differ by over 5%, and changes in resistivity to 300 K that differ by 25%. The discrepancies are such as to indicate that the preparation of Ag–Pd alloys of known composition, good homogeneity, and predictable resistivity offers serious (and perhaps unexpected) difficulties.

Pravoverov and Savitskii<sup>368,369</sup> (Ag + Pd data sets 58–61, Pd + Ag data sets 32–35, and Ag–Pd data set 23) have reported measurements on Ag–Pd alloys subjected to very prolonged annealing (124 h at 1273 K, followed by 200 h at 1073 K), with results very different from those of other workers. For alloys with over 70% silver they report essentially the same room-temperature resistivities as do other workers, but for alloys richer in palladium their values are much lower. A plot of their resistivity values against the atomic fraction of silver clearly indicates a downward cusp at 40% silver, where they obtain  $\rho_{300} = 28 \times 10^{-8} \Omega m$ , about 2/3 as large as the values obtained by others; in addition, their value for 50% silver is quite low, suggesting the presence of a kink, if not a cusp, at this composition. Plots of microhardness against composition show well-defined downward cusps at both compositions. Pravoverov and Savitskii attribute these features to the existence of ordered structures corresponding to the compounds Pd<sub>3</sub>Ag<sub>7</sub> and PdAg. Samples quenched from 1123, 1273, and 1373 K

show progressive lessening of these features, and they are entirely absent from a plot of the resistivities of samples quenched from 1473 K, as they are from a plot of microhardness against composition. The results of Pravoverov and Savitskii provide a clear indication that the order in Pd + Ag alloys can increase slowly during prolonged anneals, becoming quite high for certain composition, and that the heat treatment of these alloys can markedly affect their electrical resistivity. The thermal histories of samples used by other workers in this field are often inadequately described, but they seem to be diverse enough to account for a good deal of the scatter in the reported results.

The difference of the results of Pravoverov and Savitskii from those of all other workers with Pd + Ag alloys is so great as to suggest that they are dealing with an essentially different, more ordered, material. Unfortunately, there is also some question as to the accuracy of their measurements. In the case of the alloy with 15% palladium, their room-temperature resistivity fits in well with the results of others, but their reported increase in resistivity with temperature is less than half that reported by a number of other workers for Ag-rich alloys. Their experimental arrangement for measurements at high temperatures, though inadequately described, appears to be unconventional, and may be responsible for the fact that their high-temperature resistivities are consistently lower than those of other workers. It is not clear whether this can have any relation to the low values that they find for Pd-rich alloys at room temperature. At any rate, their data are not used in our analysis.

The Ag-Pd system is of great theoretical interest. Mott and Jones (Ref. 6, p. 297) pointed out that the  $d$ -states of the transition metal Pd have little effect on electrical conduction in the silver-rich alloys, but that electron scattering into these states comes to be the dominating factor, and produces a striking change in the behavior of the alloys as the concentration of Pd increases. A useful survey of the problem is given by Mott (Ref. 377, p. 372). A number of calculations have been based on the model of Mott and Jones, but their success has been mainly qualitative rather than quantitative. It is now evident why the behavior of the system is so complex, but the theory has suggested no useful analytic form for representation of the residual resistivities of the system, or of the even more striking peculiarities of the temperature-dependent part of the resistivities  $\rho - \rho_0$  which are illustrated in Fig. 55.

The difficulty of making a rational choice between divergent data without the assistance of a suitable theory has made it difficult (despite the relative abundance of data) to arrive at recommended values for the electrical resistivity that have small limits of error. The division of the total resistivity, for purposes of analysis, into residual and temperature-dependent parts is less useful for the attainment of accuracy in the total than it is when the parts exhibit a simpler behavior. This approach has been used, however, to obtain recommended values that reflect, as well as may be, those features in the behavior of the temperature-dependent part that are reliably indicated by the data. It is believed that the trends in the temperature-dependent part of the resistivity are more accurately represented by the recommended values than might be suggested by the error limits (absolute, not

fractional) assigned to the total resistivities.

The greater part of the available data relates to residual and room-temperature resistivities. The difference between these quantities can best be determined from measurements of the two quantities made on a single sample, since this minimizes the effect of many errors, including those of sample characterization. In our analysis the data of Kemp *et al.*<sup>376</sup> (Ag + Pd data sets 29–44, Pd + Ag data sets 13–18, and Ag-Pd data sets 10–13), Ricker and Pflüger<sup>378</sup> (Ag + Pd data sets 11–15 and Pd + Ag data sets 3–6), and Coles and Taylor<sup>45</sup> (Pd + Ag data set 1 and Ag-Pd data set 3) were used in determining values for  $\rho(c, 300 \text{ K}) - \rho(c, 0 \text{ K})$  over the entire range of  $c$ . (The wire data of Kemp *et al.* were given preference over their rod data, since only the wire data extended to intermediate temperatures.) The individual contours for  $\rho(c, 0 \text{ K})$  and  $\rho(c, 300 \text{ K})$  were then determined from the entire mass of data at liquid-helium and room temperatures, subject to the constraint of their established separation. This correlation of low- and room-temperature data in determining  $\rho(c, 0 \text{ K})$  resolved some problems of choice, and appeared to give a significant improvement in the accuracy with which  $\rho(c, 0 \text{ K})$  could be determined.

Below room temperature, the data of Kemp *et al.*<sup>376</sup> give a reasonable coverage of the silver-rich alloys, but leave series gaps between 5% and 30% silver and between 30% and 50% silver. The second of these gaps is filled by the data of Ahmad and Greig<sup>175</sup> (Pd + Ag data set 22) and of Coles and Taylor.<sup>45</sup> In the first gap one must use the data of Ricker and Pflüger,<sup>378</sup> which are scantier and less well presented. Ricker and Pflüger made no measurements below liquid-air temperature, and they apparently extrapolated their curves to 0 K in rather rough fashion. Their data for each of their samples, as read from their curves, have been adjusted to fit our recommended values for  $\rho(c, 300 \text{ K})$  by addition of an appropriate constant, with results that are useful down to about 100 K. At temperatures below 40 K the works of Murani<sup>379</sup> (Ag + Pd data sets 52–56 and Pd + Ag data sets 19–21), Edwards *et al.*<sup>380</sup> (Ag + Pd data sets 23–25 and Pd + Ag data sets 7–10), and Chen *et al.*<sup>381</sup> (Ag + Pd data sets 7–10) have provided values of  $\rho_i$  (not always concordant) for a wide range of compositions. (The values given by Murani for alloys with 62% and 70% silver are quite out of line with other results, and have been ignored.) The work of Greig and Rowlands<sup>382,383</sup> (Pd + Ag data sets 23–26) provides values of  $\rho_i$  for dilute alloys with up to 2% Ag in Pd, and the work of Schroeder *et al.*<sup>180</sup> (Ag + Pd data sets 1–4) gives values of  $\rho_i$  for up to 10% Pd in Ag.

In general, the analysis of these data began with the construction of smoothed temperature plots of  $\rho_i$  for the individual samples. In the case of dilute alloys, interpolation and smoothing was facilitated by working with the ratio of the reported  $\rho_i$  to that of the pure metal, or its differences from that of the pure metal—that is, the deviation from Matthiessen's rule (DMR). Values read from these curves were then used in constructing a family of isotherms of  $\rho_i$  over the whole range of composition, from which were read values for compositions to appear in the tables. Finally, the values thus obtained were used in constructing smoothed plots against  $T$  of  $\rho_i$  (or of a ratio or difference), from which values were read for the temperatures to appear in the table.

It may be mentioned that Kemp *et al.* considered the deviations from Matthiessen's rule to be insignificant for up to 30% Pd in Ag. Schroeder *et al.*, however, found small but measurable values for the DMR appearing rather abruptly in their sample with 10% Pd; they attribute this to disengagement of the Fermi surface from the zone boundary. Since the data of Coles and Taylor support the conclusion of Kemp *et al.* that the DMR remains very small for up to 30% Pd, we have used the data of Schroeder *et al.* for alloys with up to 10% Pd (which indicates that the DMR is negligible for alloys with less than 5% Pd) and have taken the DMR to be constant thereafter for alloys with up to 30% Pd, except at temperatures below 100 K, where the very-low-temperature isotherms indicate some variation in this practically negligible quantity.

The extension of the analysis to temperatures above 300 K had to be based primarily on the data of Ricker and Pflüger, normalized to the recommended values for 300 K, as noted above. For concentrated alloys there exist also the data of Coles and Taylor<sup>45</sup> (Pd + Ag data set 1) for an alloy with 39% silver, and the data of Ahmad and Greig<sup>175</sup> (Pd + Ag data set 22) for an alloy with 40% silver. Their results are in reasonable agreement with those of Ricker and Pflüger, and the results of Ahmad and Greig were actually given preference for the 40% Ag alloys, since they provide a value of  $\rho_0$  measured on the same sample. Measurements of Aarajis *et al.*<sup>384</sup> (Ag + Pd data set 57, Pd + Ag data sets 27–31, and Ag–Pd data set 25), still unpublished when this analysis was made, are in reasonable agreement with other results at room temperature, but indicate a much greater increase in resistivity at high temperatures.

No data exist for dilute solutions of Ag in Pd above room temperature. The interpolation between results for pure palladium and an alloy with 10% Ag was made by assuming that there would be a continuation of the tendency, indicated by the low- $T$  data, for the range of concentration in which the DMR is positive to decrease to insignificance as  $T$  rises.

The data for dilute (< 30%) solutions of Pd in Ag offer some problems. The data of Schroeder *et al.*<sup>180</sup> indicate that the DMR of a 10% alloy is positive and essentially constant from 100 to 250 K. On the other hand, the data of Ricker and Pflüger for  $T > 300$  K yield  $\rho_i$ -plots for alloys with 10%, 20%, and 30% palladium that sag markedly below the pure-silver plot as temperature rises, yielding negative DMR but at the same time indicating that the DMR is increasing algebraically over this range. If this were true, it would mean that above 300 K the DMR becomes negative and fairly large (over  $0.5 \times 10^{-8} \Omega\text{m}$ ) with increasing palladium concentration, but that this tendency is sharply reversed before 10% palladium is reached, with the DMR increasing thereafter. The data of Otter<sup>226</sup> (Ag + Pd data sets 19–22) for alloys with 1%, 2%, 3%, and 4% palladium, though not obtainable from his figures with high accuracy, are inconsistent with this idea. We have accepted as working hypothesis the idea

that through some systematic error the resistivity values of Ricker and Pflüger tend to be too low at high  $T$ , with the error greater the lower the total resistivity of the specimen. We have therefore followed the suggestion of the low- $T$  data in assuming that the DMR of these alloys is positive and constant for all  $T > 150$  K. A corresponding small modification, well within the limits of error, has been made in the high- $T$  data of Ricker and Pflüger for alloys with 40% and 50% palladium.

From this point, the analysis followed the lines indicated above for the low- $T$  data. The 300 K isotherm of  $\rho_i$ , which equals  $(\rho - \rho_0)$ , derived from low-temperature data and illustrated in Fig. 55, shows a minimum for about 40% silver and a maximum for about 52% silver, as was noted earlier by Coles and Taylor. As the temperature rises, these features of the isotherms are increasingly marked. Addition of  $\rho_0$  to  $\rho_i$  yields isotherms of  $\rho$  that are increasingly flattened for silver concentrations around 40%, and the 1100 K isotherm actually has a slight dimple in this region. Changes in the analysis of the existing data can decrease the depth of this dimple, but the existence of the deep minima in the isotherms of  $\rho_i$ , and of the flattening in the isotherms of  $\rho$ , is indicated by all data. This unexpected form of the isotherms of  $\rho$  would certainly make trouble in an analysis based on direct consideration of  $\rho$ , and might well lead to some smoothing out of a real feature of the isotherms.

The resulting recommended electrical resistivity values for Ag, Pd, and for 25 Ag–Pd binary alloys are presented in Table 10 and shown in Figs. 51, 52, and 56. The recommended values for Ag and for Pd are for well-annealed high-purity specimens, but those values for temperature below about 100 K are applicable only to Ag and Pd having residual electrical resistivities as given at 1 K in Table 10. The recommended values for Ag–Pd alloys are intended to apply to samples that are well homogenized and are annealed to remove the effects of cold work, but that have not been subjected to very prolonged annealing such as that which seems to have produced the relatively ordered alloys measured by Pravoverov and Savitskii. This is hardly an ideal characterization of a material, but no more precise one can be given for the materials from which our recommended values have been derived. The recommended values cover the temperature range from 1 to 1100 K, and are not corrected for the thermal expansion of the material. The uncertainties assigned to the recommended values, as indicated in a footnote to Table 10, are intended to represent the possible effects of measurement errors and of other difficulties in our analysis, and also include some allowance for differences in the structure of different carefully prepared samples. This latter allowance is based on the scatter in existing data but can not be precisely defined; certainly it does not define a range that includes all existing results, or all future ones. A better characterization of these alloys, and some precise reference values, are much to be desired.

TABLE 10. RECOMMENDED ELECTRICAL RESISTIVITY OF SILVER-PALLADIUM ALLOY SYSTEM†  
[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Ag: 100.00% (100.00 At.%) Pd: 0.00% ( 0.00 At.%)		Ag: 99.50% (99.49 At.%) Pd: 0.50% ( 0.51 At.%)		Ag: 99.00% (98.99 At.%) Pd: 1.00% ( 1.01 At.%)		Ag: 97.00% (96.96 At.%) Pd: 3.00% ( 3.04 At.%)		Ag: 95.00% (94.93 At.%) Pd: 5.00% ( 5.07 At.%)		Ag: 90.00% (89.88 At.%) Pd: 10.00% (10.12 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	0.60100	1	0.210	1	0.421	1	1.262**	1	2.102**	1	4.20
4	0.60100	4	0.210	4	0.421	4	1.262	4	2.102	4	4.20
7	0.60103	7	0.210	7	0.421	7	1.262	7	2.102	7	4.20
10	0.60115	10	0.210	10	0.421	10	1.262	10	2.103	10	4.20
15	0.60190	15	0.211	15	0.422	15	1.263	15	2.105	15	4.21
20	0.60423	20	0.213	20	0.424	20	1.265	20	2.110	20	4.22
25	0.60959	25	0.218	25	0.429	25	1.270	25	2.118	25	4.23
30	0.6195	30	0.229	30	0.440	30	1.281	30	2.129	30	4.24
40	0.6541	40	0.263	40	0.474	40	1.315	40	2.164	40	4.29
50	0.104	50	0.313	50	0.524	50	1.365	50	2.213	50	4.36
60	0.163	60	0.372	60	0.583	60	1.424	60	2.269	60	4.43
70	0.226	70	0.435	70	0.646	70	1.487	70	2.329	70	4.50
80	0.290	80	0.499	80	0.710	80	1.551	80	2.396	80	4.57
90	0.355	90	0.564	90	0.775	90	1.616	90	2.463	90	4.65
100	0.419	100	0.628	100	0.839	100	1.680	100	2.528	100	4.72
150	0.728	150	0.938	150	1.149	150	1.990	150	2.838	150	5.07
200	1.031	200	1.240	200	1.451	200	2.292	200	3.140	200	5.38
250	1.330	250	1.539	250	1.750	250	2.59	250	3.44	250	5.68
273	1.468	273	1.676	273	1.891	273	2.73	273	3.58	273	5.82
293	1.587	293	1.796	293	2.007	293	2.85	293	3.70	293	5.94
300	1.629	300	1.838	300	2.049	300	2.89	300	3.74	300	5.98
350	1.930	350	2.14	350	2.35	350	3.19	350	4.04	350	6.28
400	2.236	400	2.45*	400	2.66	400	3.50	400	4.34	400	6.59
500	2.863	500	3.07*	500	3.28	500	4.12	500	4.97	500	7.21
600	3.509	600	3.72*	600	3.93	600	4.77	600	5.62	600	7.86
700	4.174	700	4.38*	700	4.59	700	5.43	700	6.28	700	8.52
800	4.860	800	5.07*	800	5.28*	800	6.12*	800	6.96*	800	9.21
900	5.565	900	5.77*	900	5.98*	900	6.83*	900	7.64*	900	9.91
1000	6.297	1000	6.51*	1000	6.72*	1000	7.56*	1000	8.38*	1000	10.64
1100	7.085	1100	7.29*	1100	7.50*	1100	8.35*	1100	9.20*	1100	11.43
1200	7.822										
1235.08	8.233(s)										
1236	17.31(t)										
1400	18.69										
1600	20.88										

† Uncertainties in the electrical resistivity values are as follows:

- 100.00 Ag - 0.00 Pd:  $\pm 1\%$  up to 10 K,  $\pm 5\%$  above 10 K to 30 K,  $\pm 2\%$  above 30 K to 70 K,  $\pm 1\%$  above 70 K to 400 K,  $\pm 2\%$  above 400 K to 1235.08 K, and  $\pm 4\%$  above 1235.08 K.
- 99.50 Ag - 0.50 Pd:  $\pm 5\%$  below 70 K,  $\pm 3\%$  from 70 to 300 K, and  $\pm 2\%$  above 300 K.
- 99.00 Ag - 1.00 Pd:  $\pm 4\%$  below 70 K,  $\pm 3\%$  from 70 to 300 K, and  $\pm 2\%$  above 300 K.
- 97.00 Ag - 3.00 Pd:  $\pm 4\%$  up to 100 K and  $\pm 3\%$  above 100 K.
- 95.00 Ag - 5.00 Pd:  $\pm 4\%$  up to 100 K and  $\pm 3\%$  above 100 K.
- 90.00 Ag - 10.00 Pd:  $\pm 5\%$  up to 500 K and  $\pm 4\%$  above 500 K.

\* In temperature range where no experimental data are available.

TABLE 10. RECOMMENDED ELECTRICAL RESISTIVITY OF SILVER-PALLADIUM ALLOY SYSTEM† (continued)

[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Ag: 85.00% (84.82 At.%) Pd: 15.00% (15.18 At.%)		Ag: 80.00% (79.78 At.%) Pd: 20.00% (20.22 At.%)		Ag: 75.00% (74.74 At.%) Pd: 25.00% (25.26 At.%)		Ag: 70.00% (69.71 At.%) Pd: 30.00% (30.29 At.%)		Ag: 65.00% (64.69 At.%) Pd: 35.00% (35.31 At.%)		Ag: 60.00% (59.67 At.%) Pd: 40.00% (40.33 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	6.30*	1	8.39	1	10.52	1	12.91	1	15.7	1	18.8
4	6.30*	4	8.39	4	10.52	4	12.91	4	15.7	4	18.8
7	6.30*	7	8.39	7	10.52	7	12.91	7	15.7	7	18.8
10	6.30*	10	8.39	10	10.52	10	12.91	10	15.7	10	18.8
15	6.31*	15	8.40	15	10.52	15	12.91	15	15.7	15	18.8
20	6.31*	20	8.40	20	10.53	20	12.91	20	15.7	20	18.8
25	6.32*	25	8.41	25	10.53	25	12.92	25	15.7	25	18.8
30	6.34*	30	8.43	30	10.55	30	12.93	30	15.7	30	18.8
40	6.39*	40	8.48	40	10.59*	40	12.98	40	15.8*	40	18.9
50	6.45*	50	8.54	50	10.65*	50	13.04	50	15.8*	50	18.9
60	6.52*	60	8.61	60	10.72*	60	13.11	60	15.9*	60	19.0
70	6.60*	70	8.68	70	10.80*	70	13.19	70	16.0*	70	19.1
80	6.67*	80	8.76	80	10.88*	80	13.27	80	16.1	80	19.2
90	6.75*	90	8.83	90	10.96*	90	13.35	90	16.1*	90	19.3
100	6.82*	100	8.91	100	11.04*	100	13.43	100	16.2*	100	19.4
150	7.17*	150	9.26	150	11.39*	150	13.78	150	16.6*	150	19.9
200	7.48*	200	9.57	200	11.70*	200	14.09	200	17.0*	200	20.3
250	7.78*	250	9.87	250	12.00*	250	14.39	250	17.3*	250	20.7
273	7.92*	273	10.01	273	12.14*	273	14.53	273	17.4*	273	20.9
293	8.04*	293	10.13	293	12.26*	293	14.65	293	17.6*	293	21.1
300	8.08*	300	10.17	300	12.30*	300	14.69	300	17.6*	300	21.2
350	8.38*	350	10.47	350	12.60*	350	14.99	350	18.0*	350	21.6
400	8.68*	400	10.78	400	12.91*	400	15.30	400	18.3*	400	22.0
500	9.31*	500	11.40	500	13.53*	500	15.92	500	18.9*	500	22.8
600	9.96*	600	12.05	600	14.18*	600	16.57	600	19.6*	600	23.6
700	10.63*	700	12.71	700	14.84*	700	17.23	700	20.3*	700	24.4
800	11.31*	800	13.40	800	15.53*	800	17.92	800	21.0*	800	25.2
900	12.00*	900	14.09	900	16.22*	900	18.61	900	21.7*	900	26.0
1000	12.73*	1000	14.83	1000	16.95*	1000	19.34	1000	22.5*	1000	26.8
1100	13.52*	1100	15.62	1100	17.75*	1100	20.14	1100	23.3*	1100	27.7

† Uncertainties in the electrical resistivity values are as follows:

- 85.00 Ag - 15.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 80.00 Ag - 20.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 75.00 Ag - 25.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 70.00 Ag - 30.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 65.00 Ag - 35.00 Pd:  $\pm 4\%$ .
- 60.00 Ag - 40.00 Pd:  $\pm 4\%$ .

\* In temperature range where no experimental data are available.



TABLE 10. RECOMMENDED ELECTRICAL RESISTIVITY OF SILVER-PALLADIUM ALLOY SYSTEM† (continued)  
 † Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$

Ag: 55.00% (54.66 At.%) Pd: 45.00% (45.34 At.%)		Ag: 50.00% (49.66 At.%) Pd: 50.00% (50.34 At.%)		Ag: 45.00% (44.66 At.%) Pd: 55.00% (55.34 At.%)		Ag: 40.00% (39.67 At.%) Pd: 60.00% (60.33 At.%)		Ag: 35.00% (34.69 At.%) Pd: 65.00% (65.31 At.%)		Ag: 30.00% (29.71 At.%) Pd: 70.00% (70.29 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	22.5	1	28.4	1	35.7	1	39.7	1	39.1	1	35.5*
4	22.5	4	28.4	4	35.7	4	39.7	4	39.1	4	35.5
7	22.5	7	28.4	7	35.7	7	39.7	7	39.1	7	35.5
10	22.5	10	28.4	10	35.7	10	39.7	10	39.1	10	35.5
15	22.5	15	28.4	15	35.7	15	39.7	15	39.1	15	35.5
20	22.5	20	28.4	20	35.7	20	39.7	20	39.1	20	35.5
25	22.5	25	28.4	25	35.7	25	39.7	25	39.1*	25	35.5
30	22.6*	30	28.4	30	35.7	30	39.7	30	39.1*	30	35.5
40	22.6*	40	28.5	40	35.8*	40	39.7	40	39.2*	40	35.7
50	22.7*	50	28.6	50	35.9*	50	39.9	50	39.4*	50	35.8
60	22.8*	60	28.7	60	36.1*	60	40.1	60	39.6*	60	36.1
70	22.9*	70	28.9	70	36.2*	70	40.3	70	39.8*	70	36.3
80	23.0	80	29.0	80	36.4*	80	40.4	80	40.0*	80	36.6
90	23.2*	90	29.1	90	36.5*	90	40.6	90	40.2*	90	36.8
100	23.3*	100	29.3	100	36.7*	100	40.8	100	40.4*	100	37.1
150	23.9*	150	29.9	150	37.3*	150	41.4	150	41.2*	150	38.3
200	24.4*	200	30.5	200	37.8*	200	41.9	200	42.0*	200	39.3
250	25.0*	250	31.0	250	38.1*	250	42.1	250	42.5*	250	40.1
273	25.3*	273	31.2	273	38.2*	273	42.2	273	42.7*	273	40.4
293	25.5	293	31.4	293	38.3	293	42.2	293	42.8	293	40.6
300	25.6	300	31.5	300	38.3	300	42.2	300	42.9	300	40.7
350	26.1*	350	32.0	350	38.4*	350	42.3	350	43.1*	350	41.3
400	26.6*	400	32.4	400	38.5*	400	42.3	400	43.3*	400	41.7
500	27.6*	500	33.2	500	38.7*	500	42.2	500	43.5*	500	42.5
600	28.5*	600	34.0	600	39.0*	600	42.2	600	43.7*	600	43.1
700	29.4*	700	34.8	700	39.4*	700	42.1	700	43.8*	700	43.6
800	30.2*	800	35.5	800	39.7*	800	42.2	800	43.9*	800	44.1
900	31.0*	900	36.3	900	40.2*	900	42.3	900	44.1*	900	44.6
1000	31.7*	1000	36.9	1000	40.6*	1000	42.4	1000	44.4*	1000	45.1
1100	32.4*	1100	37.6	1100	41.1*	1100	42.6	1100	44.8*	1100	45.7

† Uncertainties in the electrical resistivity values are as follows:

- 55.00 Ag - 45.00 Pd:  $\pm 4\%$  up to 300 K and  $\pm 5\%$  above 300 K.
- 50.00 Ag - 50.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 45.00 Ag - 55.00 Pd:  $\pm 2\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 40.00 Ag - 60.00 Pd:  $\pm 2\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 35.00 Ag - 65.00 Pd:  $\pm 2\%$  up to 300 K and  $\pm 3\%$  above 300 K.
- 30.00 Ag - 70.00 Pd:  $\pm 2\%$  up to 250 K and  $\pm 3\%$  above 250 K.

\* In temperature range where no experimental data are available.

TABLE 10. RECOMMENDED ELECTRICAL RESISTIVITY OF SILVER-PALLADIUM ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Ag: 25.00% (24.74 At. %) Pd: 75.00% (75.26 At. %)		Ag: 20.00% (19.78 At. %) Pd: 80.00% (80.22 At. %)		Ag: 15.00% (14.83 At. %) Pd: 85.00% (85.17 At. %)		Ag: 10.00% (9.88 At. %) Pd: 90.00% (90.12 At. %)		Ag: 5.00% (4.94 At. %) Pd: 95.00% (95.06 At. %)		Ag: 3.00% (2.96 At. %) Pd: 97.00% (97.04 At. %)	
T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$
1	30.47	1	24.72	1	18.56*	1	12.87	1	6.18*	1	3.71
4	30.47	4	24.72	4	18.56*	4	12.87	4	6.18	4	3.71
7	30.47	7	24.72	7	18.56*	7	12.87	7	6.18	7	3.71
10	30.47	10	24.72	10	18.56*	10	12.87	10	6.18	10	3.71
15	30.47	15	24.72	15	18.57*	15	12.88	15	6.20	15	3.72
20	30.47	20	24.74	20	18.59*	20	12.40	20	6.22	20	3.75
25	30.51	25	24.77	25	18.63*	25	12.45	25	6.27	25	3.80
30	30.56	30	24.83	30	18.69*	30	12.51	30	6.34	30	3.88
40	30.71	40	24.99	40	18.87*	40	12.71	40	6.56	40	4.11
50	30.90*	50	25.21	50	19.11*	50	12.97	50	6.85	50	4.41
60	31.15*	60	25.49	60	19.41*	60	13.29	60	7.19	60	4.77
70	31.43*	70	25.81	70	19.76*	70	13.67	70	7.59	70	5.17
80	31.75*	80	26.16	80	20.14*	80	14.08	80	8.02	80	5.60
90	32.08*	90	26.53	90	20.55*	90	14.52	90	8.46	90	6.05
100	32.40*	100	26.90	100	20.97*	100	14.95	100	8.91	100	6.50
150	33.88*	150	28.67	150	22.97*	150	17.06	150	11.09	150	8.67
200	35.13*	200	30.20	200	24.75*	200	19.03	200	13.15	200	10.72
250	36.20*	250	31.56	250	26.38*	250	20.88	250	15.11	250	12.69
273	36.67*	273	32.15	273	27.08*	273	21.69	273	15.98	273	13.56
293	37.06	293	32.64	293	27.68	293	22.39	293	16.72	293	14.30
300	37.19	300	32.8	300	27.89*	300	22.63	300	16.98	300	14.56
350	38.1*	350	33.9	350	29.3*	350	24.3	350	18.8*	350	16.38*
400	38.8*	400	34.9	400	30.6*	400	25.9	400	20.5*	400	18.14*
500	40.1*	500	36.8	500	33.1*	500	28.9	500	23.8*	500	21.50*
600	41.2*	600	38.5	600	35.3*	600	31.6	600	26.9*	600	24.64*
700	42.1*	700	39.9	700	37.3*	700	34.2	700	29.8*	700	27.6*
800	43.0*	800	41.2	800	39.1*	800	36.6	800	32.5*	800	30.4*
900	43.9*	900	42.5	900	40.8*	900	38.8	900	35.0*	900	32.9*
1000	44.8*	1000	43.7	1000	42.3*	1000	40.8	1000	37.2*	1000	35.3*
1100	45.6*	1100	44.8	1100	43.7*	1100	42.6	1100	39.2*	1100	37.3*

† Uncertainties in the electrical resistivity values are as follows:

- 25.00 Ag - 75.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 20.00 Ag - 80.00 Pd:  $\pm 3\%$  up to 300 K and  $\pm 4\%$  above 300 K.
- 15.00 Ag - 85.00 Pd:  $\pm 4\%$ .
- 10.00 Ag - 90.00 Pd:  $\pm 4\%$ .
- 5.00 Ag - 95.00 Pd:  $\pm 4\%$  up to 100 K and  $\pm 3\%$  above 100 K.
- 3.00 Ag - 97.00 Pd:  $\pm 4\%$  below 50 K,  $\pm 3\%$  from 50 to 200 K, and  $\pm 2\%$  above 200 K.

\* In temperature range where no experimental data are available.

TABLE 10. RECOMMENDED ELECTRICAL RESISTIVITY OF SILVER-PALLADIUM ALLOY SYSTEM† (continued)  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

Ag: 1.00% (0.99 At.%) Pd: 99.00% (99.01 At.%)		Ag: 0.50% (0.49 At.%) Pd: 99.50% (99.51 At.%)		Ag: 0.00% (0.00 At.%) Pd: 100.00% (100.00 At.%)	
T	$\rho$	T	$\rho$	T	$\rho$
1	1.236	1	0.617	1	0.0200
4	1.236	4	0.617	4	0.0205
7	1.236	7	0.618	7	0.0217
10	1.240	10	0.622	10	0.0242
15	1.252	15	0.633	15	0.0346
20	1.280	20	0.659	20	0.0564
25	1.33	25	0.705	25	0.0938
30	1.40	30	0.773	30	0.151
40	1.62	40	0.976	40	0.335
50	1.90	50	1.253	50	0.607
60	2.25	60	1.592	60	0.940
70	2.64	70	1.98	70	1.32
80	3.07	80	2.40	80	1.75
90	3.52	90	2.85	90	2.19
100	3.97	100	3.29	100	2.63
150	6.14	150	5.47	150	4.81
200	8.21	200	7.54	200	6.89
250	10.18	250	9.52	250	8.88
273	11.06	273	10.41	273	9.78
293	11.82	293	11.17	293	10.54
300	12.08*	300	11.43*	300	10.80
350	13.92*	350	13.28*	350	12.66
400	15.70*	400	15.07*	400	14.46
500	19.13*	500	18.50*	500	17.89
600	22.32*	600	21.70*	600	21.10
700	25.3*	700	24.7*	700	24.10
800	28.1*	800	27.5*	800	26.89
900	30.7*	900	30.1*	900	29.50
1000	33.1*	1000	32.5*	1000	31.92
1100	35.2*	1100	34.7*	1200	36.21
				1400	39.80
				1600	42.70
				1827	45.14 (s)
				1830	83.0 (t)
				2000	83.0

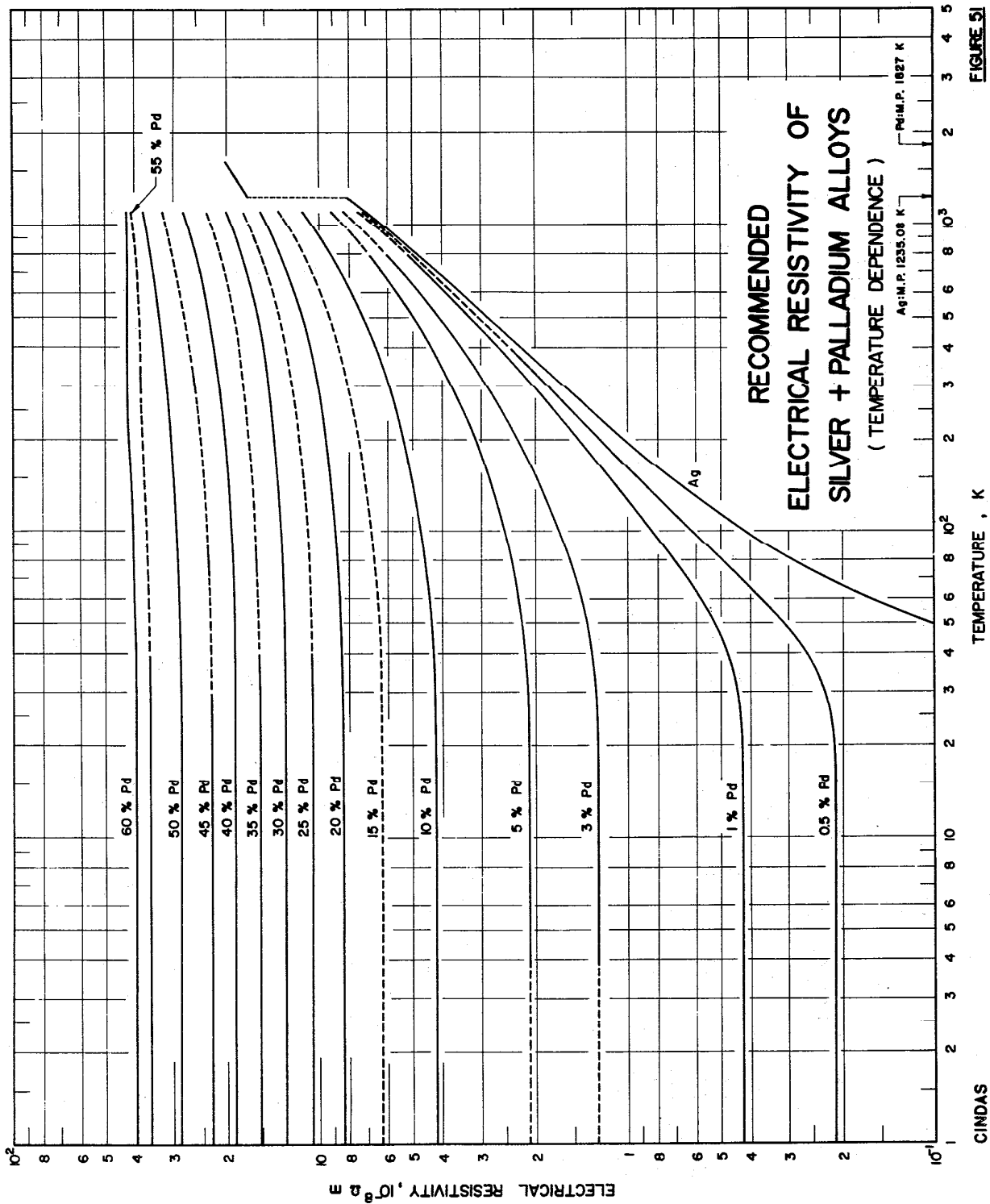
† Uncertainties in the electrical resistivity values are as follows:

1.00 Ag - 99.00 Pd:  $\pm 4\%$  up to 50 K and  $\pm 2\%$  above 50 K.

0.50 Ag - 99.50 Pd:  $\pm 4\%$  up to 50 K and  $\pm 2\%$  above 50 K.

0.00 Ag - 100.00 Pd:  $\pm 2\%$  up to 40 K,  $\pm 1\%$  above 40 K to 350 K,  $\pm 2\%$  above 350 K to 1827 K, and  $\pm 5\%$  above 1827 K.

\* In temperature range where no experimental data are available.



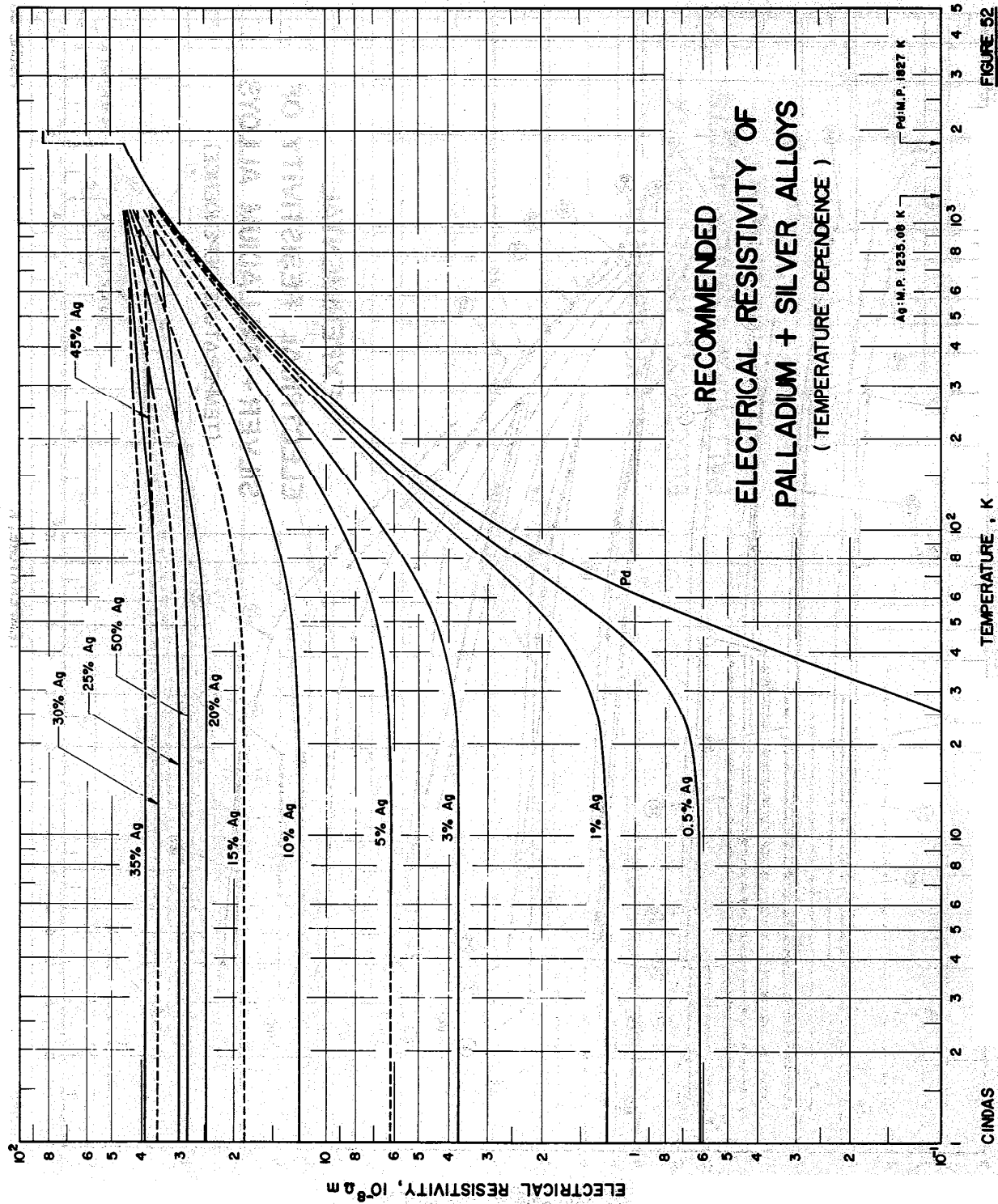


FIGURE 52

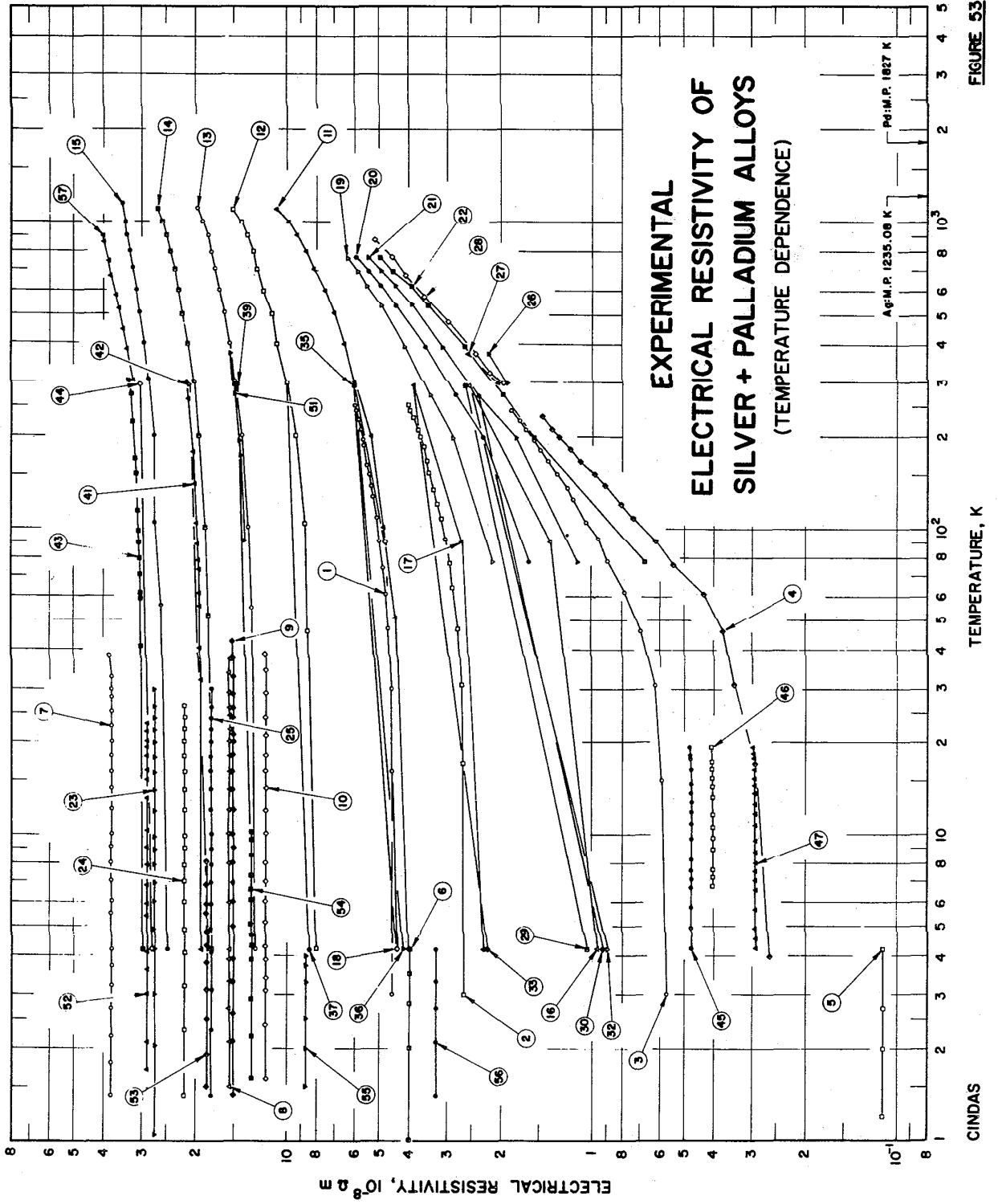


FIGURE 53

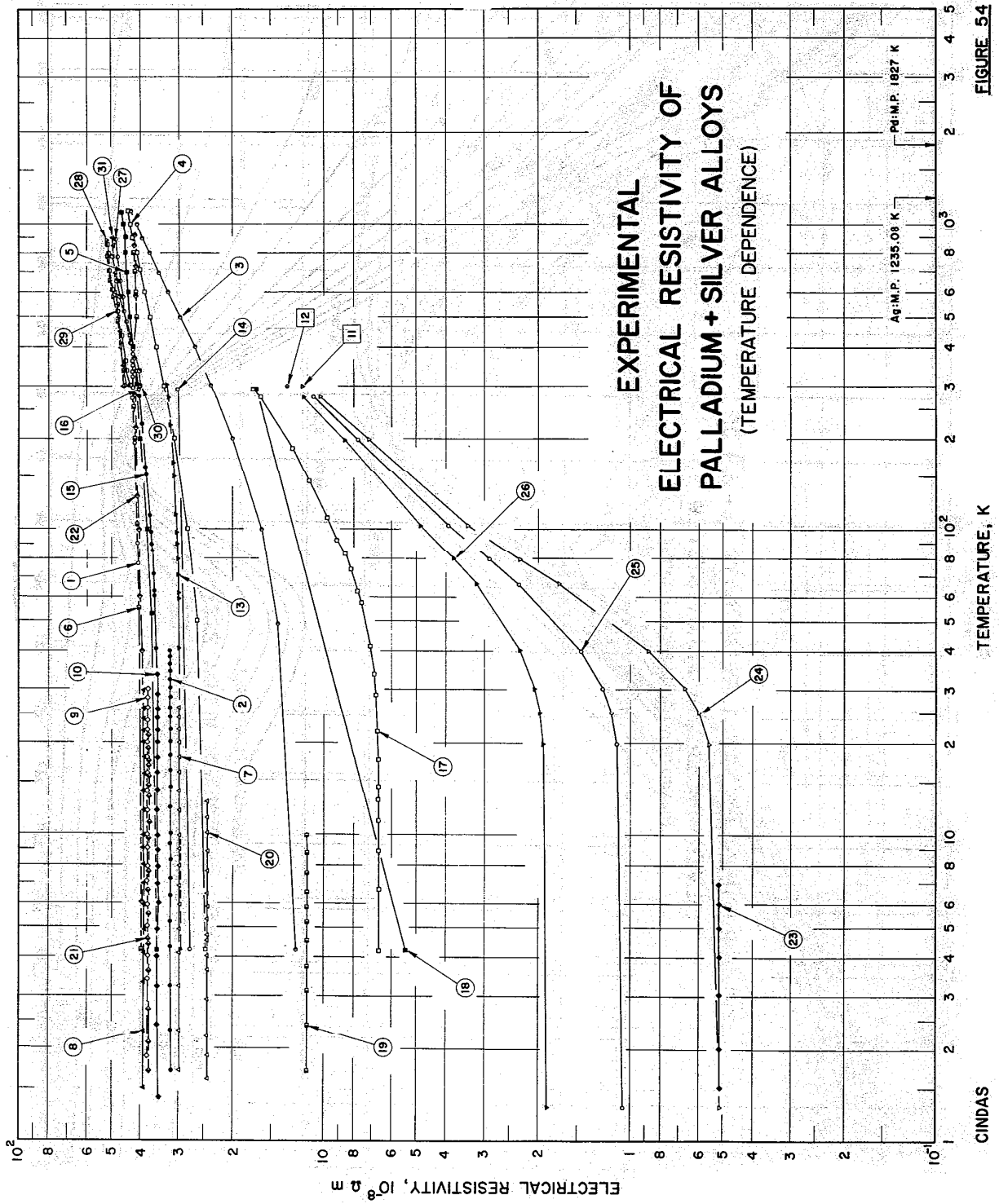
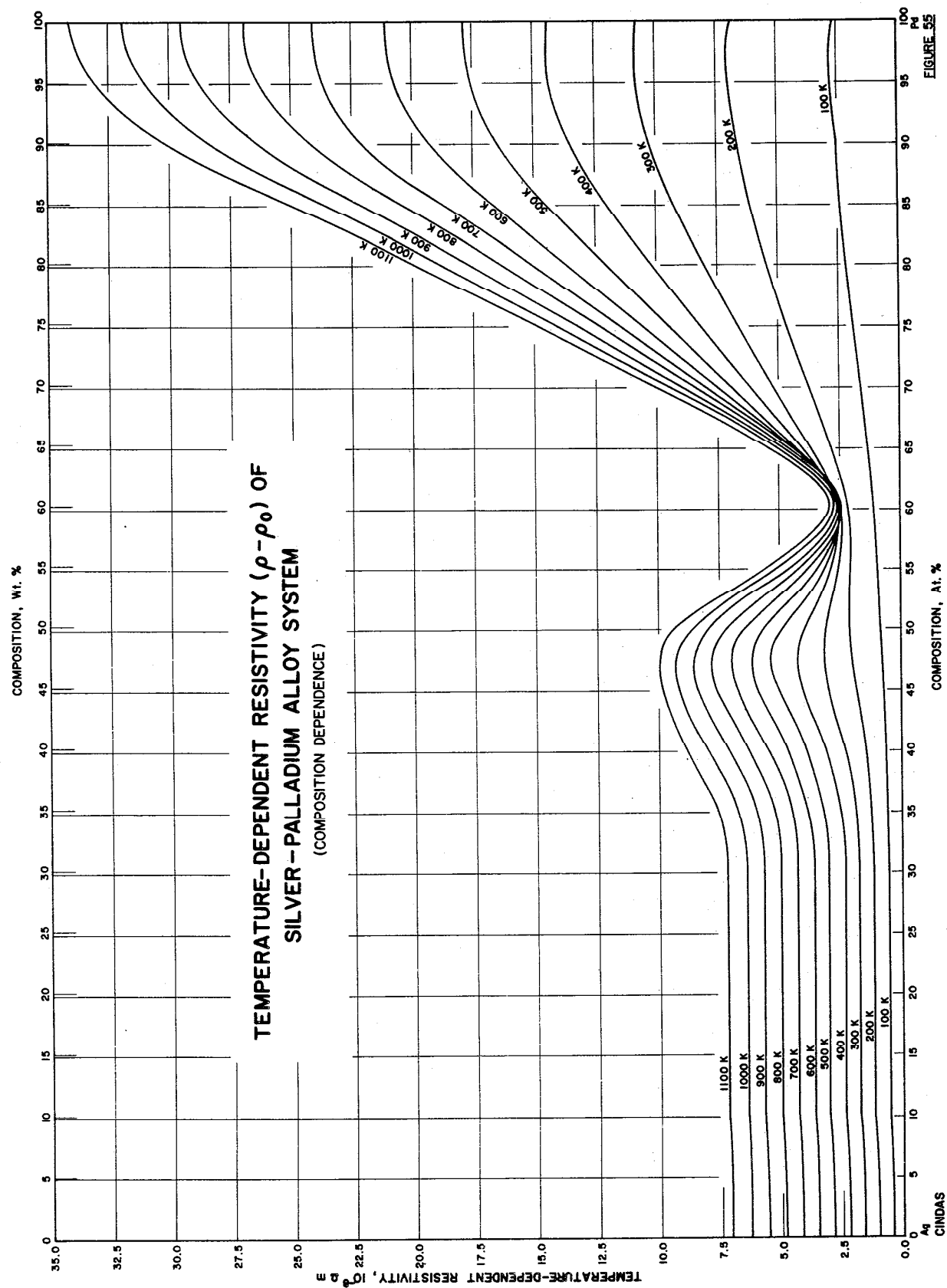
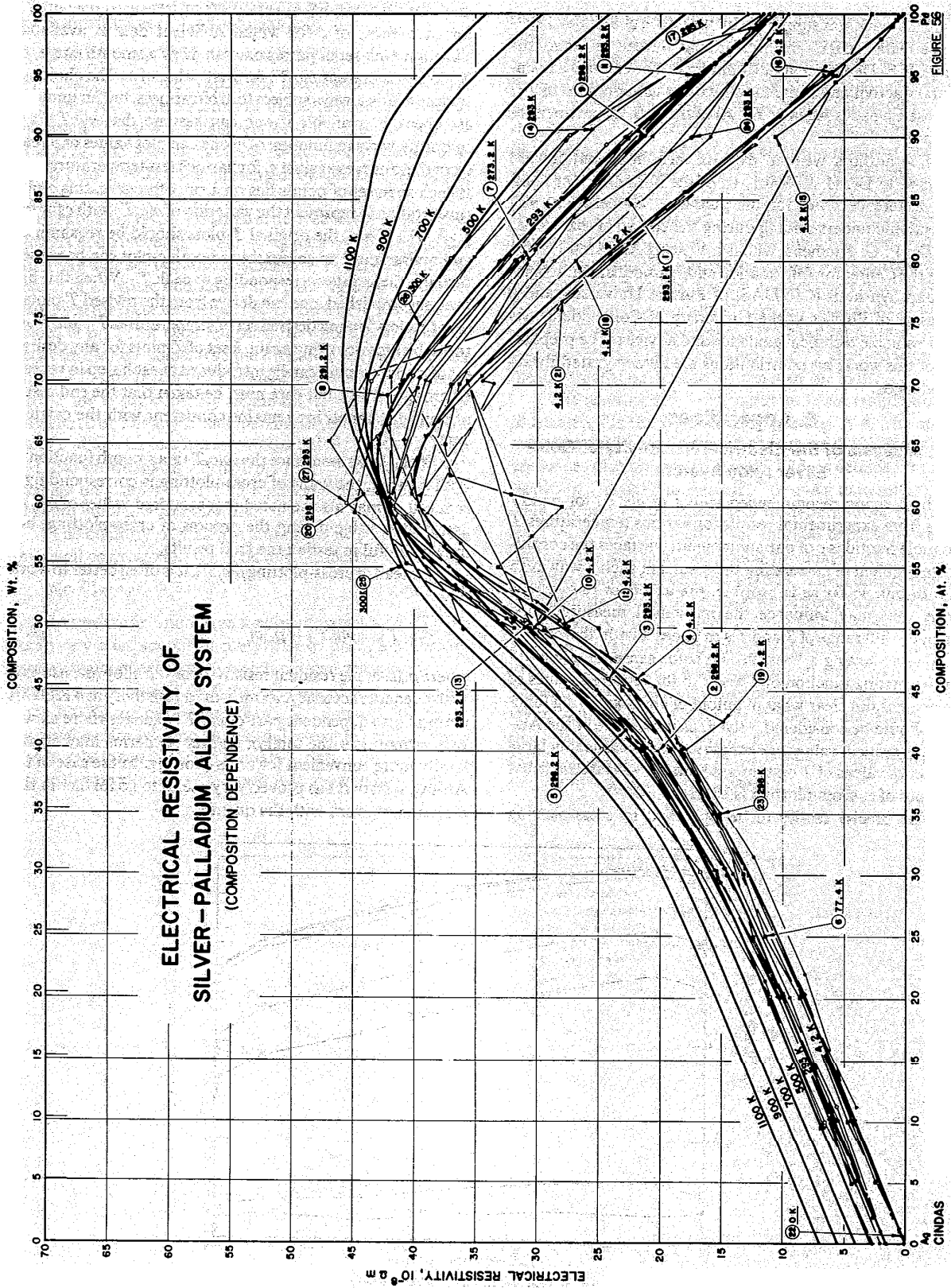


FIGURE 54







## 4. Acknowledgments

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## 5. Appendices

### 5.1. Analysis of the Electrical Resistivity of Gold-Silver Alloy System

In deriving recommended values of  $\rho(c, T)$  for binary alloys from experimental results for various temperatures  $T$  and mole fractions  $c$  of one component, one faces the considerable problem of correlating the results in such a way as to smooth out, so far as is possible, the effects of the various errors that may influence the individual measurements. When the full range of  $T$  and  $c$  is to be dealt with, this cannot be done by getting a "best fit" (in some sense) of a smooth approximating function of  $T$  and  $c$  to the reported values of  $\rho$ , since it is not clear what manifold of approximating functions should be considered. Given, as in the case of the Au-Ag alloy system, values of  $\rho$  measured for a reasonably large number of values of  $T$  on samples with a reasonable number of values of  $c$ , cross-plotting is effective.

The precise tactics to be employed in cross-plotting

may depend on the data available in a particular case. One may, for instance, begin with plots of measured  $\rho$  against  $T$  for each value of  $c$  for which sufficient data is available. Through each set of points one can draw a smooth curve, or  $T$ -plot, to represent  $\rho(c, T)$  for that value of  $c$ . The choice of such curves is always subject to arbitrariness, but an immediate check is available if one can assume that  $\rho(c, T)$  is a smoothly varying function of  $c$ : one can plot values of  $\rho$  read from these curves against  $c$ , for various test temperatures  $T_1$ . If each such set of points lies on a smooth curve, this  $c$ -plot can be taken to represent the variation of  $\rho(c, T)$  with  $c$  for the given  $T_1$ . If not, the original  $T$ -plots should be reexamined and revised until an acceptably smooth  $c$ -plot can be passed through the points corresponding to each  $T_1$ . When this has been accomplished, one can derive from the revised  $T$ -plots a set of  $c$ -plots for any desired set of temperatures  $T_i$ , and from these, by cross-plotting again, a set of  $T$ -plots for any desired set of  $c_j$ . Smoothing can be introduced at each step in repeated cross-plotting, but care must be taken that the end result of multiple smoothing remains consistent with the original data.

If one lacks assurance that  $\rho(c, T)$  is a smooth function of both  $c$  and  $T$ , the value of cross-plotting is correspondingly reduced. It may also be noted that scattered values of  $\rho(c, T)$  are of little value during the process of cross-plotting, but may be useful in testing the final results.

Instead of cross-plotting  $\rho(c, T)$ , it is often better to work with

$$\rho_i(c, T) = \rho(c, T) - \rho_0(c), \quad (\text{A1})$$

where  $\rho_0(c)$  is the residual resistivity of the alloy (or, usually, with adequate accuracy, its measured resistivity at 4 K). This temperature-dependent part of  $\rho(c, T)$  changes more slowly with  $c$  than does the total  $\rho$ , and its isotherms may form a family more convenient for cross-plotting. In the case of the Au-Ag system it has proved very useful to go further in this direction, to work with the quantity

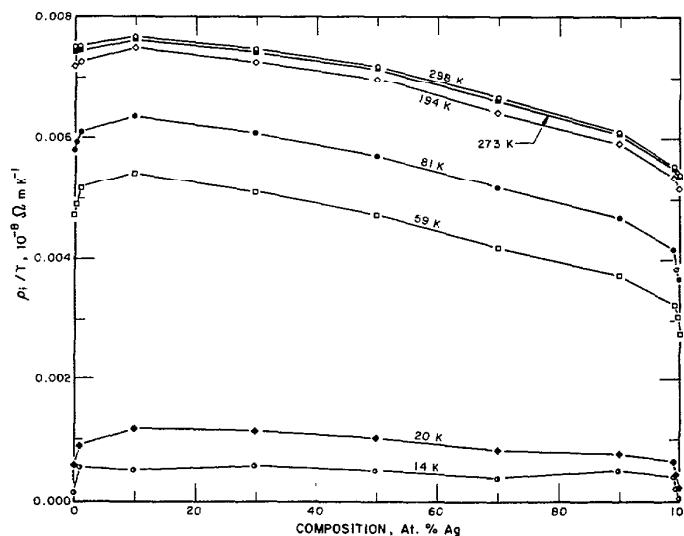


Figure A-1.  $\rho_i(c, T)/T$  as a Function of  $T$ . Pure Metal Values Recommended by CINDAS, Values for  $c = 0.25$  and  $1 \text{ At.}\%$  from data of Stewart and Huebener [301], for  $c = 10$  to  $90 \text{ At.}\%$  from data of Glaueque and Stout [29], and for  $c = 99$  and  $99.5 \text{ At.}\%$  from data of Dugdale and Basinski [29].

$$\Delta(c, T) = \rho_i(c, T) - \bar{\rho}_i(c, T), \quad (\text{A2})$$

where  $\bar{\rho}_i$  is the atomic-fraction-weighted average of the intrinsic resistivities of the pure metals:

$$\bar{\rho}_i(c, T) = c\rho_i^{(\text{Ag})}(T) + (1-c)\rho_i^{(\text{Au})}(T) \quad (\text{A3})$$

with  $c \equiv c_{\text{Ag}}$ . The motivation for this choice will be clear from Fig. A-1, where results of measurements of Giaque and Stout<sup>297</sup> (Au + Ag data sets 24–26, Ag + Au data sets 21 and 22, and Au–Ag data sets 16–20) on a series of alloys ( $c = 0.1$  to  $c = 0.9$ ) are presented by plotting  $\rho_i(c, T)/T$  against  $c$ , for seven temperatures ranging from 14 to 298 K. Corresponding values for small  $c$ , derived from the results of Stewart and Huebener<sup>301</sup> (Au + Ag data sets 59 and 60 and Au + Ag data set 14), and for small  $(1-c)$ , derived from the results of Dugdale and Basinski<sup>29</sup> (Au–Ag data set 15) are also given for these temperatures. Comparison of the plotted values of  $\rho_i/T$  for each temperature with the straight line between the end points (the pure metals), which represents  $\bar{\rho}_i(c, T)/T$ , shows that  $\Delta/T$  is small and varies only slowly with  $c$  for  $0.2 < c < 0.8$ . By definition, it vanishes as  $c$  approaches 0 or 1 at any  $T$ , and (barring highly unlikely behavior of  $\rho$  at low temperatures) as  $T$  goes to 0 for any  $c$ . Figure A-1 also shows that  $\Delta/T$  (like  $\rho_i/T$ ,  $\rho_i^{(\text{Ag})}/T$ , and  $\rho_i^{(\text{Au})}/T$ ) changes only slowly with  $T$  at high temperatures, and even down to quite low temperatures.

The quantity  $\Delta$ , which is at most a few percent of  $\rho$ , is the small correction to the good approximation

$$\rho(c, T) \approx \rho_0(c) + \bar{\rho}_i(c, T). \quad (\text{A4})$$

Irregularities and discrepancies in values of  $\rho(c, T)$  become very conspicuous in plots of  $\Delta$  or  $\Delta/T$ , and this increases the confidence with which one can reject some data as aberrant or unreliable. Cross-plotting of  $\Delta$  is convenient up to 300 K, and cross-plotting of  $\Delta/T$  down to 100 K; the range of overlap in  $T$  makes it useful to employ both types of plot in relating low- $T$  data to high- $T$  data.

As examples, Figs. A-2 and A-3 show values of  $\Delta/T$

derived from five sets of measurements, for  $c_{\text{Ag}} = 0.5$  and 0.9, respectively. The indicated curves were derived by cross-plotting values of  $\Delta$ , starting from data on samples with  $c = 0.05, 0.1, 0.3, 0.5, 0.7, 0.75, 0.9, 0.95,$  and  $0.97$  for which the authors had measured  $\rho(c, 4 \text{ K})$  as well as  $\rho$  at higher temperatures. (As will be discussed later, availability of  $\rho(c, 4 \text{ K})$  eliminates some sources of error in the determination of  $\Delta$ .) The value of  $\rho(c, 4 \text{ K})$  was available for all data illustrated in Figs. A-2 and A-3 except that of Iyer and Asimow<sup>302</sup> (Au + Ag data sets 2–5, Ag + Au data sets 11–13, and Au–Ag data set 46), for which  $\rho_0(c)$  had to be deduced from a  $\rho_0$  vs  $c$  curve and the stated  $c$ . The correction for thermal expansion of the samples, made by Iyer and Asimow, has been removed in calculating  $\Delta/T$  in order to maintain uniformity in the neglect of this correction. Data of Grüneisen and Reddemann<sup>128</sup> (Au + Ag data sets 27 and 28 and Ag + Au data sets 23 and 24) are not represented in Fig. A-2, since two of the three values of  $\Delta/T$  derived from their measurements lie outside the range of the figure.

The result of cross-plotting  $\Delta$  to lower temperatures is illustrated, for the Ag-rich alloys, in Fig. A-4. The crosses represent values read from cross-plots of  $\Delta/T$ . Also shown are values of  $\Delta$  for  $c = 0.99$  and  $0.995$ , as deduced from the results of Dugdale and Basinski<sup>29</sup> (Au–Ag data set 15), who were primarily concerned with deviations from Matthiessen's rule; their correction for thermal expansion was removed, but not their correction for change of volume on alloying, which they describe as small. These data are consistent with the idea (not necessarily correct) that  $\Delta$  increases monotonically with  $c$  at all  $T$ , and this idea has been used as a guide in extrapolating to the very small corrections at the lowest  $T$ . For small  $c$  a similar relation was found between values of  $\Delta$  derived from cross-plots of  $\Delta/T$  for  $c > 0.05$  and values derived from the results of Stewart and Huebener<sup>301</sup> (Au + Ag data sets 59 and 60 and Au–Ag data set 14) for  $c < 0.01$ . For interpolation to low values of  $c$  it is convenient to use cross-plots of  $\rho(c, T)/c$  against  $c$ .

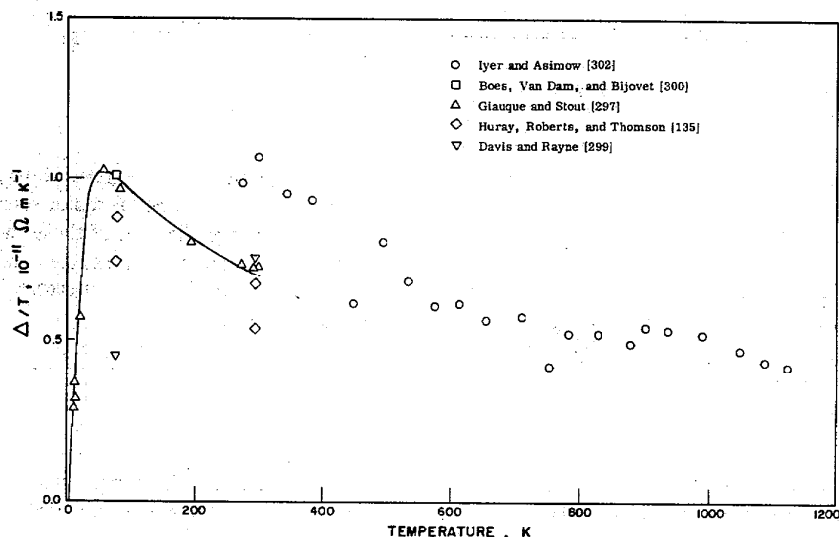


Figure A-2.  $\Delta/T$  as a Function of  $T$  for  $c_{\text{Ag}} = 50 \text{ At.}\%$ . Data Points and Estimated Curve to 300 K.

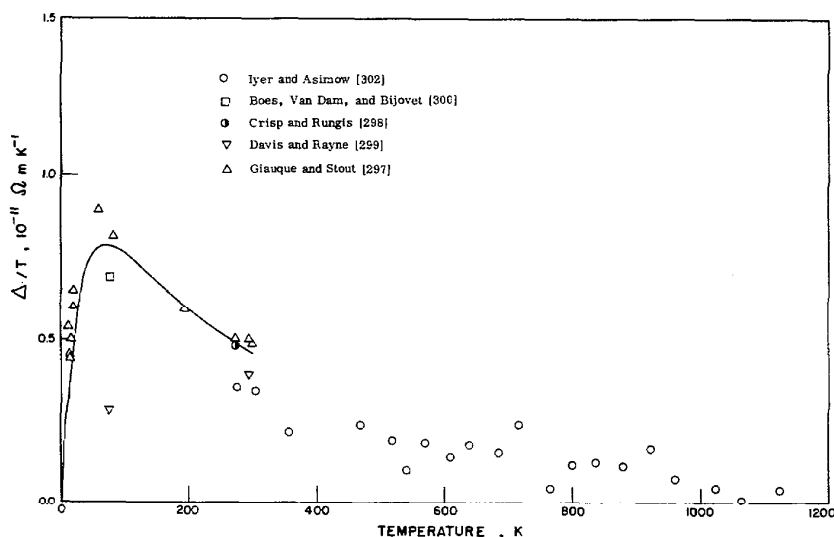


Figure A-3.  $\Delta/T$  as a Function of  $T$ , for  $c_{Ag} = 90$  At.%. Data Points and Estimated Curve to 300 K.

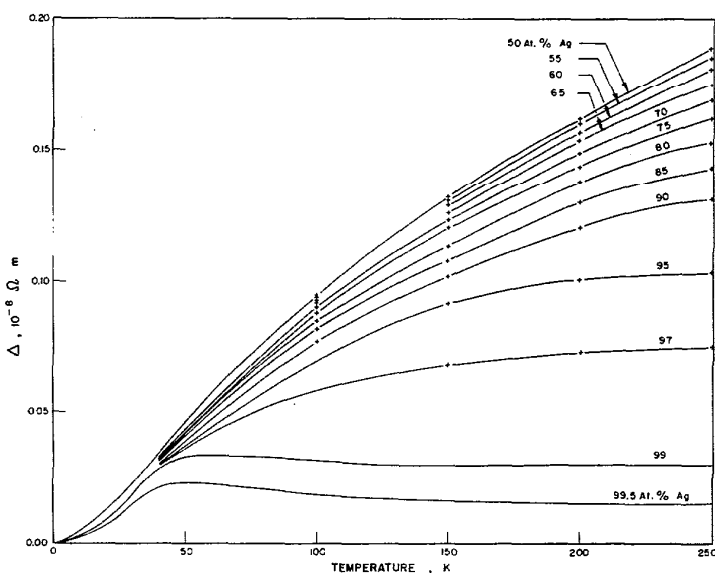


Figure A-4.  $\Delta$  as a Function of  $T$ , for Silver-Rich Alloys, as Derived from Cross Plots of  $\Delta/T$ . Values for  $c_{Ag} = 99$  and 99.5 At.% are Derived from Data of Dugdale and Basinski [29], as Described in Text.

For the solid above room temperature the only data useful in cross-plotting are those of Iyer and Asimow,<sup>302</sup> for  $c = 0.05, 0.1, 0.3, 0.5, 0.7, 0.9,$  and  $0.95$ . As is illustrated in Figs. A-2 and A-3, values for  $\Delta$  derived from their data do not always join smoothly onto values derived from other data at room temperatures and below. This appears to be due in part to errors that (as concerns data obtained for a single sample at many temperatures) may be regarded as systematic, and that are absent from the low- $T$  values of  $\Delta$ . The low- $T$  values were computed as

$$\Delta(c, T) = \rho(c, T) - \rho(c, 4 \text{ K}) - \bar{\rho}_i(c, T) \quad (\text{A5})$$

with the first two terms on the right measured on the same sample. An error  $\delta c$  in control of the  $c$  for the sample will change the sum of these two terms by just  $(\partial \rho_i / \partial c) / \delta c$ . Er-

rors in determination of the dimensions of the sample, said by Iyer and Asimow to be the major source of error in their results, will change the sum of these two terms by a fixed fraction of  $\rho_i$ , which we write as  $\rho_i \delta \ell$ , with  $\delta \ell$  a measure of the overall effect of dimensional errors. Together, these errors change  $\Delta$  by

$$\delta \Delta = \frac{\partial \rho_i}{\partial c} \delta c + \rho_i \delta \ell. \quad (\text{A6})$$

Both terms on the right tend to be small because  $\rho_i$  is smaller than  $\rho$  and is, indeed, very small at low temperatures. In processing the data of Iyer and Asimow, on the other hand, it was necessary to use Eq. (A2) instead of Eq. (A5). The errors  $\delta c$  and  $\delta \ell$  then affect only the first term on the right of Eq. (A2), and there is no partially cancelling contribution

from the second term; in addition, there is an independent error,  $-\delta\rho_0(c)$ , arising from any error  $\delta\rho_0(c)$  in the value assigned to  $\rho_0$  at the nominal  $c$ . Together, these sources of error will change  $\Delta$  by

$$\delta\Delta = \left\{ \frac{\partial\rho_0}{\partial c} + \frac{\partial\rho_i}{\partial c} \right\} \delta c + \{\rho_0 + \rho_i\} \delta\ell - \delta\rho_0(c). \quad (\text{A7})$$

The difference between Eqs. (A6) and (A7) represents a systematic difference between the  $\Delta$ 's derived from the low- $T$  data and the data of Iyer and Asimow, respectively.

Since the sources of error should be less important for the low- $T$  results, it seems reasonable to use those results as reference points in reducing the effects of the errors  $\delta c$ ,  $\delta\ell$ , and  $\delta\rho_0$  on the values of  $\Delta$  derived from the data of Iyer and Asimow. This can be done by adjusting the available parameters to make the corrected values  $\Delta - \delta\Delta$  for the high- $T$  data continue smoothly, in the region 300–400 K, the trend established by cross-plotting the low- $T$  data. The process involves no great arbitrariness because  $\delta\Delta$  for any sample is nearly a linear combination of two known functions of  $T$ : a constant, and  $\bar{\rho}_i(c, T)$ . For the Ag–Au alloys one has, with all the accuracy needed in computing this small correction,

$$\rho_i \cong \bar{\rho}_i, \quad (\text{A8})$$

$$\frac{\partial\rho_i}{\partial c} \cong \frac{\partial\bar{\rho}_i}{\partial c} = \rho_i^{(\text{Ag})}(T) - \rho_i^{(\text{Au})}(T). \quad (\text{A9})$$

Further, though  $\bar{\rho}_i$  and  $(\partial\bar{\rho}_i/\partial c)$  involve the metal resistivities in quite different ways, they change with  $T$  in nearly the same way because the  $T$ -dependences of the pure-metal resistivities are so similar. This is illustrated in Table A-1.

Since  $\rho_i^{(\text{Ag})} - \rho_i^{(\text{Au})}$  is about a third as large as  $\rho_i$ , and only small corrections are involved, one can reasonably take the  $T$ -dependence of the second of the five terms on the right in Eq. (A7) to be the same as that of the fourth. Replacing  $(\partial\rho_i/\partial c)$  by  $\kappa\rho_i(c)$ , we have

$$\delta\Delta \cong \left\{ \frac{\partial\rho_0}{\partial c} \delta c + \rho_0(c)\delta\ell - \delta\rho_0(c) \right\} + \bar{\rho}_i(T, c)\{\kappa\delta c + \delta\ell\}, \quad (\text{A10})$$

where the quantities in braces are independent of  $T$ . Adjustment of these two constants to achieve a smooth fit of high- $T$  to low- $T$  data does not, of course, make it possible to estimate the three errors  $\delta c$ ,  $\delta\ell$ ,  $\delta\rho_0$  for a particular high- $T$  sample.

In treating the Au–Ag alloys, the fit between high- $T$  and low- $T$   $\Delta$ 's was actually made on plots of  $\Delta/T$ , such as Figs. A-2 and A-3. Analysis of the low- $T$  data yielded plots that were nearly linear in  $T$  from 100 to 300 K, and appeared to fix  $\Delta$  at 300 K with an error not exceeding  $0.03 \times 10^{-8} \Omega\text{m}$  for any  $c$ . For each of the seven compositions mentioned above, smooth curves were then passed through the high- $T$  data points, with the intention of smoothing out the effect of random errors. This was done as carefully as possible by eye and French curve, without consideration of the relation of curves for different  $c$ , except in one case:  $c = 0.3$ . For this composition the three points derived from the data of Iyer and Asimow for  $293 \text{ K} \leq T \leq 350 \text{ K}$  were far out of line with the other points, and a curve passed through them could not be made to fit in with other curves, either before or after adding the correction  $-\delta\Delta$ . These three points were ignored, and the smoothed curve was passed through the remaining points with knowledge of, but no detailed attention to, the trend of the corresponding curves for other compositions. Each smoothed high- $T$  curve was then matched to the corresponding smoothed low- $T$  curve by addition of a correction  $-\delta\Delta$  that brought it to the same value at 300 K and at 400 K. The  $T$ -plots formed by this union of the high- $T$  and low- $T$  parts were then tested by cross-plotting. The results were acceptable, and further study of the possibilities led to no change in the initial  $T$ -plots. From these  $T$ -plots a complete set of  $c$ -plots was derived, and from these in turn a complete set of  $T$ -plots.

Figure A-5 illustrates the effect of the correction  $-\delta\Delta$  on the high- $T$  data shown in Fig. A-3; it also shows the final  $T$ -plot for  $c = 0.9$ . Figure A-6 shows the final  $c$ -plots of  $\Delta/T$ , which are particularly useful for interpolation or extrapolation at high  $T$ .

It is now necessary to consider the uncertainty in the values of  $\rho(c, T)$  derived by adding the estimated  $\Delta(c, T)$  to the interpolative approximation given by Eq. (A4). This uncertainty arises, not just from uncertainties involved in constructing plots of  $\Delta$ , but from the fact that one must use throughout, not the exact values of  $\rho_0(c)$  for alloys and of  $\rho_i(T)$  for the pure metals, but the best available approximations.

We consider first the uncertainties in the process of correcting the high- $T$  data, of which a detailed study was made in the case of  $c = 0.5$ . It was found that alternative choices of the smoothed curve through the uncorrected data points, together with different ways in which the smoothed high- $T$  curves could be fitted to the low- $T$  curve without an evident discontinuity in the slope, could shift the inferred value of  $\Delta$  at 1000 K only by  $\pm 0.1 \times 10^{-8} \Omega\text{m}$ . Since independent adjustments of this magnitude in the  $T$ -plots for different  $c$  would make trouble with the  $c$ -plots,  $\pm 0.1 \times 10^{-8} \Omega\text{m}$  seems to be a reasonable, and even high, estimate of the uncertainty in  $\Delta$  at 1000 K due to uncertainties in the fitting process. To this error of fitting one must add the uncertainty of the low-temperature  $\Delta$  at 300 K. Estimates of the possible constructional errors in  $\Delta$ , intended to be safe maxima, are shown in Table A-2. These apply to the construction of all the original  $T$ -plots, for  $c$  ranging from 0.05 to 0.95.

Table A-1. Values of  $\rho(T)/\rho(300 \text{ K})$

T, K	$\frac{\rho_i^{(\text{Ag})}(T) - \rho_i^{(\text{Au})}(T)}{\rho_i^{(\text{Ag})}(300\text{K}) - \rho_i^{(\text{Au})}(300\text{K})}$	$\bar{\rho}_i(T)/\bar{\rho}_i(300 \text{ K})$				
		Mole Fraction of Silver				
		0.1	0.3	0.5	0.7	0.9
300	1	1	1	1	1	1
600	2.13	2.15	2.15	2.15	2.15	2.15
900	3.34	3.45	3.44	3.44	3.43	3.42
1200	5.43	5.01	4.98	4.95	4.92	4.89

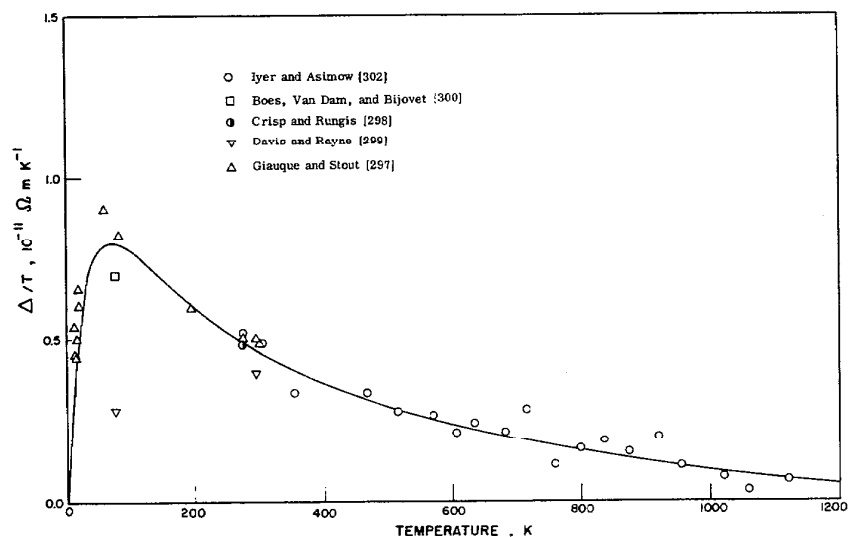


Figure A-5.  $\Delta/T$  as a Function of  $T$ , for  $c_{Ag} = 50$  At.%. Data Points of Iyer and Asimow are Adjusted as Described in Text, and Estimated Curve is Extended to 1200 K.

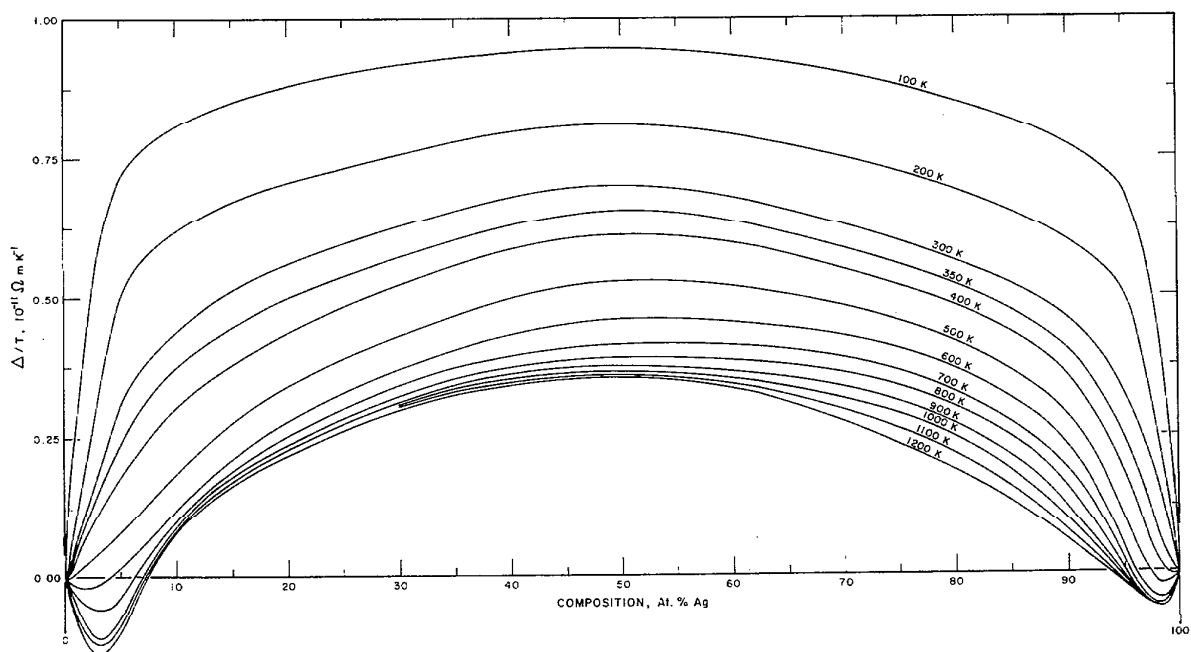


Figure A-6. Final Plot of  $\Delta/T$  as a Function of Composition for Fixed Temperatures.

Table A-2. Estimated Maximum Error in Constructing T-Plots

T, K	Uncertainty in $\Delta$ , $10^{-8} \Omega\text{m}$
100	0.015
200	0.02
400	0.04
600	0.06
800	0.085
1000	0.11
1200	0.14

In this method of analysis, the primary reason for subtracting  $\rho_0(c)$  and  $\bar{\rho}_i(c, T)$  from the observed  $\rho(c, T)$  is to get a smaller or more slowly changing quantity [ $\Delta(c, T)$ , or  $\Delta/T$ , or  $\Delta/c$ ] to study. Then inevitable errors in the assumed  $\rho_0(c)$ ,  $\rho_i^{(Ag)}(T)$ , and  $\rho_i^{(Au)}(T)$ , if smoothly changing, will result only in smooth changes in the  $c$ -plots and  $T$ -plots that represent  $\Delta$ . Smoothness of the plots constructed from given data on  $\rho$  may thus provide some check on the smoothness, but none on the accuracy of the assumed  $\rho_0$  and  $\rho_i$ . To the extent that the analysis only smooths out the contribution to  $\Delta$  of the experimental errors in  $\rho$ , recommended values of  $\rho(c, T)$  derived as

$$\rho(c, T) = \rho_0(c) + \bar{\rho}_i(c, T) + \Delta(c, T) \quad (\text{A11})$$

will not contain errors due to the inaccuracies in  $\rho_0$  or  $\bar{\rho}_i$ , these being cancelled out by the difference between the "exact" and the derived values of  $\Delta$ . If, however, one constrains the derived  $\Delta$  to have special properties known to be possessed by the exact  $\Delta$ , this will no longer be the case. If, for instance, one imposes on the derived  $\Delta$ 's the conditions that they vanish as  $c \rightarrow 0$ , as  $c \rightarrow 1$ , and as  $T \rightarrow 0$ , then errors in the assumed  $\rho_0(c)$  will necessarily appear as errors in the derived  $\rho(c, 0 \text{ K})$ , and errors in the assumed  $\rho_i^{(Ag)}$  and  $\rho_i^{(Au)}$  will appear as errors in the derived  $\rho(1, T)$  and  $\rho(0, T)$ , respectively. This is the best one can do unless the data under consideration justify a different extrapolation to the indicated limits—in which case one would in effect be using them to arrive at improved estimates of  $\rho_0$  and of  $\rho_i$ .

In the present case, to extrapolate the alloy data smoothly:  $c = 0, 1$  would yield values of the  $\Delta$ 's that are negative, and values of  $\rho(0, T)$  and  $\rho(1, T)$  that are unacceptably low. The plots of  $\Delta$  in Fig. A-6 have therefore been constructed subject to the condition that the  $\Delta$ 's vanish as  $c \rightarrow 0, 1$ . The possibility of removing the somewhat ill-defined minima near the ends of the curves, by reinterpretation of the data for  $c = 0.05, 0.1, 0.9$  and  $0.95$ , has been examined. The minima for small  $c$  can be removed by changing the

corrections discussed above, while maintaining the smoothness of cross-plots, but this cannot be done with the minima for large  $c$ . The initial and most natural interpretation of the data is that presented in Fig. A-6.

An estimate of the constructional uncertainties remaining in the  $\Delta$ 's of Fig. A-6, after the full cross-plotting procedure, is given in Table A-3; to these should be added any systematic errors not removed in the reconciling of high- $T$  and low- $T$  data.

The uncertainties in the values of  $\rho$  computed using Eq. (A11) have been estimated as follows. For the more concentrated alloys,  $c$  or  $1 - c$  equal to or greater than  $0.05 \cdot 10^{-8} \Omega\text{m}$ , the estimated error has been taken to be the estimated error in  $\rho_0$  (in the first row of Table A-4) plus twice the estimated constructional error. Inclusion of the first term reflects the doubt that the uncertainty in  $\rho_0$  has been much reduced in the cross-plotting, and the doubling of the second term is intended to allow for systematic errors not removed in that process. For the most dilute alloys, the estimated error has been taken to be the estimated constructional error in  $\Delta$ , plus the uncertainty in  $\rho_0$ , plus the uncertainty in the  $\rho_i$  of the pure solvent metal (first or last column of Table A-4). The estimated uncertainties are shown in Table A-4, both in absolute terms, and as a percentage of the estimated  $\rho$ .

The low estimates of errors for the concentrated alloys,  $0.3 < c < 0.7$ , reflect some optimism that the correlation of high- $T$  and low- $T$  data have reduced (by about 50%) the errors estimated by Iyer and Asimow for the high temperature data; the percentage error in  $\rho$  due to the uncertainty in  $\Delta$  also tends to be small because  $\rho$  is itself so large. The percentage uncertainty is decidedly larger for the more dilute ( $c = 0.01 - 0.03$ ) alloys, for which observations are entirely lacking for  $T > 373 \text{ K}$ , and interpolations of  $\Delta$  are relatively insecure.

Table A-3. Estimated Uncertainties in the Final Values of  $\Delta$ 

T, K	Uncertainty in $\Delta$ , $10^{-8} \Omega\text{m}$		
	Mole Fraction of Silver		
	0.01	0.03-0.97	0.99
100	0.005	0.015	0.01
200	0.005	0.02	0.01
400	0.02	0.03	0.02
600	0.025	0.04	0.02
800	0.03	0.06	0.03
1000	0.04	0.08	0.04
1200	0.05	0.10	0.05

Table A-4. Estimated Uncertainties in the Recommended Values for the Electrical Resistivity of Gold-Silver Alloy System.

T, K	Uncertainty in $\rho$ , $10^{-8} \Omega\text{m}$ and % (in parentheses)												
	Mole Fraction of Silver												
	0.00	0.01	0.03	0.05	0.10	0.30	0.50	0.70	0.90	0.95	0.97	0.99	1.00
0	0	0.01	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.01	0
50	0.004 (2.0)	0.019 (3.6)	0.039 (3.5)	0.058 (3.5)	0.058 (1.9)	0.058 (0.8)	0.058 (0.6)	0.058 (0.7)	0.058 (1.7)	0.058 (3.1)	0.049 (4.2)	0.019 (3.9)	0.004 (4.0)
100	0.008 (1.3)	0.028 (2.9)	0.053 (3.4)	0.065 (3.0)	0.065 (1.9)	0.065 (0.8)	0.065 (0.7)	0.065 (0.8)	0.065 (1.7)	0.065 (3.0)	0.066 (4.4)	0.026 (3.3)	0.006 (1.5)
200	0.015 (1.0)	0.035 (2.0)	0.055 (2.3)	0.07 (2.4)	0.07 (1.6)	0.07 (0.8)	0.07 (0.7)	0.07 (0.8)	0.07 (1.6)	0.07 (2.5)	0.08 (3.7)	0.035 (2.5)	0.010 (1.0)
300	0.011 (0.5)	0.051 (2.0)	0.066 (2.1)	0.08 (2.1)	0.08 (1.6)	0.08 (0.9)	0.08 (0.7)	0.08 (0.8)	0.08 (1.6)	0.08 (2.3)	0.09 (3.3)	0.05 (2.5)	0.010 (0.6)
400	0.03 (1.0)	0.08 (2.4)	0.09 (2.3)	0.09 (2.0)	0.09 (1.5)	0.09 (0.9)	0.09 (0.7)	0.09 (0.8)	0.09 (1.6)	0.09 (2.2)	0.11 (3.3)	0.07 (2.7)	0.02 (0.9)
600	0.10 (2.1)	0.16 (3.1)	0.17 (3.0)	0.10 (1.6)	0.10 (1.3)	0.10 (0.9)	0.10 (0.7)	0.10 (0.8)	0.10 (1.3)	0.10 (1.9)	0.16 (3.5)	0.10 (2.6)	0.05 (1.4)
800	0.15 (2.2)	0.22 (3.2)	0.24 (3.2)	0.11 (1.4)	0.11 (1.2)	0.11 (0.8)	0.11 (0.7)	0.11 (0.8)	0.11 (1.3)	0.11 (1.7)	0.22 (3.7)	0.14 (2.7)	0.07 (1.4)
1000	0.22 (2.5)	0.31 (3.4)	0.33 (3.5)	0.13 (1.3)	0.13 (1.1)	0.13 (0.8)	0.13 (0.8)	0.13 (0.9)	0.13 (1.3)	0.13 (1.6)	0.29 (3.9)	0.19 (2.9)	0.10 (1.6)
1200	0.33 (2.9)	0.44 (3.9)	0.46 (3.9)	0.15 (1.2)	0.15 (1.1)	0.15 (0.8)	0.15 (0.8)	0.15 (0.9)	0.15 (1.3)	0.15 (1.5)	0.36 (4.0)	0.24 (2.9)	0.13 (1.6)

## 5.2. Methods for the Measurement of Electrical Resistivity

At the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) of Purdue University, the experimental methods for the measurement of electrical resistivity have been classified into various categories according to a similar scheme used by CINDAS for the classification of methods for the measurement of thermal conductivity (Ref. 399, pp. 13a-25a). This classification scheme of CINDAS is presented below. Note that the letters in parentheses following the respective methods are the code letter used in the "Method Used" column of the Table of Measurement Information for indicating the experimental methods used by the various authors.

### Methods for the Measurement of Electrical Resistivity

#### A. Steady-State Methods

1. Voltmeter and ammeter direct reading method (V) (Ref. 400, p. 159; 401, pp. 244-5)
2. Direct-current potentiometer method (A) (Ref. 19, pp. 151-8)
  - a. 4-probe potentiometer method
3. Direct-current bridge methods (B) (Ref. 19, pp. 144-51)
  - a. Kelvin double bridge method
  - b. Mueller bridge method
  - c. Wheatstone bridge method
4. Van der Pauw method (P) (Refs. 402 and 403)
5. Galvanometer amplifier method (G) (Ref. 12, pp. 159-62)

#### B. Non-steady-state Methods

1. Periodic current method
  - a. Direct connection to sample
    - (1) Alternating-current potentiometer method (C) (Ref. 19, pp. 161-2)
    - (2) Alternating-current bridge method (D) (Ref. 19, p. 162)
  - b. No connection to sample
    - (1) Mutual inductance method (M)<sup>404</sup>
    - (2) Self-inductance method (S)<sup>405</sup>
    - (3) Rotating field method (R)<sup>406</sup>
2. Non-periodic current method
  - a. Direct connection to sample
    - (1) Transient (subsecond) method (T)<sup>407</sup>
  - b. No connection to sample
    - (1) Eddy current decay method (E) (Refs. 408 and 19, p. 103)

## 5.3. Conversion Factors for the Units of Electrical Resistivity

The recommended values and experimental data for the electrical resistivity of alloys tabulated in this work are in the units:  $10^{-8} \Omega\text{m}$ . Conversion factors for the units of electrical resistivity, which may be used to convert the values given in ( $10^{-8} \Omega\text{m}$ ) to values in other units, are given in Table A-5.

Table A-5. Conversion Factors for the Units of Electrical Resistivity

Units to Convert to	Multiply the Value Given in ( $10^{-8} \Omega\text{m}$ ) by
ohm-meter ( $\Omega\text{m}$ )	$1 \times 10^{-8}$
ohm-centimeter ( $\Omega\text{cm}$ )	$1 \times 10^{-6}$
ohm-inch ( $\Omega\text{in.}$ )	$3.937 \times 10^{-7}$
ohm-foot ( $\Omega\text{ft}$ )	$3.281 \times 10^{-8}$
microhm-centimeter ( $\mu\Omega\text{cm}$ )	1
abohm-centimeter ( $\text{ab}\Omega\text{cm}$ )	$1 \times 10^3$
statohm-centimeter ( $\text{stat}\Omega\text{cm}$ )	$1.113 \times 10^{-18}$
emu (= $\text{ab}\Omega\text{cm}$ )	$1 \times 10^3$
esu (= $\text{stat}\Omega\text{cm}$ )	$1.113 \times 10^{-18}$
ohm-circular mil per foot ( $\Omega\text{cmil ft}^{-1}$ )	6.015

Example:  $1.000 \times 10^{-8} \Omega\text{m} = 3.937 \times 10^{-7} \Omega\text{in.}$



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