FOREWORD

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This report covers work conducted from 1 June 1961 to 30 April 1962. The persons engaged on this project include Dr. N. Fuschillo, Mr. R. A. Lindberg, with consulting aid from Mr. C. E. Nelson (Tables 2.1 and 3.1), Mr. E. W. Childs (Supplemental Data, section 3.4), and Dr. H. E. Podall (Supplemental Data, Sections 1.6 and 3.5).

ABSTRACT

Existing data and theory concerning the electrical conductivity, oxidation resistance and mechanical properties of

1. Pure Metals
2. Metallic Alloys
3. Metallic Binary Compounds

are presented and analyzed to determine the best approach to developing improved electrical conductors for use at temperatures up to 700° and 1200°C. Recommendations are made for experimental research and development in pure metals, metallic alloys, and metallic binary compounds. Considerable data has been collected and systematized in tables and graphs on the electrical, mechanical, and oxidation-resistant characteristics of these conductors. This should enable the design engineer to select the best electrical conductor to suit specific requirements of temperature, oxidation or mechanical environment, and cost.

This technical documentary report has been reviewed and is approved.

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INTRODUCTION

Considerable emphasis has been given to the development of electronic components and circuits capable of operation at elevated temperature for the guidance and control aspects of spacecraft and missiles. Components and circuits which can operate at temperatures up to 500°C are under intensive development. However, the problem of providing high-temperature electrical conductors has been relatively neglected. This situation is surprising in view of the essential function provided by conductors in transmitting information and power between various electronic systems and electromechanical mechanisms in suborbital and spacecraft. Many pounds of electrical conductive wire, terminal blocks, printed circuit, or microwave components are involved in such vehicles. It is clearly desirable that such components fulfill their technical mission in the high-temperature environment at the highest reliability, and at lowest possible weight and cost.

In addition to such space age applications, there are the important present day and potential applications of high temperature conductors in the field of direct conversion of heat to electricity. Suitable high-temperature conductors are essential to the efficient operation of the thermoelectric, nuclear-electric, thermionic, plasma, high-temperature fuel-cell, magnetohydrodynamic and proposed fusion systems for direct conversion of heat to electricity.

The principal areas of application for high-temperature conductors may be summarized as follows:

1. Dc to r-f power cables, hookup wire, and printed circuit boards.
2. Dc to r-f terminal blocks, bus-bars, and switch-gear.
3. UHF coaxial cables and CW antennas.
4. CW and MW wave guides and cavities.
5. UHF, CW, and MW antennas.
6. Direct conversion interconnections, (e.g., n to p connections in thermoelectrics), input, and output leads.
7. High-temperature electromagnet, transformer, electric motor, and dynamo windings.

The ideal properties of such high-temperature conductors are as follows:

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1. As high a specific electrical conductance as possible (except in certain resistor applications).
2. A low-temperature coefficient of conductance.
3. A smooth and reproducible temperature-resistance relationship.
4. Freedom from oxidation by means of chemical stability or by means of adequate protection.
5. Low-cost and easy nonstrategic availability.
6. Ease of formation into specific geometries by metal forming, joining, electroplating, metalizing, or other techniques.
7. Low density.
8. High tensile strength.
9. Low creep rate or geometrical stability.
10. Low vapor pressure.

Different applications have differing requirements. In some missile applications the conductive components would only have to stand high-temperature environments for a limited time, perhaps for a few seconds. Some applications involve only one or two short exposures to high temperatures. Other applications, especially those concerned with aircraft, some spacecraft, and direct energy conversion, require long life and recycling ability. In UHF, CW, and MW applications high-surface conductance, low-temperature coefficient of resistance, and thermal reproducibility of resistance is very important. On the other hand, for dc or low-frequency applications, bulk conductivity is of importance. In most aerospace applications, low weight for a given conductance, inexpensiveness, ease of workability, form stability, and reproducibility of the characteristics listed are important. Clearly, it is difficult to generalize concerning the most important of the characteristics listed for high-temperature conductors; all ten of the characteristics listed are advantageous with a decided emphasis on high conductivity, long life-time, reproducibility, weight, cost, and ease of fabrication.

Present state-of-the-art has emphasized Pt-Rh alloys as the best available high-temperature conductors. These alloys provide moderately low conductivities, combined with good oxidation resistance, workability, and geometrical and electrical stability. These alloys will be difficult to improve upon for the temperature range from 700°C to 1200°C. They suffer, however, from a number of disadvantages which include, very high cost, relatively high resistance and temperature coefficient of resistance, and their mechanical or electrical properties are not suitable in regard to the higher temperature ranges (up to 1200°C) considered in this study.

The importance of high conductivity of materials to aerospace and other applications depends on the importance of the reduction of ohmic loss and Joule heating to the efficiency of the system concerned. The high frequency communications applications of good conductors are antennas, cavities and waveguides. A lowering of the electrical conductivity of such systems affects the electrical Q. This normally affects the intensity of the information carried and the energy efficiency of the transmission process. It does not, however, seriously affect the quality of the electrical information carried. Thus, if the resistance of an antenna, waveguide, or cavity is suddenly increased, the intensity of the information carried will decrease and the signal will appear to fade. Since this is not accompanied by appreciable distortion, higher electric amplification can be used to increase the signal intensity. Thus, antennas have been made out of stainless steel of resistivity of the order of 60 micro-ohm-cm at room temperature. Where intensity is not a problem because sufficient electronic amplification can be provided, low temperature dependence of electrical conductivity is often more convenient in cyclic temperature environments than a low absolute electrical conductivity. It is for this reason that this work contains a substantial amount of information on metals and alloys of low temperature variation of electrical resistivity although their electrical resistivity is normally high.

In general, mechanical rigidity and dimensional stability are more fundamental requirements in high frequency communications applications than is very low electrical conductivity. In addition, the highest temperature environments for antennas and waveguides are associated with the skin temperatures of space vehicles during reentry. Here aerodynamic considerations necessitate a smooth streamlined surface with a minimum of spatial projections. Thus, antennas, waveguides, and cavities are buried beneath the skin of the vehicle. In space vehicles, the communications antenna and associated waveguide is embedded in quartz, which not only presents a smooth surface to the aerospace environment but also provides thermal protection and mechanical support for the antenna and waveguide.

Naturally, a higher electrical conductivity for these high electrical conductivity communication components is desirable. However, the general consensus of opinion amongst antenna and waveguide designers is that the conductivity problem is not a pressing one, but if materials of lower conductivities (by a factor of from two to ten) could be found, they would certainly be welcome, other things being equal. The platinum-rhodium alloys dominate existing technology in this field and they are quite adequate for the purpose even though they exhibit conductivities of about forty times less than that of copper, and twenty times less than gold. One other factor, however, should be stressed here, and this is the question of cost.

Material costs are not generally as important to defense contractors as they should be in the interest of economy. The fact that platinum-rhodium waveguide costs about $1000 per foot, which is of the order of 100 times the cost of the same item made out of copper, may constitute an important saving when space systems become more of a production item.

Another important present day application of high temperature electrical conductors to aerospace systems is the DC power cables and connecting wire. When these need to run near the skin of the vehicle, temperatures above 700°C may well be encountered. Again, the expensive platinum-rhodium alloy cables are used in current practice. The technological consideration here should be a saving of weight and material cost. Several systems are tabulated in this report which compete favorably with Pt-Rh alloys, and doubtless even better results could be provided by further research. This conclusion applies, in general, to all of the applications of electrical conductors listed above. However, the requirements of each application are so particular that further general discussion is not appropriate except for the newer requirements for conductors in direct heat to electricity energy convertors discussed below.

In a thermoelectric, nuclear-thermoelectric, or thermionic conversion, high electrical conductivity materials of good mechanical and oxidation resistant properties at elevated temperatures up to 1200°C are necessary for conducting electrical energy from n-type to p-type semiconductors or between individual thermionic modules. In all the above methods of direct conversion, good high temperature electrical conductors are required to lead high current densities of the order from 1 to 10,000 amperes or more out of the heat to electricity convertor to voltage transformers or ion propulsion units. It is to be stressed that direct convertors of heat to electricity are normally high-current low-voltage devices in which the existance of adequate electrical conductors plays an important part.

Because of the diverse environmental requirements for electrical conductors for various classes of applications, considerable data has been collected, systematized, tabulated, and referenced in this work so that the design engineer can select the conductor system which best meets the electrical, mechanical and environmental requirements of a particular application.

In general, this study has included three types of conductors for high temperature, electrical conductor applications:

1. Pure metals.

   a. Pure metals
   b. Mechanically-supported pure metals
   c. Pure metals protected by oxidation-resistant coatings

2. Metallic alloys.

   Alloys in which the over-all mechanical, thermal, and oxidation resistance over the component pure metals are improved without an unacceptable decrease in electrical conductivity and electrical stability.

3. Metallic compounds.

In the first section of this report we show that all pure metals are unsatisfactory in regard to one of three desirable characteristics for high temperature conductor applications; (1) electrical conductivity; (2) oxidation resistance, and (3) adequate mechanical properties. In that section of the report are discussed general approaches to overcoming these limitations by using, either (a) various systems for the mechanical support of high-conductivity, high-oxidation-resistant pure metals or (b) general systems for the oxidation protection of pure metals.

In addition to the supported and oxidation-protected approaches to pure metals, there exists the possibility of improving both the mechanical properties and the oxidation resistance properties of pure metals of high conductivity by making suitable alloying additions, providing that the resistivity of the metal is not increased substantially (say beyond 20 micro-ohm-cm at room temperature). This approach is discussed in section 2 of this report.

The third approach to the high-temperature conductor problem considered in this study is that of forming metallic compounds of high electrical conductivity, suitable oxidation resistance, and suitable mechanical properties. This approach is discussed in section 3 of this report. Theoretical study has shown no reason why a binary compound should not be found of higher conductivity than Ag, Cu, or Au.

Data on the resistivity of pure metals up to their melting point is relatively extensive. Most of this experimental work, however, was accomplished before 1920 when the dependence of resistivity of pure metals on purity, cold work and crystalite size, and orientation was not widely recognized. There is a real scientific need for this data to be retaken with single crystals of refractory metals as a function of orientation. This is especially the case in regard to explaining the deviations from the theoretical straight line dependence on the resistivity of metals at elevated temperatures considerably above the Debye temperature. The data on pure metals and liquid metals, however, is extensive enough from a materials engineering standpoint to give a much more complete discussion for pure metals than is possible for metallic alloys and compounds.

While the data compiled on metallic alloys and metallic compounds in this report may seem extensive, it consists only of a small fraction of the minimum amount of data required for proper analysis of possibly useful metallic alloy and compound systems. In the past, due to a lack of interest in the electrical properties of metallic alloys and compounds, especially at high temperatures, very little basic data exists in this field. To explore quantitatively the areas in which no information exists, a thorough analysis has been made of Hansen's "Constitution of Binary Alloys". In table 3.1 are listed the well-defined binary compounds which have melting points greater than 1000°C, together with thermal data and crystallographic structure data. Also included are references to electrical data in other tables of this investigation. It will be observed that some electrical data exists on 8% of the systems in table 3.1, but this data only rarely involves the temperature variation of conductivity. In table 3.1, the compounds on which room-temperature resistivity data exists are underlined once. Those on which temperature variation data also exists are underlined twice. Clearly, much further work needs to be accomplished on the electrical and associated properties of metallic compounds.

In table 2.2 are compiled the binary alloy systems in which either or both of the elements have a melting point of less than 1000°C, but which do not contain compounds of a melting point greater than 1000°C. A brief description is given of each system stating: (a) if compounds with melting points less than 1000°C exist; (b) if no compounds exist; (c) if the phase diagram is relatively simple or complex; and (d) if electrical data at room temperature or at elevated temperatures exist. The systems on which room-temperature resistivity data exists are underlined once. Those on which temperature variation data also exists are underlined twice.

It will be observed that some sort of electrical data exists in 40% of the systems considered; but this data is very seldom either for an extensive range of compositions or temperatures, and less often for both. Obviously, much work remains to be accomplished on the electrical properties of metallic alloys.

The relative scarcity of information concerning the electrical properties of alloys and compounds at room temperature, and more especially at elevated temperatures, is hardly surprising. First, the engineering interest in high-temperature conductors is only of recent origin except for studies on pure metals for resistance thermometers and alloys for resistors and switching contacts. The second reason is that scientific interest has been stimulated in the direction of low-temperature studies rather than for high temperatures. This is because changes in resistance as a function of temperature at low temperatures is of much greater fundamental importance to the verification of solid-state theory of electro-phonon, and electron-impurity ion or electron interaction. In addition, the temperature variation properties of metals above the Debye temperature is approximately in accordance with theory. This is not the case for the absolute values of the resistivity, except in the case of the alkali metals. However, this latter discrepancy can only be removed by the interaction of theory and experiment, at low temperatures and at higher temperatures. Thus, low-temperature research is essential to the elucidation of room-temperature and high-temperature conductivity data.

In section 4 of this report — Conclusions and Recommendations — recommendations are made for specific area's for future research and developement.

1. PURE METALS AS HIGH-TEMPERATURE CONDUCTORS

1.1 Introduction

1.1.1 General

Present state-of-the-art has emphasized Pt-Rh alloys as the best available high-temperature conductors. These alloys provide moderately low conductivities, combined with good oxidation resistance, workability and geometrical and electrical stability. These alloys will be difficult to improve upon for the temperature range from 200°C up to 600°C. They suffer, however, from a number of disadvantages which include very high cost, relatively high resistance and temperature coefficient of resistance, and their mechanical or electrical properties are not suitable in regard to the higher temperature ranges of up to 1200°C considered in this study. Microwave practice at room temperature has often emphasized the desirable features of gold-plated silver or copper waveguides by reason of the oxidation resistance of gold, and the sensitivity of very low-loss waveguides and cavities to surface irregularities caused by oxidation. It is one of the principal conclusions that similar cladding or plating techniques may be used with other materials, in addition to the copper-gold combination, to provide superior AC, DC, R-F, UHF as well as CW and MW conductors for high-temperature environments. A detailed discussion of the alloying approach will be given in the section 2. However, the following discussion of pure metals (both solid and liquid) is important, not only as concerns their potential use as unsupported or supported high-temperature conductors, but also because a thorough understanding of both the limitations and advantages of pure metals is obviously important in discussion of how the conductor materials can be improved for specific applications, by alloys and compounds of pure metals.

In this section on pure metals, data is also included on the Pt-Rh group of alloys for the purpose of comparison.

One of the principal conclusions of this section on pure metals is that Pt-Rh alloys can be improved upon by a factor of between 5 and 20, as far as electrical conductivity is concerned, by various pure metals supported on various classes of rigid substrates, to provide mechanical support.

1.1.2 Theoretical

The theory of electron transport in metals is well known for its complexity and inability to predict the observed magnitudes of electrical conductivity of metals, except in the case of certain monovalent metals such as sodium. The theory is, at best, only pseudo-quantitative, but is of some usefulness in establishing guidelines for research programs concerned with the development of high-temperature conductors. In this section of the report, the technically important physical concepts of the electronic conductivity of metals are reviewed and used to obtain a qualitative understanding of the electrical conductivity in the temperature range from 0°C to 1200°C.

In a perfectly periodic lattice, a beam of electrons moving in a given direction will continue to move in that direction indefinitely. A perfect lattice, therefore, has no resistance whatever. If, however, the crystal lattice is not perfectly periodic, the electrons will be scattered and it is from this scattering that electrical resistance arises. The departures from periodicity in the crystal which produce electronic scattering and hence electrical resistance may be summarized:

a. The displacement of atoms from their mean equilibrium position in the lattice due to their thermal motion.

b. The presence of foreign atoms in solid solution or of displaced atoms or vacant lattice sites.

c. The breakdown of the solid in going to liquid or amorphous states.

The classical free electron theory of a metal gives the well-known expression:

$$\sigma = \frac{F}{i} = \frac{Ne^2\tau}{m} \qquad (1)$$

for the electrical conductivity, σ, of a metal. N is the number of free electrons per unit volume, e and m are the electronic charge and mass of a conduction electron, F and i are the electric field in the metal and the resultant electric current, and τ is the average time between two successive collisions. In the quantum theory of electrical conductivity, this formula is still qualitatively valid providing the following modifications are made:

a. Since the acceleration of an electron in a solid due to a field, F, is generally less than that for a free electron, N in the above equation must be replaced by an effective number (N_{eff}) of electrons in a given band, or m by an effective electronic mass in a given band to take into account the binding of the conduction electrons to the ionic cores of the lattice. N_{eff} is defined so that $N_{eff}e^2F\ t/m$ is the electric current produced by the electric field F in the time t.

b. The time τ must be calculated from quantum mechanical methods giving an average time $\bar{\tau}$, by calculating the average probability $\bar{P}$ per unit time that an electron suffers a collision and then writing $\bar{\tau} \approx 1/\bar{P}$.

The relative values for N_{eff} for different metals can be ascertained from the measured values of σ at a given temperature (273.16°K) if τ can be determined. The probability per unit time that an electron suffers a collision is proportional to the square of the mean displacement, $\bar{x}$, of the atoms under thermal vibration. Using Einstein's model for the metal crystal and thus considering each atom to vibrate about its mean position at frequency ν, the Einstein characteristic temperature θ is defined by the relation

$$h\nu = k\,\theta \qquad (2)$$

The equation of motion for the atom is

$$M\,\frac{dx^2}{dt^2} + b\,x = 0 \qquad (3)$$

where -(bx) is the restoring force on an atom of mass M displaced a distance x from its mean position. Hence,

$$b/M = 4\pi\nu^{2} \qquad (4)$$

If $\overline{x^2}$ is the mean square displacement in a given direction we have

$$\begin{aligned} &1/2b\overline{x^2} = \text{mean potential energy} = 1/2kT \text{ for } T>\theta \text{ and} \\ &1/2b\overline{x^2} = \frac{1/2h\nu}{\exp\,(h\nu/kT)-1} \text{ for } T<\theta \end{aligned} \qquad (5)$$

It follows that for the high temperature case,

$$\bar{P}\sim\overline{x^2} = \frac{kT}{b} = \frac{h^2T}{4\pi^2Mk\theta^2} \qquad (6)$$

Therefore,

$$R\sim\sigma^{-1}\sim\bar{P}\sim\overline{x^2}\sim\tau^{-1}\sim\frac{h^2T}{4\pi^2Mk\theta^2} \qquad (7)$$

or

$$\frac{T}{\rho} = \text{const}\,\frac{e^2N_{eff}}{m}\left|\frac{\theta^2}{MT}\right| \qquad (8)$$

or

$$\frac{\rho}{T} = \text{const}\,\frac{m}{e^2N_{eff}}\left|\frac{M}{\theta^2}\right| \qquad (8a)$$

where the constant is a function of universal constants and atomic volume. It follows that N_{eff} should be proportional to $\sigma MT/\theta^2$. In following text table are shown values of σ and $\sigma M/\theta^2$ at a temperature of 273.16°K for metallic conductors tabulated in order of atomic number. Two important observations are immediately apparent from this table:

a. The metals characterized by one electron outside a closed shell, i.e., the alkali and noble metals, have high values of $\sigma M/\theta^2$ indicating high values of N_{eff}. These values drop by a factor between two and four on passing to the divalent metals next to them in the table.

b. Even lower values of $\sigma M/\theta^2$ or N_{eff} are indicated for the transition metals.

In addition a review of the conductivity data indicates that the electrical conductivities of metals fall into the ranges:

a. Monovalent metals

$5.3 \text{ (Cs)} \leq 10^{-6}\sigma \leq 67 \text{ (Ag)}$

b. Divalent metals

$4.2 \text{ (Hg)} \leq 10^{-6}\sigma \leq 28 \text{ (Ca)}$

c. Transition metals

$1.1 \text{ (Mn)} \leq 10^{-6}\sigma \leq 23 \text{ (Rh)}$

Metal	Conductivity at $0^\circ C \times 10^{-4}$ ohm cm	M	θ	$\sigma/M\theta^2 \times 10^2$
Li	11.8	6.940	363	12.9
Be	18	9.02	1,000	2.0
Na	23	22.997	202	24
Mg	25	24.32	357	8.1
Al	40	26.97	395	9.5
K	15.9	39.096	163	15.3
Ca	23.5	40.08	230	11.1
Ti	1.2	47.90	342	0.21
Cr	6.5	52.01	495	0.51
Fe	11.2	55.84	420	1.14
Co	16	58.94	401	1.7
Ni	16	58.69	375	1.9
Cu	64.5	63.57	333	9.1
Zn	18.1	65.38	213	6.1
Ga	2.45	69.72	125	2.25
As	2.85	74.91	291	0.45

Metal	Conductivity at 0°C x 10^{-4} ohm cm	M	θ	$\sigma/M\theta^2 \times 10^2$
Rb	8.6	85.44	85	14
Sr	3.3	87.63	171	1.3
Zr	2.4	91.22	288	0.32
Mo	23	96.0	380	1.7
Ru	8.5	101.7	426	0.46
Rh	23	102.91	370	1.6
Pd	10	106.7	270	1.3
Ag	66.7	107.880	223	12.4
Cd	15	112.41	172	4.5
In	12	114.76	198	2.7
Sn	10	118.70	260	1.2
Sb	2.8	121.76	140	1.2
Cs	5.6	132.91	54	14
Ba	1.7	137.36	113	1.0
La	1.7	138.92	152	0.53
Ce	1.4	140.13	..	..
Pr	1.6	140.92	..	..
Hf	3.4	178.6	213	0.42
Ta	7.2	180.88	228	0.77
W	20	184.0	333	1.0
Os	11	191.5	256	0.9
Ir	20	193.1	316	1.0
Pt	10.2	195.23	240	0.01
Au	49	197.2	175	8.1
Hg	4.4	200.61	80	3.4
Tl	7.1	204.39	140	1.8
Pb	1.0	207.22	86	3.4
Bi	1.0	209.00	100	0.5

The Theory of the Properties of Metals and Alloys, N. F. Mott, H. Jones, Daver Publications, New York, N. Y., (1958), pg 246-47.

The large differences in conductivity between groups of monovalent and divalent metals, and the smaller differences between the latter and the transition metals, are largely due to the lower number of conduction electrons per atom in the divalent and multivalent metals. It might be thought that the availability of the d band as a path for conduction in parallel with the s band would increase the conductivity, but this is far from the case. For example compare the resistivities (in microhm-cm) of the transition metals, nickel, platinum and paladium with the noble metals immediately following them in the periodic table:

Ni	Pd	Pt
7.4	10.8	10.5
Cu	Ag	Au
1.7	1.6	2.2

It is believed that the high resistivities of the transition metals are caused principally by collisions in which the s electron is scattered into unfilled states in the d band. This extra scattering mechanism is absent when the d band is filled. The electrical conductivity contributions arising from electrons in the two bands of a divalent or polyvalent metal are additive. It follows that:

$$\sigma = \left(\frac{N_1 \tau_1}{m_1^*} + \frac{N_2 \tau_2}{m_2^*} \right) e^2 \tag{9}$$

where the numerals refer to the two contributing bands. The existence of metallic conductivity in the transition metals is largely due to conduction by the s electrons.

The results of the previous table give only a relative indication of the effective number of conduction electrons as a function of atomic number. It is obviously important to inquire into the absolute values for effective conduction electrons per atom. Unfortunately, this is not a subject in which there exists a great deal of certainty for the majority of metals. Denoting the effective number of free electrons per atom by N_{eff} and the actual number by n_o, the electrons are free if $N_{eff} = n_o$. For this condition to be satisfied, the electron energy $E = h^2k^2/2m$. Experimental and theoretical evidence from a number of sources indicate that this is the case for the alkali metals.

In general, if the electron energy is proportional to the square of the wave vector,

$$E = \frac{\alpha h^2 k^2}{2m}, \tag{10}$$

then $N_{eff} = \alpha n_o$. The ratio m/α is usually referred to as an effective mass, m^*. This is the case for the noble metals Cu, Ag, and Au. Electronic heat capacity data give effective mass ratios (m^*/m) of 1.012, 0.992, 0.884, respectively, for these metals. On the other hand, optical measurements give values for N_{eff} of 0.37, 0.89, and 0.73 for Cu, Ag, and Au, respectively. However, the first of these values is inconsistent with resistivity and electronic specific heat data, both of which show that N_{eff} is almost exactly the same in Ag and Au, and, that in Cu, the effective number of electrons is not much different than in Ag.

If the electron energy near all (or part) of the surface of the Fermi distribution has the more general form

$$E = \frac{h^2}{2m} (\alpha_1 k_x^2 + \alpha_2 k_y^2 + \alpha_3 k_z^2) \tag{11}$$

then the effective number of electrons depends on the direction of the current j in the x direction, e.g., $N_{eff} = \alpha_1 n_o$. Equation (11) may be applied to many of the divalent metals where the Fermi surface overlaps into higher Brillouin zones.

In the transition metals, the d band of levels (corresponding to the inner d state of the free atom) are not fully occupied, thus leaving "positive holes" in the d band. These holes are responsible for the ferromagnetism or high paramagnetism, low electrical conductivity and its anomalous variation with temperature, high Seebeck coefficients, and the high electronic specific heat of the transition metals. The triad of Ni, Pd and Pt are probably the best understood of the transition metals. An analysis of data on the above phenomena indicates that these metals have from 0.55 to 0.6 holes per atom and an approximately equal number of electrons in the s band which are responsible for the electrical conductivity and the cohesion of the metals.

Mott(1) obtains the following picture of electrical conductivity in the transition metals. The current is carried by s electrons, with effective mass not very different from that of a free electron, as in the noble metals. On the other hand, the resistance is mainly due to scattering processes in which the electron makes a transition from the s to the d band; the probability of such a transition is proportional to $N_d(E)$, the density of states in the d band. Evidence in favor of this hypothesis may be drawn from the resistance of alloys of these metals with Cu, Ag, and Au, from their thermoelectric properties and from their resistivities at high temperatures.

$N_d(E)$ is proportional to the cube root of the number of particles (in this case positive holes) in the d band. Hence, the conductivity σ is proportional to

$$\frac{\text{number of electrons in s band}}{(\text{number of positive holes in d band})^{1/3}}$$

Equations (7) and (8) suggest that a linear dependence of resistance on temperature should exist at temperatures above the Einstein characteristic temperature. At high temperature however, the resistance-temperature curves are not quite linear for most metals. For Cu, Ag, Au, and W the ratio ρ/T increases with increasing temperature. For Cu, Ag, and Au, this result is due to thermal expansion and a consequent decrease in characteristic temperature with increasing temperature. This may be seen directly from equation (8a) where a decrease in θ at elevated temperatures leads to increased values of ρ/T. However, this explanation will not satisfy the experimental data for W, Pt, Pd or Ta, for which ρ/T decreases with increasing temperature. For these metals, the resistance is determined mainly by scattering processes due to s to d band electron transitions, which have a probability determined by the density of states, N(E), in the d band and the range of energies kT at the surface of the Fermi distribution. For the transition metals Pd and Pt, the d band is nearly full; therefore N(E) decreases very rapidly with increasing E. It follows that electrons with high energy have a considerably lower probability of being scattered than those of lower energy. Thus as the temperature increases, the rate of change of resistance with temperature decreases as the interband electron scattering decreases. (This explanation is not true for tungsten where the d band is not nearly filled.)*

The preceding discusion has been concerned exclusively with electrical resistance due to electron scattering caused by high temperature lattice vibrations. The other form of electron scattering relevant to the fabrication of materials of high electrical conductivity at high temperatures is scattering caused by foreign atoms or impurities in the lattice.

It was first shown by Matthiessen that the resistance change of a metal due to a small concentration of another metal in solid solution is independent of temperature. That is, if ρ is the resistivity of an alloy, then $d\rho/dT$ is independent of concentration. The relatively high resistance of alloys and Mattiessen's rule are explained simply by the quantum theory of electrical conductivity. As has been previously stated, if an electron could move quite freely through a perfect lattice, it would have no resistance. The resistance of a pure metal is due to thermal agitation of the atoms which destroys the lattice periodicity. When a foreign atom is present in solid solution, the periodicity of the field within the lattice is broken at that point. Thus, electrons may be deflected by that atom and a resistance can arise even in the absence of any thermal agitation. Using equation (1), the resistivity of a metal may be rewritten as

$$\rho = \frac{m}{Ne^2\tau} \tag{12}$$

where τ^{-1} is the number of times per second that an electron is deflected. Let τ_i^{-1} be the number of times per second that an electron is deflected by an impurity atom, and τ_T^{-1} be the number of times per second that it is deflected due to the thermal oscillation of the atoms. Then

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*A more detailed discussion on the temperature variation of resistivity in metals is given in section 1.4.1 on the discussion of data.

$$\tau^{-1} = \tau_i^{-1} + \tau_T^{-1} \tag{13}$$

The total resistivity can then be written

$$\rho = \rho_i + \rho_T \tag{14}$$

where

$$\rho_i = \frac{m}{Ne^2}\,\tau_i^{-1} \text{ and } \rho_T = \frac{m}{Ne^2}\,\tau_T^{-1} \tag{15}$$

The resistivity ρ_i is equal to the resistivity of the alloy at 0°K and is independent of temperature, and ρ_T will be approximately proportional to the temperature at sufficiently high temperatures. Clearly, Matthiessen's rule will be satisfied if the effective number of free electrons is unaltered by the addition of foreign atoms and if the thermal vibrations of foreign atoms produce the same scattering as thermal vibrations of solvent metal atoms. In general, neither of these conditions will be satisfied exactly in practice. While it can be expected that an addition of foreign atoms to one percent may change ρ_T of the solvent by about one percent, it may change ρ_i by a much greater amount.

As indicated above, the resistivity ρ_i of an alloy at 0°K is due to a breakdown of the periodicity of the lattice field. This may be attributed to two effects: (1) the lattice may be distorted by the foreign atom, the neighboring atoms, therefore, being pushed out of position, or (2) the field within the foreign atom will differ from what it would be at the same lattice point in the pure metal. The latter effect is generally more important (and is the only one which has been studied in any detail for metals), and the extra resistivity ρ_i is caused by the difference between the fields in the two atoms. It is useful to consider this scattering process in greater detail.

Equation (12) may be expressed

$$\rho = \frac{m}{Ne^2} \cdot \left(\frac{v\,A_i}{V}\right) \tag{16}$$

where A_i is the collision cross section of the scattering imperfection (either a point defect or a thermal vibration can be considered), v is the electron velocity, and V is the atomic volume. Now consider a metal at absolute zero temperature containing a small proportion, x, of foreign atoms in solid solution. The entire resistivity ρ is then due to scattering by foreign atoms and equation (16) can be rewritten as

$$\rho_i = \frac{m}{Ne^2} \cdot \left(\frac{xvA_i}{V}\right) \tag{17}$$

where A_i is the effective electron scattering area presented by each foreign atom. Mott$^{(1)}$ has derived the following equation:

$$A_i = 0.86\ \pi r_o^2 \cdot \left(\frac{E_o - E_o^1}{E_{max}} \right)^2 \qquad (18)$$

where r_o is the atomic radius, $E_{max} = (1/2)h\nu^2$ (the energy of the electrons with the maximum energy in the Fermi distribution), E_o is the energy of the lowest state of the solvent metal, and E_o^1 is the corresponding quantity for one of the dissolved atoms. Thus, the increase in resistivity due to an admixture of 100X percent of another metal in solid solution is obtained from equations (17) and (18). Agreement of this theoretical result with experiment is fairly good for the noble metals as both solute and solvent in the case of dilute solutions (of the order of one or two percent).

Norbury was the first to point out the dependence of the increase in resistance ρ_i on the relative valencies of the solvent and solute atoms. If the metals have the same valence, the resistivity increase will be small, but if the valencies differ, ρ_i will be large. In this connection, Linde found experimentally that if $(z+1)$ is the number of electrons outside a closed d shell in the dissolved atom and 1 the number in the solvent, then $\rho_i = (\text{const})\ z^2$. This result has a simple theoretical explanation. The core of the dissolved atom carries a positive charge, $+(z+1)e$, which is greater than that for an atom of the solvent metal by ze. It is this excess charge which causes the scattering, giving rise to ρ_i. But according to the Rutherford scattering law, the intensity of scattering is proportional to the square of the scattering charge and hence to z^2. It follows that the excess resistivity ρ_o is proportional to z^2.

1.1.3 References for Section 1.1.2

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2. F. Seitz, *Modern Theory of Solids*, McGraw-Hill Book Co., New York, 1940.

3. "Metallic Conductivity," *Handbuch Der Physic*, XIX, Springer-Verlag, Berlin, 1956.

4. H. Jones, "Theory of Electrical and Termal Conductivity in Metals," *Handbuch Der Physic*, XIX, Springer-Verlag, Berlin, 1956.

5. W. Hume-Rothery, "Atomic Theory for Students of Metallurgy," The Institute for Metals, London, England, 1948.

6. J. Bardeen, "Conduction in Metals and Semiconductors," *Handbook on Physics*, McGraw-Hill Book Co., 1958, pp. 4-73.

7. *Structure of Metals*, Institution of Metallurgists, London, England, 1959.

8. W. Ehrenberg, *Electric Conduction in Semiconductors and Metals*, Clarendon Press, Oxford, 1958.

9. N. Cusack, *Electrical and Magnetic Properties of Solids*, Longmans, Green and Co., 1958.

10. A. H. Wilson, *Theory of Metals* (Second Edition), Cambridge, 1954.

11. "Proceedings of the International Conference on Electron Transport in Metals and Solids, "*Can. J. Phys.* *12A*, *34*, 1956.

12. *Nuovo Cimento*, *Suppl*. *7*, Series 10, August 1957.

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16. N. F. Mott, *Proc. Camb. Phil. Soc.*, *32*, 218, 1936.

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19. W. V. Hanson, "Temperature Dependence of Electrical Resistance, "*Phys. Rev.* *88*, 1321 (1952).

20. R. Smoluchowski, "Statistical Theory of Properties of Solid Solutions," *Phys. Rev.* *84*, 511 (1951).

21. G. Boreluis, "Phenomenological Aspects of the Resistivity of Pure Metals," *Can. J. Phys.*, *12A*, *34*, 1336 (1956), Electrical and Magnetic Properties.

22. J. Friedel, "Metallic Solid Solutions," *Can. J. Phys.*, 12A 34, 1190 (1956).

23. J. Friedel, "Metallic Alloys," *Nuovo Cimento*, *Suppl.* *7*, Series 10, 1958.

24. J. M. Ziman, "Transport Properties of Solids, "*Nuovo Cimento*, *Suppl.* *7*, Series 10, 1958.

25. M. Hansen, W. R. Johnson, J. M. Parks, "Correlation Between Electrical Conductivity and Temperature Coefficient of Resistance of Solid Solution Alloys," *J. Metals* *1184*, Dec. 1951; 1125, Nov. 1952

26. W. R. Hibbard, "Electrical Resistivity of Dilute Binary Terminal Solid Solutions," *J. Metals* *594*, May 1954.

27. A. T. Robinson and J. E. Dorn, "Effect of Alloying Elements on the Electrical Resistivity of Aluminum Alloys," *J. Metals*, June 1951.

1.2 Compilation and Treatment of Data

The elements selected for investigation are chromium, cobalt, copper, gold, hafnium, iridium, iron, nickel, niobium, osmium, palladium, platinum, rhenium, rhodium, ruthenium, tantalum, thorium, titanium, tungsten, uranium, vanadium, zirconium, silver.

All of these elements with the exception of silver (MP=961°C) and gold, (MP=1063°C), copper (MP=1084°C), uranium (MP=1132°C) have melting points in excess of 1450°C and have annealing temperatures of the order of 1200°C. Silver and copper have been included because of their position as materials having the highest conductivity in the room temperature range. However, these metals suffer serious limitations due to oxidation even at 500°C. Gold, on the other hand, in spite of its softness can be used nearly to its melting point if mechanically supported on a compatible substance as substrate, since it has very high conductivity and excellent resistance to oxidation.

The following properties are investigated:

a. Electrical

1. Resistivity as a function of temperature
2. Temperature coefficient of resistivity
3. Resistivity minimum and average values at selected reference temperatures 20°C, 500°C, and 1200°C
4. Resistivity of selected liquid metals as a function of temperature

b. Thermal

1. Melting point
2. Boiling point
3. Vapor pressure as a function of temperature

c. Structural

1. Crystalographic structure
2. Phase changes as a function of temperature

d. Chemical

1. Oxidation characteristics
2. Available methods for prevention of oxidation

e. Mechanical

1. Modulus of electricity at 20°C, 500°C, and 1200°C
2. Tensile strength or ultimate strength (ASM standard) and ductility
3. Creep characteristics (low load)
4. Hardness

f. Typical Fabrication Characteristics

1. Working (forming) temperature (cold and/or hot)
2. Strain hardening exponent
3. Forming characteristics for machining, turning, swaging, forging, drawing, and extrusion
4. Heat treatment (i.e. annealing temperatures)
5. Joining (welding, brazing, soldering, etc.)

The results of this literature research are summarized in tables 1.1 through 1.15 and in figures 1 through 10. The references referred to in the tables are listed under "references" after table 1.15. In the summary of tables and figures which follow, a key to these tables and figures are given by means of a summary of the subject and objectives of each of them. The results of these tables and figures are discussed in detail in the following sections of this report.

SUMMARY OF TABULATIONS

Table Number	Subject	Objective
1.1	Electrical Resistivities Vs. Temperature for Selected Pure Elements; and Temperature Coefficients of Electrical Resistivity (0° -100°C) - for Selected Pure Elements.	Basic Data and Reference Sources for the study of the high-temperature electrical resistivity properties of selected pure elements.
1.2	Maximum and Minimum Electrical Resistivity vs. Temperature for Selected Pure Elements.	To attempt to establish smooth characteristics of electrical resistivity vs. temperature for selected pure elements. (Based on data of Table 1.1.
1.3	Selected Precious Metal Alloys: Resistivity vs. Temperature	To establish a comparative reference class of materials for comparison with the electrical properties of pure metals.
1.4	Minimum Resistivity vs. Temperature Characteristics of Selected Pure Elements.	To determine the feasibility of a smooth curve of ($\rho_{minimum}$) vs. temperature.

SUMMARY OF TABULATIONS (Continued)

Table Number	Subject	Objective
1.5	Relative Resistivity vs. Temperature Characteristics of Selected Pure Elements.	To obtain the desired smooth characteristic functions by employing the numerical average between the limits of (ρ Minimum) and (ρ Maximum) vs. temperature for selected pure elements.
1.6	Supplemental Data: Resistivity vs. Temperature for Selected Pure Elements.	Previous limited data requires supplemental data to obtain sufficient plotting points to support the validity of a smooth function of ρ vs. temperature.
1.7	Supplemental Data: Resistivity vs. Temperature for Selected Pure Elements.	Same as 1.6 above.
1.8	Derived Basic Data of Resistivity vs. Temperature for Pure Elements.	Data Derived from smoothed curve fitting of ρ (Avg) vs. Temperature; after figures 1, 2, and 3.
1.9	Selected Properties (Resistivity and Vapor Pressure) vs. Temperature for Certain Pure Liquid Metals.	To indicate the potential of certain pure liquid metals (and to compare against solid elements and/or selected precious metal alloys) as high-temperature high-conductivity materials.
1.10	Relative Orders of B.P.'s Liquid Ranges to B.P.'s and Availability of Electrical Resistivity Properties of Selected Pure Liquid Metals.	To indicate potential electrical characteristics of pure liquid metals, of M.P. $<$ 1200°C and B.P. $>$ 1200°C.
1.11	Selected Pure Elements: Physical and Mechanical Properties	To establish the relative merit of pure elements for high-temperature Electrical conductivity purposes as based on consideration of all the properties selected.

SUMMARY OF TABULATIONS (Continued)

Table Number	Subject	Objective
1.12	Selected Pure Elements: Vapor Pressure vs. Temperature	Lifetime determination in vacuum.
1.13	Creep Characteristics of Certain Pure Elements	Assessment of mechanical suitability.
1.14	Typical Fabrication Characteristics of Selected Pure Elements.	Assessment of fabrication suitability.
1.15	Relative Cost of Selected Pure Metals.	Cost optimization

SUMMARY OF FIGURES

Figure Number	Subject	Objective:
1	Resistivity of Selected Pure Elements vs. Temperature	To obtain smooth fitted curves for: Re., Ru., Pt., Pd., Ir., Rh., and Au.
2	Resistivity of Selected Pure Elements vs. Temperature	To obtain smooth fitted curves for: U., Th., Ta., Ni., W., Mo., Au., and Ag.
3	Resistivity of Selected Pure Elements vs. Temperature	To obtain smooth fitting curves for: Ti., Zr., Hf., Fe., Nb., Cr., and Co.
4	Resistivity of Selected Precious Metal Alloys vs. Temperature	To obtain approximate curves for alloys indicated: (1) 10% Rh-Pt; (2) 20% Rh-Pt; and (3) 40% Rh-Pt. (limited Available Data.)
5	Relative Resistances of Selected Pure Elements vs Temperature	To obtain smooth fitted Re., Ru., Pt., Pd., Ir., rh., and Au.

SUMMARY OF FIGURES (Continued)

Figure Number	Subject	Objective
6	Relative Resistances of Selected Pure Elements vs. Temperature	To obtain smooth fitted curves for U., Th., Ta., Ni., W., Mo., and Au.
7	Relative Resistances of Selected Elements vs. Temperature	To obtain smooth fitted curves for Ti., Zr., Hf., Fe., Nb., Cr., and Co.
8	Relative Resistances of Selected Precious Metal Alloys vs. Temperature	To obtain approximate curves for: (1) 10% Ph-Rt; (2) 20% Rh-Pt; and (3) 40% Rh-Pt.
9	Selected Properties, (Resistivity, and Vapor Pressure vs. Temperature) of Selected Pure Liquid Metals.	To utilize available data in order to obtain an approximation of the usefulness of selected pure liquid metals for high temperature, high electrical conductivity purposes.

The sources used for the data and literature research are summarized as follows:

(A) Library of Congress, Washington, D. C.

1. Open-catalog files.

2. Selections from Science and Reference Sections.

3. Metallurgical Abstracts, Institute of Metals.

(B) National Bureau of Standards Library, Washington, D. C.

1. Selection from cross index files;

2. and, Metallurgical Abstracts, Institute of Metals.

(C) Office of Technical Services; U.S. Department of Commerce; Bibliographies of Government Reports; Government sponsored Reports, and Government Sponsored Translations.

(D) A.S.T.I.A. Bibliographical Services, Arlington Hall, Virginia.

(E) Melpar, Inc., Technical Library, Falls Church, Virginia.

(F) Melpar, Inc., Extensive Communications to and from selected Industrial Firms and Academic Institutions, listed below.

(1) Anaconda Sales Company
25 Broadway, New York 4, New York

(2) Bee Chemical Company, Logo Division
2700 East 170th Street
Lansing, Illinois

(3) The Carborundum Company; Metals Division
Post Office Box 32, Akron, New York

(4) Chase Brass and Copper Company;
Rhenium Division
Waterbury 20, Connecticut

(5) Cleveland Tungsten Inc.
10200 Meech Avenue
Cleveland 5, Ohio

(6) Clevite Corporation
Mechanical Research Division
540 East 105th Street
Cleveland 8, Ohio

(7) Climax Molybodenum Company
1270 Avenue of the Americas
New York 20, New York

(8) E.E. Du Pont De Nemours and Comany, Inc.
Pigments Department - Metal Products
Wilmington 98, Delaware

(9) Engelhard Industries, Inc.
Research and Development Division
497 Delaney Street
Newark 5, New Jersey

(10) Engelhard Industries, Inc.
Baker Platinum Division
113 Astor Street

(11) Fansteel Metallurgical Corp.
Metals and Fabrication Division
North Chicago, Illinois

(12) Firth Sterling, Inc.
Special Products Division
3113 Forbes Avenue
Pittsburgh 30, Pennsylvania

(13) General Electric Company
Lamp Metals and Components Department
21800 Tungsten Road
Cleveland 17, Ohio

(14) Goldsmith Brothers
Division of National Lead Company
900 West 18th Street
Chicago 8, Illinois

(15) Haynes Stellite Division of Union Carbide Corporation
New Products Department, General Offices
Kokomo, Indiana

(16) Johnson, Matthey and Company, Inc.
608 Fifth Avenue
New York 20, New York

(17) Metals and Controls, Inc.
Division of Texas Instruments Inc.
34 Forest Street
Attleboro, Massachusetts

(18) Metals and Residues, Inc.
Refractory Metals
65 Brown Avenue, Post Office Box 92
Springfield, New Jersey

(19) National Bureau of Standards
Chemistry Division
Washington, D. C.

(20) Oregon Metallurgical Corporation
Albany, Oregon

(21) Phelps Dodge Refining Corporation
300 Park Avenue
New York 22, New York

(22) Philips Elmet Corporation
Subsidiary of North American Philips Company, Inc.
Elmet Division, Molybdenum and Tungsten Products
Lisbon Road, Lewiston, Maine

(23) Shieldalloy Corporation
Division of Metallurg, Inc.
West Boulevard, Newfield, New Jersey

(24) Stauffer Chemical Company
Stauffer Metals Division
1201 South 47th Street
Richmond 4, California

(25) Sylvania Electric Products, Inc.
Chemical and Metallurgical Division
Towanda, Pennsylvania

(26) The University of Tennessee
Department of Chemistry
Knoxville, Tennessee

(27) Union Carbide Metals Company
1300 Lakeside Avenue
Cleveland 14, Ohio

(28) Vanadium Corporation of America
Greybar Building
420 Lexington Avenue
New York 17, New York

(29) Vanadium Corporation of America
Research Center
Cambridge, Ohio

(30) Virginia Polytechnic Institute
Department of Metallurgical Engineering

(31) Wah Chang Corporation
Woolworth Building
New York 7, New York

(32) Westinghouse Electric Corp.
Lamp Division
Bloomfield, New Jersey.

1.3 Analysis of Results

1.3.1 Electrical Properties

Table 1.1 summarizes the compilation of data for the pure metals selected and also a selection of noble metal alloys of well known resistance properties. These have been included in this section on pure metals for purposes of comparison of the best-known low-resistivity alloys which can be used as high-temperature conductors. The table lists melting point, temperature coefficient of resistivity, values of resistivity at 0°C, 500°C, and 1200°C, and finally the reference. The bracketed items in the reference numbers refers to the reference listing following the tables of this section and the following numbers refer to the appropriate pages of the reference.

The large spread of resistivity values encountered in this table are summarized in Table 1.2 where the maximum and minimum resistivities at 0°C, 500°C, and 1200°C are presented, and is indicative of the lack of precision and care in experimental work in this field. This spread of values arises because of variations in degree of chemical purity and physical defect density which would give rise to varying values for ρ_o in the equation

$$\rho = \rho_T + \rho_o \text{ (impurities)} + \rho_o \text{ (physical defects)}$$

The consequences of this equation can manifest themselves in numerous different ways which may be summarized as follows:

a. Differing initial purities and defect densities at room temperature change ρ_o, from specimen to specimen.

b. A change in ρ_o with temperature due to combinations of the following causes:

1. ρ_o (physical defects) changes as a function of temperature due to high temperature annealing.
2. ρ_o (impurities) changes with temperature due to external oxidation and diffusion and internal oxidation.
3. ρ_T and ρ_o (physical defects) changes with temperature during a crystallographic phase change.
4. Spurious effects, such as contact resistance, changes in dimensions and inaccuracies in temperature measurement, affect the accuracy of the data.

(Since the first three of these effects are time dependent and described by various rate equations with differing activation energies, it is difficult to obtain valid experimental data unless great experimental care is taken in the measurements.)

c. Anisotropy in electrical resistivity in noncubic metals can lead to different resistivities in different directions. Thus, unless the crystallities in a polycrystalline sample are oriented at random (this is not generally the case after wire drawing) differing values for the resistivity is to be expected from sample to sample. In addition.it should be noted that even cubic metals under a state of anisotropic strain exhibit anisotrophy in electrical resistivity. Hence an additional condition for the elimination of errors due to anisotropic resistivities is an isotropic strain or zero strain in the specimen. The conditions giving rise to a net anistropic effect are also subject to temperature variations described by various rate equations (e.g. strain anneal, crystallity growth, recrystallization).

It follows that the minimum values for the resistivity are those which are most likely to correspond to the purest and most strain-free materials. An examination of the standard of the sophistication of the experimental work in the field of high temperature resistivity measurements supports this conclusion. Minimum resistivities have been summarized in table 1.4 for this reason. The data on precious metal alloys given in table 1.4 is derived from table 1.3 which was condensed from table 1.2 by a comparison of the available data presented in table 1.1. Thus table 1.4 also shows a comparison of the minimum resistivities at 0°C, 500°C, 1200°C of pure metals with the available data on precious metal alloys. It will be observed that there are a number of pure metals which are quite superior to the Pt-Rh alloys, widely used in practice in the region from 500° to 1200°C, as far as electrical resistivity is concerned. In the "Reference" columns of table 1.4, the resistivity data is referred to Groups I through VIII. The maximum and minimum resistivities at 20°C, 500°C, and 1200°C for each of these groups are tabulated at the end of table 1.4. The resistivities of the elements in Groups I and II are comparable but significantly less than those in Group III through VIII. The values listed under Group IV (Pt-Rh) alloys are clearly superior to all groups except I and II.

The mean resistivities at 20°C, 500°C, and 1200°C are summarized in table 1.5, and are useful as a tabulation of the values most likely to be found for the resistivities of these elements unless special precautions are taken with regard to purity and strain. Also tabulated in table 1.5 are values or relative resistivity R_{500^oC}/R_{20^oC} for the selected elements and precious metal alloys. This compilation is useful for the selection of metals with low temperature variation of resistance properties.

It is obviously desirable to represent the results of tables 1.2, 1.3, 1.4, and 1.5 graphically. In order to obtain smooth curves relating to resistivity and relative resistance at various temperatures, it is however, necessary to obtain supplemental data. This data at intermediate temperatures is tabulated in table 1.6 for the resistivities and in table 1.7 for the relative resistivities. A less exhaustive compilation of data was used for table 1.6 and 1.7 than was used in the previous tables. The results for the resistivities are plotted in figures 1, 2, and 3 for pure metals and in figure 4 for Pt-Rh alloys which serves as our standard for practical comparison. In these figures, 1, 2, and 3.the minimum, and maximum values are shown by the horizontal bars and the best smooth curve is drawn through the data. The smoothed values for the resistivity derived from the curves are tabulated in table 1.8, and obviously have a greater significance than the unweighed arithmetic mean of the maximum and minimum values tabulated in table 1.5. A similar treatment was used to arrive at figures 5, 6, and 7 for the relative resistivities of the pure elements as a function of temperature. The smoothed values for the relative resistivities derived from these curves are also indicated in table 1.8. The values for the relative resistivities for Pt-Rh alloys, as a function of temperature, are shown in figure 8 and follow the values tabulated in 1.5. Finally, a further summary of the electrical properties of pure metals is given in table 1.9, (Typical Characteristic Properties of Selected Pure Metallic Elements), for the sake of the completeness of this master table.

Pure liquid metals are of possible interest as electrical current conductors provided the difficult containment problem can be solved. Thus, the lowest resistivity measured in the range 0 to 1200°C is still silver, even though this metal is molten at temperatures in excess of 961°C. Molten gold has desirable properties of low resistivity and high oxidation resistance at temperature above its melting point of 1063°C. The results of the literature research for data on pure liquid metals is summarized in tables 1.11 and 1.12 and illustrated in figure 9.

1.3.2 Thermal Properties

The melting and boiling points of the selected pure metals and precious metal alloys are given in table 1.11.

The melting points, boiling points, and vapor pressures of the liquid metals are given in table 1.9 and 1.10 which summarize the electrical and thermal properties of liquid metals. The vapor pressure data for pure solid metals summarized in table 1.11 were calculated with the data summarized in table 1.12 using the equation given as a footnote to table 1.12. The relevance of this vapor pressure data to weight loss and life-time of high-temperature conductors and conductive coatings, especially in vacuum, is readily apparent. This extensive compilation of the vapor pressures of solid and liquid metals should be of value to other applications of refractory metals in outer space and high temperature environments.

1.3.3 Structural Properties

The crystallographic structures and structural or phase changes as a function of temperature are also summarized in table 1.11. This data is valuable for several reasons, which are summarized:

1. In the interpretation of the resistivity curves illustrated in figures 1 through 8. Whenever a phase change occurs the resistivity temperature relation is effected since ρ_T and ρ_0 change as the crystal structure changes.

2. The noncubic structures (e.g., H.C.P.) exhibit anisotropic resistivities and therefore show a greater spread of values since the resistivity depends on the randomness of orientation of the crystallities.

3. The non-cubic structures are brittle and not easily worked mechanically.

1.3.4 Chemical Properties

The oxidation characteristics are also summarized in table 1.11 as a function of temperature together with the principal methods of oxidation protection by atmosphere. If the coating or cladding techniques are to be used (e.g. gold on molybdenum or tungsten), a sufficient thickness of coating by electrolytic or vapor deposition must be used to prevent penetration of oxygen through microcracks and by diffusion. (See section 1.6.) This usually requires coating of thickness several mils to tens of mils. In general, pure metals have a greater resistance to oxidation and corrosion at moderate temperatures (e.g., on the order of 500 to 700°C) than inpure metals.

1.3.5 Mechanical Properties

The mechanical properties of pure metals of relevance to the structural stability and workability of electrical conductors are summarized in table 1.11, under the various categories in the "mechanical properties" section of this table. The modulus of elasticity under tension is given at 20°C and 500°C. The tensile or ultimate strength (stress per unit area (psi) at fracture) is also given as a function of temperature, together with the percent elongation at fracture which gives an indication of the ductility of the metal. The hardness in the annealed state at room temperature is given in terms of the available hardness indices in which the greater the index number the greater the hardness (e.g. Vicker Parmetal No. (VPN), Vickers Hardness No. (VHN), Knoop Hardness No. (KHN), Grimmel Hardness No. (BHN), Rockwell A Scale (R_A). Descriptions of these hardness scales are given in references 2, 3, and 4. The creep characteristics under low to very moderate loads at various temperatures are summarized for the pure metals in table 1.8. The meaning of the various headings in the case of copper, for example, is; for copper (Electrolytic Through Pitch) (reference (4) page 1008), at 204°C under a stress of 5000 psi applied for a 1000 hours, the average creep rate is 0.42 microinch/inch/hour.

1.3.6 Fabrication Characteristics

In general, pure metals which crystallize in cubic systems are generally easier to fabricate than other structures. The fabrication characteristics of the pure metals selected for this investigation are summarized in table 1.14, which is self-explanatory. The strain hardening exponent (references 4 and 5) gives a measure of the extent of strain hardening occurring during forming. For metal with a high strain exponent (e.g., rhenium), frequent anneals are required during forming operations.

For further details on the characteristics tabulated, working temperature (cold or hot), strain hardening exponent, machining, turning, swaging, forging, drawing, extrusion, heat treatment (or annealing conditions), and joining, refer to the last column of the table.

1.4 Discussion of Data

1.4.1 Theoretical

Equation (8) for the high-temperature resistivity of a metal may be written

$$\rho_T = \text{const} \left(\frac{m^*}{N_{eff}} \right) e^2 \left(\frac{M}{\Theta^2} \right) T$$

(with $T >$ the Debye temperature Θ) were the constant is a function of several different universal constants and the atomic volume. It is worthwhile to consider this equation in relation to the pure metals selected for study for high-temperature conductivity applications. The monovalent metals considered, Ag, Cu, Au, contribute nearly one electron per atom on an average to the conduction band and thus half-fill the first Brillouin Zone. As a consequence, the E-k (electron energy - wave number) relation is approximately parabolic and the effective electron mass m^* is nearly equal to m, the free electron mass, as in the Sommerfield model. In this model the periodic part of the potential in a metal due to the ion-cores is averaged out and assumed to be a constant throughout the metal. As may be expected from the above equation, the alkali metals having a high N_{eff} have the highest conductivities. Divalent metals would be insulators but for the fact that the first and second Brillouin zones overlap in one or more directions. In those directions in which the Brillouin zones are more than two thirds filled, the E-k relationship is far from parabolic and the assumptions of the Sommerfield model are no longer even approximately applicable. Thus, the effective mass m^* is $>$ m and the electron atom ratio (N_{eff}/N) is significantly less than unity. Under these circumstances, the conductivity of the divalent metal is several times less than that of a monovalent metal. The transition metals overlap between the s-p and d bands introduces additional electron scattering mechanisms into the conduction process, which further increases the ratio m^*/m leading to even lower conductivities than those exhibited by divalent metals and metals of higher valence. This behavior is shown in the data by a comparison of the resistivities of the monovalent metals Au and Ag with the other elements. All the elements shown are transition metals or rare earth metals (Zr, Hf, U, Th, etc.).

The equation for the conductivity under discussion predicts that, provided the characteristic temperature of the lattice Θ is constant, the resistivity should be proportional to absolute temperature. Reference to figures 5, 6, and 7 shows all specimens show at least some deviation from this predicted behavior. For Cu, Au, Ag, W, Mo, Ni, Fe, Cr, ρ/T increases with increasing T. For Cu, Au, Ag, this can be accounted for by the decrease in characteristic temperature which would occur as the lattice expands under thermal expansion. Assuming that $\rho/T \sim 1/\Theta^2$, it can be shown that $\rho/T = \text{const} \; (1 + 2 \sim \gamma T)$ where $\sim$ is the expansion coefficient and $\gamma = -d(\log \Theta)/d(\log V)$. This, however, gives satisfactory agreement for only the monovalent metals. A satisfactory explanation for the transition metals is more difficult. For W, Mo, Cr, Ni, Co, Fe, Nb, (ρ/T) decreases with decreasing temperature (also shown by Pt, Pd, Rh, Ir, Ta, Ti, Ru, Re, Hf, Zr, Th). Mott has explained this behavior in the transition metals with nearly full d bands as follows:

For metals with incomplete d bands which overlap the s-d band, the resistance is largely determined by scattering processes which arise when the electron jumps from the s to the d band. The probability for such a process is proportional to the density of available states N(E) in the d band in the range of energies kT at the surface of the Fermi distribution. For the transition metals Pd and Pt, and d band is nearly full, so that N(E) decreases rapidly with increasing E; at high temperatures, the electrons with high energies have a smaller probability of being scattered than those with low energy, thus leading to a decrease in ρ/T at high temperatures. This assumption, however, is not true for tungsten where the d band is not nearly filled.

In addition to these explanations, we have to remember that ρ/T will tend to decrease with increasing temperature if the metal is annealing out a significant amount of cold work (e.g. Tungsten), since ρ_0 is then decreasing. On the other hand, if a significant amount of internal or external oxidation is occurring, ρ_0, and thus (ρ/T), will increase with increasing temperature. At temperatures near the melting point evaporation rates become very high and ρ/T can increase with increasing temperature due to geometry. In general, high-temperature resistivity measurements have been crude and there is much need for careful experimental work at high temperatures.

1.4.2 Technological

It is appropriate to discuss the materials requirement from an overall materials engineering point-of-view, rather than from that of solid-state physics.

In addition to the obvious requirement of high electrical conductivity from 0 - 1100 ± 100°C, the conductivity must be accurately reproducible on thermal cycling in air, and the material must have good mechanical properties. The material should be homogeneous and, for microwave applications, be capable of fabrication with a high degree of surface smoothness. Other requirements include availability and cost of refinement and processing into operational geometries. The first criterion implies that the material must be resistant to oxidation at high ambient temperatures, and have an annealing temperature, with respect to electrical resistance, below the maximum environmental temperature. Operating temperature ranges may be conveniently divided into two regions as far as practical materials are concerned, e.g., from 0 - 600° ± 100°C and from 0 - 1100° ± 100°C. A consideration of materials suitable for the higher range alone would eliminate a number of possible materials which could find application in the field of military electronics.

The conductive material should operate with reproducible properties up to a maximum temperature, $T_{(max)} \simeq (2/3)\ T_{mp}$. The factor two-thirds is an empirical, though somewhat arbitrary, annealing constant. Thus, for the upper limiting temperature of operation (1200°C), systems with melting points above about 1500°C may be considered. For the lower operating limit (600°C), systems with melting temperatures above 1000°C are acceptable. A compilation of metallic elements with melting points within these ranges is shown ($1000^{\circ}C < T_{mp} < 1500^{\circ}C$) and ($T_{mp} > 1500^{\circ}C$) in the following tabulation together with appropriate resistivity data. Since metallic or intermetallic systems having a high annealing temperature of resistance and low resistivity are required, the values of the ratio (T_{mp}/ resistivity) are tabulated for each metal. Because this ratio is the best available qualitative index of the suitability of a given metal (resistance annealing temperature or, in some cases, oxidation temperature, should replace $T_{mp} \simeq (3/2)T_{max}$), the elements in the tabulation are arranged in decreasing order of this ratio.

In general, there are two methods of discussing the technological significance of the large mass of data collected in tables 1.1 to 1.14 and figures 1 to 9. The first method consists of examining a single property such as electrical resistivity, oxidation resistance, or machinability and discussing it for each of the elements considered and then repeating the process for all the properties considered. The second method consists of discussing all of the relevant properties of each metal taken in turn. Both methods of treatment will be attempted in this discussion, but of necessity in a concise manner.

Conciseness is achieved in the first method of presentation by arranging the metals in decreasing order of preference for each desirable property. This is accomplished below in six scales of preferences for six properties of the metals which are important in their use as high-temperature conductors.

1. Listing of metals in order of highest of electrical conductivity:

   a. at 20°C: Cu, Ag, Au, Rh, Ir, W, Mo,Co, Ni, Fe, Ru, Pt, Ta, Cr, Th, Nb, Re, Hf, U, Zr, Ti.
   b. at 500°C: Cu, Au, Rh, Ir, Mo, W, Pd, Pt, Cr, Ru, Ta, Ni, Nb, Th, Re, U, Re, Hf, Zr, Ti.
   c. at 1200°C: Mo, W, Pd, Pt, Ru, Ni, Ta, Cr, Th, U, Nb, Re, Co, Fe, Zr, Ti, and Hf. (Elements Cu, Ag, Au, U with M.P. < 1200°C have been omitted; if they are included, liquid Ag, Cu and Au will precede Mo.)

2. Listing of metals in order of lowness of temperature coefficient of resistance:

a. at 50°C: U, V, Ta, Pt, Nb, Th, Au, Pd, Ir, Os, Ag, Re, Zr, Hf, Ti, Rh, Mo, Ru, W, Cu, Cr, Fe Ni, Co.
b. at 500°C: U, Ti, Cr, Nb, Pd, Ta, Zr, Pt, Ir, Re, Th, Ag, Au, Mo, Rh, Hf, W, Ru, Co, Ni, and Fe.
c. at 1200°C: U (liq.), Ti, Zr, Pd, Nb, Th, Ta, Pt, Re, Cr, Ru, Hf, Ir, Rh, Mo, W, Ni, Ag (liq.), Fe, Au (liq.), Co.

3. Listing of metals in decreasing order of oxidation resistance at elevated temperature (between 500 and 1200°C). Within each group a, b or c, the preference cannot be established on a general basis but the metals in group a are preferable to those in group b and those in groub b are preferable to those in group c.

a. Au, Pt
b. Ir, Rh, Pd, Os
c. W. Ta, Nb, Re, Cu, Ag, Ni, Mo, Th, Co, Fe, V, Cr, Hf, Zr, U, Ti

4. Listing of crystal structures of metals in decreasing order of preference for reproducibility in electrical resistivity properties and desirability of mechanical properties:

a. F.C.C. Au, Cu, Ag, Pt, Pd, Ni, Re, Th
b. B.C.C. Mo, W, Ta, Nb, Cr, V
c. H.C.P. Hf, Os, Ru
d. Cubic - Two phase structures Ir, Rh, Fe
e. Mixed Structures - 2 phases Co, Ti, Zr
f. Mixed Structures - 3 phases U

5. Listing of metals in order of lowness or vapor pressure near their melting points:

W, Re, Mo, Os, Ta, Hf, Ir, Nb, Ru, Pt, Rh, Pd, Th, U, Zr, V, Ti, Fe, Au, Co, Ni, Cr, Cu, Ag

6. Listing of Young's modulus at Elevated Temperatures in decreasing order of preference:

a. Os, Ir, Re, Ru
b. W, Mo, Rh, Cr
c. Ni, Co, Fe, Ta
d. U, Pt, Hf, V
e. Ti, Pd, Cu, Zr, Nb
f. Au, Ag, Th

An invesion of this order gives a very rough indication of the ease of fabrication of the metals listed.

Metal	M.P.	Temperature Coefficient of Resistance	Resistivity microhom-cm			M.P. x 10^8		
$T_{mp} > 1500^\circ C$	$^\circ C$		@ $20^\circ C$	@ $500^\circ C$	@ $1200^\circ C$	@ $20^\circ C$	@ $500^\circ C$	@ $1200^\circ C$
Tungsten	3410	0.0051	5.5	17.7	40.	6.2	1.92	0.853
Molybdenum	2610	0.0047	5.5	16.2	35.	4.74	1.61	0.746
Iridium	2454	0.0051	5.5	15.0	(29.7)	4.46	1.64	(0.826)
Rhodium	1963	0.0046	4.8	14.5	(29.)	4.09	1.35	(0.677)
Ruthenium	2500	0.0051	10.5	34.0	50.	2.38	0.735	0.500
Osmium	2700	0.0042	9.5	-	-	2.84	-	-
Tantalum	2996	0.0038	14.0	34.2	59.5	2.14	0.876	0.504
Platinum	1769	0.0039	11.0	28.5	48.	1.61	0.621	0.368
Iron	1537	0.0065	9.86	60.7	122.	1.56	0.253	0.126
Rhenium	3180	0.0044	19.5	53.0	86.5	1.63	0.600	0.368
Palladium	1552	0.0040	11.65	27.2	44.5	1.33	0.570	0.349
Chromium	1895	0.0059	14.3	32.0	67.5	1.33	0.592	0.281
Niobium	2468	0.0040	18.3	41.7	(72.)	1.35	0.592	(0.343)
Thorium	1750	0.0040	16.5	46.0	68.	1.06	0.380	0.257
Hafnium	2222	0.0044	34.3	103.5	179.7	0.648	0.215	0.124
Zirconium	1852	0.0044	43.3	111.5	122.	0.428	0.166	0.152
Titanium	1668	0.0045	61.0	130.5	154.	0.273	0.128	0.108
Vanadium	1900	0.0034	22.0	-	-	0.864	-	-
$1000 < T$ (mp) $< 1500^\circ C$								
Copper	1083	0.0055	1.56	4.71	(9.84)	6.94	2.30	(1.10)
Gold	1063	0.004	2.32	6.7	(13.9)	4.58	1.59	(0.765)
Uranium	1132	0.0034	43.00	53.2	(67.00)	0.263	0.213	(0.169)
Nickel	1453	0.0069	7.20	35.5	53.	2.02	0.398	0.274
Cobalt	1495	0.0078	6.50	31.3	95.	2.30	0.478	0.157

Note: Values are taken from table 1.8.
Values in brackets are obtained by extrapolation of data in figures 1 to 4.

We now briefly discuss each of the elements selected for study in turn.

Gold (figures 2, 6 - tables 1.11, 1.14)

Pure gold is far from ideal as a structural material, even though the resistivity properties are very excellent. Resistivity values range from about 2.2 to 11.8 microhm-cm for the temperatures at 20°C and 900°C, respectively. Certainly gold is the ideal oxidation-resistant material and it may be used as a high-temperature conductor up to its M.P. and beyond if properly supported mechanically, e.g., gold-plated Pt-Rh, Mo, W, graphite, or an insulating substrate.

Rhodium and Iridium (figures 1, 5 - table 1.11, 1.14)

These precious metal elements, rhodium and iridium, have essentially similar properties. By reason of the relative difficulties associated with fabrication, they are conventionally restricted in use as alloying elements with Pt and/or Pd.

The purest grades of Rh and Ir may be considered for high-temperature electrical application up to 1200°C provided means are used to prevent oxidation at the high-temperature end of this range, e.g., employment in a closed system protected by a high purity inert gas or adequate cladding with platinum or gold or non-conductive coatings.

Both elements are of the face-centered cubic structure, similar to copper and gold, and if of equivalent purity, should have similar fabrication characteristics. This is essentially true for the purest grades, but cost considerations place the greater demand for industrial grades which are essentially hardening alloys with other precious metals.

Values of resistivity at 20°C and 500°C are:

Rh: 4.81 and 14.6 microhm-cm, respectively
Ir: 5.49 and 15.1 microhm-cm, respectively

Evidence of successful application of these elements for practical applications are typified by:

Ir - small special purpose crucibles;
Rh - mirror coatings, electroplated on metallic objects, thermocouple with Pt, and some pure wrought Rh uses.

Platinum: (figures 1, 5 - table 1.11, 1.14)

Pure platinum is similar to gold in many of the mechanical and fabrication properties, and is ideally suitable for high-temperature conductor applications up to about 1200°C. However, for the dual consideration of both structural and electrical application, Pt must be alloyed with selected precious metal hardeners; Rh, Ir, and Ru. Of the possible alloys of Pt, the Pt-Rh series are to be preferred on the basis of their superior oxidation resistance and minimum weight loss characteristics during exposure to elevated temperature. In recognition of this, the alloys of (Pt-Rh) have been included as reference materials, in Tables 1.1. through 1.5 and in figure 4 and 8. One should note the competitive position of the three (Pt-Rh) alloys selected as references in regard to their resistivity values at 1200°C. At this temperature of the solid pure elements considered, only Pd, Pt, Ru, Mo, W, can compete against the Pt-Rh alloy group.

Palladium: (figures 1, 5- tables 1.11, 1.14)

Palladium is very similar to platinum with respect to ductility and strength, but suffers a significantly greater weight loss at elevated temperatures due to a greater vapor pressure;i.e.,at 1500°C, v.p. Pt=1x 10^{-6}mm. of Hg; v.p. Pd=6 x 10^{-2}mm. of Hg. (Ref, (4), 1189, 1193). When appropriate, Pd nominally is considered in preference to Pt because of lower cost per unit of weight, and lower density. However, to obtain good mechanical as well as electrical properties, Pd requires hardening with ruthenium.

The electrical resistivity of Pd, at 1200°C is significantly low and is competitive to the reference (Rh-Pt) alloy group of figure 4. In addition, further examination of figure 1, discloses that Pd has greater linearity characteristics and lower slope of resistiviity vs. temperature over the temperature region of 20°C to 1200°C than either Pt, Ru, or Re. Further comparison of this degree of linearity of Pd to the other elements of figure 2, indicates that Ta is comparable in this regard.

In view of these considerations, pure Pd can therefore be considered a favorable candidate for high-temperature electrical purposes, preferably as the coated element on an appropriate high-temperature structural base.

Copper and Silver: (figures 2, 6 - tables 1.11, 1.14)

As far as resistivity is concerned, the other pure elements considered do not compete, and few even approach, the excellent electrical conductivity of these two established electrical conductors. For high-temperature applications however, these elements are limited by their oxidation resistance, mechanical softness, and relatively low melting points (silver MP=961°C, copper MP=1083°C). Silver begins to oxidize appreciably at 200°C in dry air and at room temperature in moist air. Copper begins to oxidize at 100°C. However, if these elements can be adequately protected from oxidation, there is no reason why silver should not be used up to 600° - 700°C and copper up to 800° - 900°C. An obvious approach to this problem is to coat these materials by electroplating, cladding,or vapor-plating techniques with gold and platinum. For rapid cycling applications of only one or two cycles (missiles), the alloying of the base elements with the coating should produce no difficulties. For continued use at high temperatures, an intermediate coating of oxide or some material not alloying with copper or silver could be used as an intermediate coat. In addition, the high conductivity of these materials, their relatively low cost and other advantages may make feasible the encapsulation of power or communication cables in non-oxidizing atmospheres.

Rhenium: (figure 1,5 - tables 1.11 and 1.14)

This metal begins to oxidze at 350°C, but the rate of oxidation does not become very rapid at temperatures up to 500°C or 600°C. Its high resistivity at temperatures as low as 600°C, (60 microhm-cm) seem to offer no advantages at these temperatures to gold or platinum. Rhenium, however, in its evaporated form, makes an extremely good high-temperature resistor for electronic circuitry. Its mechanical properties (crystal habit H.C.P.) also leaves musch to be desired.

Molybdenum and Tungsten: (figure 2,6 - table 1.11 and 1.14)

For applications at temperatures in the range 900°C to 1200°C and beyond, the electrical and mechanical properties of these elements are superior to all other pure elements. Much recent work on the forming and working of these materials has largely overcome earlier difficulties in this area. Mechanical elements can serve as high-temperature conductors without further support. The disadvantage of these metals (especially molybdenum) for high-temperature conductors is their susceptibility to oxidation. Protective atmospheres or vacuum can overcome these problems but are inconvenient for the solution to the oxidation problem except in special applications such as long power and control cables. It is possible that cladding or plating these metals with Au, Pt, or Pd would yield practical conductors if excursion to temperatures in excess of 800°C are not overly frequent.

Tantalum: (figure 2, 6 - tables 1.11 and 1.14)

Tantalum oxidizes in air at temperatures above 300°C. It has good mechanical properties and can be formed into sheets, wire, or rod with rather greater ease than tungsten. Its resistivity however is almost twice as great as that of tungsten and molybdenum and this offers only some mechanical advantages over these two metals. These advantages could be suitably capitalized if coating with gold, platinum or palladium proved to be feasible.

Cobalt, Iron, and Nickel: (figures 1, 3, 6, 7 - tables 1.11, 1.14)

These ferromagnetic elements are rendered unsuitable for high-temperature conductor applications by virtue of their high resistance at temperatures in excess of 500°C, very steep temperature coefficient of resistivity, and the effects of magnetic transformation on their electrical resistivity. An examination of figures 1, 2, and 3 illustrates these conclusions. A possible field of application exists for mechanically good alloys of these metals (e.g., stainless steel wire or sheet) as a substrates for thick gold or platinum coatings.

Titanium, Zirconium, Hafnium: (figure 3 - table 1.11, 1.14)

These elements may be eliminated from consideration as high-temperature conductors due to their high resistivity and large temperature coefficients of resistivity. In addition, the mechanical forming and oxidation-resistant properties of these elements are generally undesirable.

Osmium: (tables 1.1, 1.11, 1.14)

Osmium exhibits a low room-temperature resistance. It is, however, subject to oxidation at temperature in excess of 200°C. Its H.C.P. crystal habit renders this material difficult to fabricate. The high melting point (2700°C) and low-loss vapor pressure of this material indicate that the metal may be worthy of further literature search to determine its resistivity up to 1200°C. If the relatively low resistivity values given at room temperature continue to be relatively small up to 1200°C, there might be applications for this metal as a high-temperature conductor up to or in excess of 1200°C, provided proper oxidation protection is provided by an inert gas, vacuum, or suitable coatings.

Chromium and Niobium: (figures 3, 7 - tables 1.11, 1.14)

These metals are similar to tantalum in their electrical resistivity behavior and function of temperature. However, like tantalum, oxidation at a few hundred degrees centigrade and high electrical resistivity does not favor their use as high-temperature conductors. Niobium, however, might serve as an alternate to tungsten or tantalum as a high-temperature supporting substance for gold or platinum.

Uranium: (figures 2, 6, - tables 1.11, 1.14)

A combination of high resistivity and nonlinear resistivity characteristics, due to phase changes, poor oxidation resistance at very moderate temperatures, and poor mechanical qualities, eliminates this material from consideration except in special situations (e.g. nuclear-thermoelectric energy conversion). It is interesting that, due to the sluggishness of the phase changes in uranium (table 1.11), an almost zero change in resistivity with temperature would be obtained for rapid changes in temperature.

Thorium: (figures 2, 6 - tables 1.11, 1.14)

This metal is superior to uranium electrically, mechanically (single phase

FCC), and in regard to oxidation resistance. It does, however require oxidation protection at about two hundred degrees centigrade. This combined with its relatively high resistivity, eliminates thorium from consideration, except for high temperature conductors in nuclear thermoelectric devices. However, this application for thorium or uranium might become very important in the future if present developments in this field fulfill their present promise.

1.5 Summary and Conclusions

In the previous parts of this section we have tabulated, analyzed, and interpreted the properties relevant to pure metallic elements as high-temperature conductors. We have found that there is no single metallic conductor which can meet all of the desirable qualities of low electrical resistivity, high oxidation resistance, good mechanical strength and ease of forming. Of the pure metals, platinum and gold (up to 900°C) and to a lesser extent, rhodium and palladium are probably the best pure elements for high-temperature conductors. These metals, however, do not compete in mechanical properties with Pt-Rh alloys. At temperatures beyond 900°C, tungsten, molybdenum, and to a lesser extent, ruthenium, and tantalum offer the best potential and are superior to Pt or (Pt-Rh) alloys in their electrical properties. In those cases where oxidation is rapid (molybdenum), the duty cycle of the conductor must be given careful examination.

Among the pure elements, ruthenium definitely warrants research on forming techniques and wire drawing. If it were not for difficulties in this direction, ruthenium would be quite a good high-temperature conductor for the full range up to 1200°C. Its resistivity is moderately low and it exhibits relatively good oxidation resistance. Moreover, the technology of this metal is so little known that significant reductions in resistivity should be possible when careful attention is given to the reduction of chemical impurities and structural defects.

Attention should be given to the hot drawing, extrusion, and machining of this metal and to the electrolytic and vapor-deposition techniques for plating substrate structures easier to form. Dilute alloys of ruthenium with Pt, Rh, Ir, Ag, and Au are also worthy of experimental concideration.

Gold is another element worthy of further experimental consideration. The alloys of gold do not seem to have been subjects for extensive high-temperature electrical resistivity investigation. It is quite possible that the hardening additions which may be found for gold would not affect prohibitively its electrical resistivity. Such research may thus produce the gold alloy high-temperature conductor equivalent of platinum-rhodium alloys.

In addition to the techniques of alloying for the improvement of the mechanical properties of metals, there exists the possibility of cladding, electrolytic plating or vapor plating (see section 1.6) one metal with another to provide combinations of metals, which meet particular duty requirements better than either of the pure metals alone. In this way highly conductive oxidation-resistant coatings of pure gold can be applied to copper, silver, rhodium, iridium, platinum, (platinum-rhodium), palladium, ruthenium, molybdenum, tungsten, and tantalum to improve the bulk and surface conductives of these materials up to 1000°C or even up to 1200°C. In some of these combinations, the lifetime would be limited to several minutes or a few cycles in the high-temperature environment, due to diffusion and alloying. However, missile and some spacecraft applications require only one or two exposures to high temperatures. It is possible that the useful lifetime of these coatings can be increased, in cases where alloying or diffusion is a serious problem, by the inclusion of a thin layer of some other coating between the gold and the substrate. Similar considerations apply to the coating of these metals (e.g., Ag, Au, Rh, Ir, Pd, Ru, Mo, W, Ta) with pure platinum, which has excellent oxidation resistance up to its melting point of 1769°C. The resistivity of these coatings would be two or three times higher than those of gold on these metals, but platinum would extend oxidation protection to temperatures of the order of 1500°C. Lower resistivity conductors of similar characteristics can be obtained using rhodium, palladium, or ruthenium.

The case of silver is of interest here as it introduces a principle which might be advantageous in missile and spacecraft applications. At temperature in excess of 961°C, the silver in the platinum-clad silver would become molten. However, liquid silver is still the best pure metallic conductor even at 1200°C, as shown in figures 2 and 9. Thus, if electrolytic or cladding techniques could be used to put an appreciable thickness of platinum or other suitable material on the silver, the platinum would form a containing tube for the liquid metal. The resultant system would have elctrical properties which would be far superior to molybdenum or tungsten for short duty times such as those encountered in missiles and some spacecraft applications. This same principal could equally be applied to the aluminum, gold, and perhaps even the less reactive of the highly conductive alkali metals.

A further modification of the cladding or plating principle for gold and platinum remains to be considered; the use of semiconducting or insulating, from stable, mechanical substrates. Platinum or gold can be electrolytically or vapor-plated to considerable thickness onto graphite waveguide shapes

which can be machined with some precision. It is possible the useful waveguide cavities and antennas as well as d.c. power conductors can be fabricated by this means, which would be advantageously serviceable at temperatures up to 1200°C and higher. Similar considerations apply to the use of fused quartz as a substrate except for significantly less ease of forming as compared to graphite (fused quartz could be used for the important case of wires). A possible approach to quartz-plated wires consists in vapor-plating fine quartz wire shich is known to have higher strength-to-weight ratio than any other easily formed material; then to electroplate a considerable thickness of pure platinum or gold on the metalized quartz wire substrate.

Mechanical support for pure gold or platinum wire, for high temperature, can also be provided by intertwining the pure metal wires with quartz fibre or with tungsten or tantalum wire. Here the quartz, tungsten, or tantalum would provide the mechanical strength for the contact while the pure gold or platinum would provide a low electrical conductivity combined with a high oxidation resistance. Alternately, the gold may be mechanically supported by thick external coatings of a dielectric (e.g., glass or metal).

1.6 Supplementary Data

Vapor Plating of Metals and Insulating Coatings

Vapor plating has been successfully employed for the deposition of a variety of metallic coatings. This method is of particular value for the deposition of refractory materials of high purity. However, the less refractory materials, such as copper, can also be deposited by this method and may offer some advantages (such as greater crystallinity) over more conventional methods, such as electroplating.

The degree of crystallinity of the costing obtained by vapor plating generally depends upon the deposition or substrate temperature; the higher the temperature the greater the crystallinity. In general, it may be expected that a more stable starting compound requires a higher decomposition or substrate temperature, and that the resulting coating should be more crystalline than that obtained from a less stable starting compound. One can, therefore, in a sense, control the physical properties of the coatings obtained by vapor plating by judicious selection of the starting compound as well as the deposition conditions.

Finally, it should be noted that the metallic coatings can be doped with various metallic or metalloidal compounds by including an appropriately volatile source of the doping element with the starting compound prior to or during deposition. Thus, for the preparation of a gold coating doped with 10% (atomic) palladium, the acetylacetonate derivative of each of these metals might be vaporized and thermally decomposed in a hydrogen atmosphere at the heated substrate.

Pure Metals

Group VI-A (Mo, W)

Molybdenum has been vapor deposited on a variety of substrates by thermal decomposition of $MoCl_5$ at 1400°C, reduction of $MoCl_5$ with hydrogen at 900°C, and by thermal decomposition of molybdenum carbonyl in the presence of hydrogen at about 600°C. The purest and most crystalline deposits are generally obtained by thermal decomposition of $MoCl_5$. However, the reduction of $MoCl_5$ with hydrogen is somewhat easier to carry out because of the lower deposition temperature that can be employed. Single crystal deposits have also been produced by the latter method.

Another approach worthy of consideration is by thermal decomposition of molybdenum 1,1,1,5,5,5,-hexafluoro-acetylacetomate in the presence of hydrogen. This compound should be quite volatile and sufficiently stable in the vapor phase to permit controlled reduction to a crystalline deposit.

Tungsten coatings have been readily produced by reduction of tungsten hexachloride with hydrogen at 600-700°C and by thermal decomposition of tungsten carbonyl in the presence of hydrogen at 350-600°C. In the latter case, purer coatings (free of carbon) are obtained than in the case of molybdenum carbonyl--presumably because of the greater ease of decomposition of tungsten carbonyl.

As in the case of molybdenum, the fluorinated acetylacetonate derivative of tungsten might be a convenient source for the deposition of tungsten primarily because of the lower volatilization temperature.

Group VIII-B (Rh, Ir)

The vapor deposition of rhodium and iridium is much less well-known than that of molybdenum and tungsten, undoubtedly because of the relative scarcity of metals. However, they have presumably been deposited from their mixed chlorocarbonyls similar to the compounds employed for platinum.

It would appear that more suitable compounds for use in the vapor deposition of rhodium and iridium would be the acetylacetonate derivatives, $Rh(AA)_3$ -b.p. 280°C (d), and $Ir(AA)_3$ -b.p. 290°C (d) (AA = acetylacetonate group). A more volatile derivative would undoubtedly be the hexafluoroacetylacetonate. Next to these materials, the vapor deposition of rhodium from di-rhodium octacarbonyl, $Rh_2(CO)_8$, and iridium from its respective carbonyl derivative, $Ir_2(CO)_8$, would be of interest. The prime advantage would be in their greater volatility. This might, however, be offset by their more ready decomposition to less crystalline deposits.

Group VIII-C (Pd, Pt)

Platinum has been vapor - deposited from its chloro-carbonyl derivative at 600°C and from its acetylacetonate derivative at 350-450°C in vacuo. Little or no information is available on the vapor deposition of palladium.

In the case of each of these metals, it would seem that the compound of choice would be either the acetylacetonate or preferably the hexafluoroacetylacetonate derivative. Vapor deposition in the presence of hydrogen would seem most desirable to minimize oxide formation.

Other compounds of interest, primarily because of their high volatility, are bis-(triethylphosphine) platinum dimethyl, $(Et_3P)_2PtMe_2$ (b.p. 130°/12 mm) as a source of platinum, and bis-(triethylphosphine) palladium dimethyl, $(Et_3P)_2PdMe_2$ (sublimes in vacuo at 49-50°) as a source of palladium.

Group I-B (Cu, Ag, Au)

Copper has been vapor deposited from its formate and acetylacetonate derivatives at 350-450°C. Little or no information is available on silver and gold, presumably because of their ease of deposition by electroplating and the unavailability of convenient volatile sources of these metals.

Next to the acetylacetonate derivatives, as in the case of the Group VIII-B and VIII-C metals, the organometallic derivatives would provide a more volatile source for these metals. Attractive candidates for investigation include cyclopentadienyl copper triethylphosphine, sublimes at 60°C/0.001mm Hg, and di-propyl gold bromide ($n\text{-}Pr_2AuBr$), liquid, b.p. 95°C (d).

Chemical Deposition

Another approach of possible utility here is the chemical deposition approach involving complex aluminum hyride or borohydride derivatives of the desired metals.

This method would involve liquid phase deposition of the metal from the complex hydride derivative by thermal or chemical decomposition at the substrate surface. It is believed that this method should be of particular value for the deposition of copper, silver, and gold coatings. Specific examples may be depicted as follows.

$$Cu(BH_4)_2 \xrightarrow{\Delta} Cu + B_2H_6 + H_2$$

$$Cu(AlH_4)_2 + 6HOAc \longrightarrow Cu + 2Al(OAv)_3 + 7\ H_2$$

Vapor Plating of Insulating Compounds

High temperature insulating compounds for possible use as barrier layers or protective coatings include zirconia (ZrO_2), hafnia (HfO_2), and thoria (ThO_2). Although very little has been reported in the open literature on the vapor deposition of these materials, it would seem that this method provides an attractive approach to the formation of such coatings.

Zirconia has been vapor deposited by reaction of zirconium tetrachloride with hydrogen and carbon dioxide at a heated substrate (800-1000°C).

$$ZrCl_4 + 2H_2 + 2CO_2 \longrightarrow Zro_2 + 4HCl + 2CO$$

No information is reported on HfO_2 and ThO_2 coatings.

The approach being used at Melpar which appears promising consists of thermal decomposition of appropriate alkoxide derivatives of these metals. Thus, in the case of hafnia, the thermal decomposition of hafnium tert-butoxide is under study.

Other compounds of possible greater value for the deposition of these metal oxides are the bis-hexafluoroacetylacetonate bis-alkoxide derivatives, $M(AA)_2(O\underline{t}\text{-}Bu)_2$.

$$M(AA)_2(O\underline{t}\text{-}Bu)_2 \longrightarrow MO_2 + 2AAH + 2CH_2 = C(CH_3)_2$$

where AA=hexafluoroacetylacetonate group.

TABLE 1.1

BASIC DATA ON PURE METALS (ELECTRICAL RESISTIVITY 20,500, 1200°C) TEMPERATURE COEFFICIENT OF RESISTIVITY (0-100°C, M.P. °C)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			Reference
			20°C	500°C	1200°C	
Cobalt	1495	7.8×10^{-3}	7.	33.	96.0	(1)
Cobalt		6.04×10^{-3}	6.24	----	----	(2), 673,636
Cobalt		6.37×10^{-3}	5.68 (0°C) or (6.45)*** (20°C)	32.20	91.9	(3), 117,634
Cobalt	1495 ± 1	6.04×10^{-3}	6.24			(4), 120,46
Cobalt			6.24			(6), 21
Cobalt			9.7			(7), 79
Cobalt	1490 ± 20		5.60 (0°C)			(20), 459
Cobalt	1478		9.7			(23), (1-04)
Cobalt			6.24			(27), 246

Element	M.P. (°0)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Copper	1083	5.5×10^{-3}	1.4 1.6	4.55	8.1 (949°C)	(1), (I-C-7)
Copper		4.3×10^{-3}	1.673			(2), 673,636
Copper			1.72			(3), 634
Copper	1083 ± 0.1	6.8×10^{-3} (20°C)	1.6730	5. (estm)	22.5 estm	(4), 48,1203,1204
Copper		----.	1.6730	----	----	(6), 21
Copper		4.115×10^{-3}	1.682			(7), 79,1380,1383
Copper		4.8×10^{-3}	----			(13), 31; Cu-99.9% electrolytic-tough pitch
Copper	1083		1.67			(20), 459
Copper		3.93×10^{-3}	1.72			(21), 159
Copper		(4.31×10^{-3})***	(1.69)***	(9.31)*** (1000°C)		(22), 1312
Copper	1083		1.68			(23), (1-04)
Copper			1.55 (°C)			(27), 246

* Temperature Coefficient of Resistance - $\alpha = \frac{1}{Ro}\left(\frac{R_{100} - Ro}{100}\right)$ of the resistance between 0° and 100°C.

** Electrical Resistivity: ρ, (Rho)

*** - Calculated value

TABLE 1.1 (Cont'd.)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Chromium	1847	2.6×10^{-3}	12 - 13	32.3	66.5 (1004°C)	(1), (I-C-5)
Chromium		5.88×10^{-3}	21.0			(2), 636,673
Chromium			13.0			(3), 634
Chromium	1875	3.00×10^{-3}	12.9 (0°C)			(4), 48,1200,46
Chromium	----		13.0 (28°C)	----	----	(6), 21
Chromium			13.1			(7), 79
Chromium	1875		12.8			(16), 61
Chromium	1800 ± 50		14.1			(20), 459
Chromium	1921		13.1			(23), (1-04)
Chromium	----		15.4			(28), 246

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Gold	1063.6	3.6×10^{-3}	2.3	6.7	12.1 (949°C)	(1), 1-G-3
Gold		3.9×10^{-3}	2.3	11.8 (900°C)		(2), 673,637
Gold			2.44			(3), 634
Gold	1063.0 ± 0.0	4×10^{-3}	2.35	(6.5)		(4), 48,1185,( ) Derived from curve
Gold			2.19 (°C)	----	----	(6), 21
Gold			2.42			(7), 79
Gold		4×10^{-3}	2.35			(11), 291
Gold	----	----	----	----	32.76	(14), 41
Gold	1063		2.19 (0°C)			----
Gold	1063		2.42			(23), (1-04)
Gold			2.04 (0°C) (2.20)*** (20°C)			(27), 247

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Hafnium	2222	3.05×10^{-3}	38.5	96.0	138. (977°C)	(1), (I-H-1)
Hafnium		4.43×10^{-3} (200°C)	32.4			(3), 185,634
Hafnium	2222 ± 30	3.8×10^{-3}	35.1 (25°C)			(4), 48,1205
Hafnium	1975	30.				(16), 61
Hafnium			29.4 (0°C)			(27), 246

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Iridium	2457	4.17×10^{-3}	5.	----	----	(1), (I-J-1)
Iridium		3.9×10^{-3}	5.3	15.1	----	(2), 673,637
Iridium		3.925×10^{-3}	4.90			(3), 315
Iridium	----	----	4.9	----	----	(3), 634
Iridium	2454 ± 3	3.925×10^{-3}	5.3	----	----	(4), 48,1196
Iridium			5.3			(6), 21
Iridium		3.92×10^{-3}	6.08			(7), 79,1688
Iridium		4×10^{-3}	5.3			(11), 291
Iridium	2442	----	5.3	----	----	(16), 61
Iridium	2454 ± 3	(3.92×10^{-3})***	5.3	15.1	----	(17), 44,43
Iridium		(3.925×10^{-3})***				(17), 44
Iridium	2454 ± 3	----	5.3			(20), 459
Iridium	2454	----	6.08			(23), (1-Ch)
Iridium			5.0			(27), 246
Iridium	2410	4×10^{-3}	5.3	----	----	(36), 3

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Iron	1539	4.50×10^{-3}	10	56.	122	(1), (I-J-2)
Iron		6.51×10^{-3}	9.71	43.1 (400°C)	105.5 (800°C)	(2), 673,637
Iron			10.	----	----	(3), 634
Iron	1536.5 ± 1	6.51×10^{-3}	9.71	(38.8)***	(111.7)***	(4), 48,1206,1209,46, (Cole) Value, Iron Table Relative Resistance
Iron		6.35×10^{-3}	9.80			(7), 438
				54.5a	112.4a (950°C)	(7), 79,437 (a.Data of Burgess & Kelberg)
Iron	1539 ± 3°C	----	9.71	----	----	(20), 459
Iron		6.34×10^{-3}	9.78			(21), 159
Iron		6.50×10^{-3}	(9.77)***	(52.7)***	(112.)*** (1000°C)	
Iron	1535		9.8			(23), (1-04)
Iron			8.93 (0°C)			(27), 246

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			Reference
			20°C	500°C	1200°C	
Molybdenum		(4.13×10^{-3}	5.63	----	----	(15), 362
	2610		5.21			(16), 61
Molybdenum		4.6×10^{-3}	5.7			(18)
Molybdenum	2625 ± 50		5.17 @ 0°C			
			4.34 0°C (4.74)*** (20°C)			(27), 246
Molybdenum			6.36 @ 18 to 20°C	18.2	37.8	(30), 21 from graph
Molybdenum	2625	4.7×10^{-3} (20° -100°C)	5.26	----	----	(31), (Re-2)
Molybdenum	2620	(3.61×10^{-3})***	6.4	17.5	37.5	(32), Bulletin No. (2.0.1) & (2.0.2), & graph
Molybdenum	2622 ± 10	4.7×10^{-3} (20 to 100°C)	5.65	17.1	35.2 (1127°C)	(34), 6
Molybdenum	2610		5.78 @ 27°C	23.9 @ 727°C	35.2 (1127°C) and 47.0 (1527°C)	(37), 13, 15; Regarding Mo: Full density (37), 15; Regarding: Mo: Full density
Molybdenum		(5×10^{-3})*** (0° to 800°C)	5. (0°C)	25 (800°C)	47 (1600°C)	(38), 1

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Molybdenum	2617	4.15×10^{-3}	5.5	16.5	31.8	(1), I-M-4
Molybdenum		4.6×10^{-3}	5.17 (0°C)			(2), 673
Molybdenum			5.7	17.6	31.0 (1000°C)	(2), 638
Molybdenum	2625	4.7×10^{-3}	(5.53)***		35.2 (1127°C) 37.4@1200°C; by interpolation	(3), 277,278
					41.2 (1327°C)	(3), 278
	----	----	5.78	----	----	(3), 634
Molybdenum	2610	----	5.2 @ 0°C	18 (estm)	33. (estm)	(4), 49,47,1215,1216
Molybdenum			5.17 @ 0°C			(6), 21
Molybdenum			4.77			(7), 81
Molybdenum	2682 ± 10	(4.34×10^{-3})***	(5.72)***	18 estm	37.4 estm	(8), 193
Molybdenum		4.62×10^{-3}	5.78 @ 27°C	----	(37.4)***	(11), 26, Very pure Molybdenum wire value obtained by interpolation
Molybdenum		5×10^{-3}	4.8 (25°C) (4.68)*** 20°C			(12), 30

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Nickel	1455	6.15×10^{-3}	7.	34.	(48.5)(@977°C)	(1), (I-N-3)
Nickel		6.81×10^{-3}	6.844	----	----	(2), 673
Nickel			6.84	34.2	(45.5)(@900°C)	(2), 638
			7.8	----	----	(3), 634
Nickel	1453	6.9×10^{-3}	6.84	38.3 (estm)	51.2 (estm)	(4), 49,47,1217,1218
Nickel			6.84			(6), 21
Nickel			6.9			(7), 81
Nickel		6.36×10^{-3}	6.844			(7), 1644; Ni 99.99% purity
Nickel		6.36×10^{-3}	6.84			(8), 218
Nickel	1455 ± 1		6.84			(20), 459
Nickel		4.91×10^{-3}	7.24			(21), 159
Nickel		(6.63×10^{-3})	(7.23)	(34.5)	(48.1) @1000°C	(22), 1312
Nickel			6.24 @ 0°C			(27), 246

TABLE 1.1 (Cont'd)

Element	M.P. (^{o}C)	* α (0-100^{o}C)	** ρ Microhm - Cm			References
			20^{o}C	500^{o}C	1200^{o}C	
Niobium	2467	2.84×10^{-3}	14.5	35.	(50.)(893^{o}C)	(1), (I-N-4)
		3.95×10^{-3}	13.1	----	----	(2), 673
Niobium	2415 ± 15^{o}	3.95×10^{-3}	13.2	----	----	(3), 394,634
Niobium	2468 ± 10	3.95×10^{-3} (0-600^{o}C)	12.5			(4), 48,1202,46,: , for commercial grade Niobium
Niobium			13.1 (18^{o}C)			(6), 21
Niobium			20.			(7), 79
Niobium	2415		14.8			(16), 61
Niobium		3.95×10^{-3}	14.1			(18)
Niobium	1982		20.			(23), (1-04)
Nibium	2415		(15.22)(80^{o}C)	38.96@600^{o}C		(32), , Bulletin No. (1.0.1)

Element	M.P. (^{o}C)	* α (0-100^{o}C)	** ρ Microhm - Cm			References
			20^{o}C	500^{o}C	1200^{o}C	
Osmium	2700	----	----	----	----	(1), (I-O-1)
Osmium		4.2×10^{-3}	9.5			(2), 673
Osmium	2700 (estm)	4.2×10^{-3}	9.5 @ 0^{o}C			(3), 317,634
Osmium	2700 ± 200	4.2×10^{-3}	9.5 20^{o}C			(4), 49,1217,47
Osmium			9.5 20^{o}C			(6), 21
Osmium		4.2×10^{-3}	9.			(7), 81,1689
Osmium		4.2×10^{-3}	9.5			(11), 291
Osmium	3000		9.5			(16), 61
Osmium	2700 ± 200		9.5			(20), 459
Osmium		or(9.83)@20^{o}C	9.07 @ 0^{o}C			(27), 246
Osmium	3000	4.2×10^{-3}	9.5			(36), 3

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Palladium	1557	4.03×10^{-3}	12.5	(27.7)(@477°C)	----	(1), (I-P-1)
Palladium		3.77×10^{-3}	10.8	----	----	(2), 673
Palladium	----	----	10.8	27.5	40.0 (1000°C)	(2), 638,636
Palladium	1552	3.77×10^{-3}	10.8			(4), 49,1193,47
Palladium			10.8			(6), 21
Palladium			10 0°C (?)			(7), 81
Palladium		3.8×10^{-3}	10.8			(11), 291
Palladium		3.77×10^{-3}				(17), 37, Data of Holborn
Palladium		(3.7×10^{-3})***	(12.5)***	26.8 to 28.7	44.8	(17), 37, Table 17., after Data of Connybeare
Palladium	1554 ± 1		10.8			(20), 459
Palladium			10. @ 0°C or (10.75) 20			(27), 246
Palladium	1552	3.8×10^{-3}	10.7			(36), 3
Palladium			10.7			(36), 9; Electrodeposited Palladium

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Platinum	1774	3.92×10^{-3}	10.5	(15.4)(@143°C)	----	(1), (I-P-2)
Platinum	----	3.92×10^{-3}	9.81 @0°C	----	----	(2), 673
Platinum	----	----	10.6	27.9	43.1 @ 1000°C 55.4 @ 1500°C	(2), 638 (2), 638
Platinum	----	3.92×10^{-3}	10.58	----	----	(3), 312
Platinum	----	----	10.6	----	----	(3), 634
Platinum	1769	3.927×10^{-3}	10.6	(26.3) (estm)	(47.) estm	(4), 49,1189,47
Platinum	----	----	9.83 (0°C)			(6), 21
Platinum	----	----	9.83 (0°C)			(7), 81
Platinum	----	(3.07×10^{-3})	10.8	(26.7) (estm)	46.5	(10)
Platinum	----	3.93×10^{-3}	10.6	----	----	(11), 291
Platinum	----	3.5×10^{-3}	11.4	----	----	(11), 294, Pt. (99.51% Pt), grade crucible
Platinum	----	$(3.92 \times 10^{-3}$	10.59	27.88	48.34	(17), 20
Platinum	1773.5 ± 1		9.81 @ 0°C	----	----	(20), 460

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Platinum	----	3.69×10^{-3}	10.6	----	----	(21), 159
Platinum	----	(3.92×10^{-3})	(10.55)	(27.9)	(48.4)	(22), 1312
Platinum	----	----	9.78 0°C	----	----	(27), 246
Platinum	1769	3.92×10^{-3}	10.6	----	----	(36), 3
Platinum	----	3.923×10^{-3}	9.81 @ 0°C	----	----	(36), 5; Grade-JMC-Thermocouple-Pure-Platinum
Platinum	----	----	10.6			(36), 9; Electro-deposited Platinum

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Rhenium	2990	4.37×10^{-3}	18.	51.	83.	(1), (I-R-2)
Rhenium	----	----	21.1	25. (@ 100°C)	132 (@ 2500°C)	(2), 638
Rhenium	(3167)±50°C)	3.11×10^{-3}	21.0	----	----	(3), 357,358,634
Rhenium	3180 ± 20	3.95×10^{-3}	19.3	52.6	80.5@1100°C (83.8)@1200 87.0@1300°C	(4), 49,47,1220,1221 by interpolation, 1221, ref (4)
Rhenium	----	----	21.	----	----	(7), 81
Rhenium	3180	----	19.3	----	----	(16), 61
Rhenium	3180	3.95×10^{-3} (20° - 100°	19.0			

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Rhodium	1966	4.45×10^{-3}	4.8	----	----	(1), (I-R-3)
Rhodium	----	4.57×10^{-3}	4.3 @ 0°C	----	----	(2), 673
Rhodium	----	----	4.7	14.6	----	(2), 638
Rhodium	----	4.57×10^{-3}	4.51 (0°C) 4.50 (0°C)	----	----	(3), 315 (3), 634
Rhodium	1966 ± 3	(4.57×10^{-3})	4.51 (0°C)	----	----	(4), 49,47,1196
Rhodium	----	----	4.5	----	----	(6), 21
Rhodium	----	----	4.93	----	----	(7), 81
Rhodium	----	4.36×10^{-3}	4.51 @ 0°C	----	----	(7), 1687
Rhodium	----	4.4×10^{-3}	4.5	----	----	(11), 291
Rhodium	1960	----	4.7	----	----	(16), 61
Rhodium	1966 ± 3°C	(3.68×10^{-3}) (4.36×10^{-3}) to (4.57×10^{-3})	4.68	(14.85) @ 509°C	----	(17), 46,47,48 (17), 48
Rhodium	1966 ± 3	----	4.3 @ 0°C	----	----	(20), 460
Rhodium	----	----	4.53 @ 0°C	----	----	(27), 246
Rhodium	1960	4.6×10^{-3}	4.7	----	----	(36), 3
Rhodium	----	----	4.7	----	----	(36), 9; Electro-deposited Rhodium

TABLE 1.1 (Cont'd)

Element	M.P (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Ruthenium	2500	5.07 x 10^{-3}	6.7	35.	52.5	(1), (I-R-4)
Ruthenium	----	----	7.6 (@ 0°C)	----	----	(2), 673
Ruthenium	2400 (estm)	4.49 x 10^{-3}	(7.16 to 7.6)	----	----	(3), 317,634
Ruthenium	2500 (± 100)	----	7.6	----	----	(4), 49,47,1220,1221
Ruthenium	----	----	7.6 @ (0°C)	----	----	(6), 21
Ruthenium	----	----	10. 14. (@ 0°C)	----	----	(7), 81 (7), 1688
Ruthenium	----	4.6 x 10^{-3}	7.2	----	----	(11), 291
Ruthenium	2250	----	9.5	----	----	(16), 61
Ruthenium	2400 to about 2450	----	14.4 (18°C)	----	----	(17), 54
Ruthenium	2500 ± 100	----	10. @ 18°C	----	----	(20), 460
Ruthenium	----	----	11.75 @ 0°C	----	----	(27), 246
Ruthenium	2250	4.2 x 10^{-3}	9.5	----	----	(36), 3

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Silver	961	4.33 x 10^{-3}	1.6	4.8	----	(1), (I-S-4)
Silver	----	4.1 x 10^{-3}	1.6	----	----	(2), 673
Silver	----	----	1.59	4.7	(7.6)(@ 900°C)	(2), 638
Silver	----	----	1.59	----	----	(3), 634
Silver	960.80	4.1 x 10^{-3}	1.59	(4.41) estm	----	(4), 49,47,1181,1182
Silver	----	----	1.59	----	----	(6), 21
Silver	----	----	1.62	----	----	(7), 81
Silver	----	4.1 x 10^{-3}	1.72	----	----	(11), 291
Silver	----	----	----	----	19.4 @ 1200°C	(14), 43
Silver	960.5	----	1.62	----	----	(20), 460
Silver	----	3.61 x 10^{-3}	1.62	----	----	(21), 159
Silver	----	(4.08 x 10^{-3})	(1.62)	(4.72)	(7.64) @ 900°C	(22), 1312
Silver	----	----	(1.4 @ 0°C) (1.51) @ 20°C	----	----	(27), 264
Silver	----	----	1.495 @ 0°C	----	----	(27), 246
Silver	960.8	4.1 x 10^{-3}	1.6	----	----	(36), 12
Silver	----	----	1.6	----	----	(36), 16; Electro-deposited Silver

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Tantalum	2987	3.34×10^{-3}	13.	33.	58.	(1), (I-T-1)
Tantalum	----	3.8×10^{-3}	13.5	----	----	(2), 673
Tantalum	----	----	13.5	35.0	60***	(2), 638 *** obtained by interpolation between values at 500°C & 1500°C
Tantalum	----	----	12.4 (18°C)	51. @ 927°C	59 @ 1127	(3), 634, 394
					(65.8 @ 1327	(3), 394
Tantalum	(2996) (± 50°)	3.83×10^{-3}	12.45 @ (25°C)	----	(61.5)	(4), 49, 47,1222,1223 (by interpolation)
Tantalum	----	----	12.4 (18)°C	----	----	(5), 21
Tantalum	----	----	15.5	----	----	(7), 81
Tantalum	2996	----	13.5	----	----	(16), 61
Tantalum	----	3.8×10^{-3}	13.5	----	----	(18)
Tantalum	2996	3.8×10^{-3}	13.5	----	----	(19), 2
Tantalum	3000 ± 100	----	14.6 (18°C)	----	----	(20), 460
Tantalum	----	----	(13.87) (@ 0°C)	----	----	(27), 246
Tantalum	2940	3.8×10^{-3}	12.4	----	(54 @ 1000°C) (71 @ 1500°C) (60.8) 1200°C By interpolation data (32)	(32), Bulletin No. 3.0.1

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Thorium	1707	3.16×10^{-3}	20	49	71	(1), (I-T-4)
Thorium	----	2.3×10^{-3}	18.62	----	----	(2), 673
Thorium	(1840) (± 50°C)	----	13.0***	----	----	(3), 445 *** data on Iodide Thorium, by Marden et.el.
Thorium	----	----	18.6 (20°)	----	----	(3), 634
Thorium	1750	3.8×10^{-3}	13.0 @ 0°C	----	----	(4), 49,47,1224,1225
Thorium	----	----	19.	----	----	(6), 21
Thorium	----	----	18.	----	----	(7), 81
Thorium	1690 ± 10	----	18.	----	----	(8), 302
Thorium	1750	2.3×10^{-3}	18.	----	----	(9), 215 after work of Bender, (1949)
			(13-14) esta	----	----	(9), 215 for pure Thorium and quoted by Ref 9 after work of (1) Marden and Rentschler (1927) and Meisner and Voigt (1930)
Thorium	----	$\underline{3.96 \times 10^{-3}}$	----	----	----	(9), 218, after work of DeBoer (1939). & assumed to be the most correct
Thorium	1800 ± 150°C	----	18.62			(20), 460

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Titanium	1680	4.5×10^{-3}	42	124	149	(1), (I-T-7)
Titanium	----	3.5×10^{-3}	55.	----	----	(2), 673
Titanium	----	----	55.	135***	(165 @ 800°C)	(2), 638***by interpolation between 400°C and 600°C)
Titanium	1690	----	47.8 (@ 25°C)	----	----	(3), 462
Titanium	1668 ± 10	----	42.	125 (estm)	----	(4), 49,47,1225
Titanium (99.9%)	----	4.25×10^{-3}	(54.98)(@25°C)	----	----	(5), 87
Titanium	----	----	(80) (@ 0°C)	----	----	(6), 21
Titanium	1690	----	47.8 (20°C)	----	----	(8), 349
Titanium	1820 ± 100	----	(80) (@ 0°C)	----	----	(20), 460

TABLE I

Element	M.P. (°C)	** α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Tungsten	3377	3.64×10^{-3}	6.5	17.5	39.0	(1) (I-T-7)
Tungsten	-	4.6	5.5	-	-	(2) 673
Tungsten	-	-	5.5	18.0	38.4***	(2) 638 *** by interpolation between values at 1000°C and 2000°C.
Tungsten	(3410 ± 10) (3380)	4.82×10^{-3}	5.48 @ 0°C	-	-	(3) 490
Tungsten	3410	-	5.65 @ 27°C	(17.9 estm.)	(39.0 estm.)	(4) 49,47,1225; drawn wire.
Tungsten	-	-	5.5	-	-	(6) 21
Tungsten	-	-	5.48	-	-	(7) 81
Tungsten	3395 ± 15	5.1×10^{-3}	5.5	(18.7)	40.	(8) 374
Tungsten	3410	-	5.5	-	-	(16) 61
Tungsten	-	4.6×10^{-3}	5.5	-	-	(18)
Tungsten	3410	4.6×10^{-3}	5.5	17.	38.00	(20) 3; Data after Espe & Knoll, Werkstoffkunde der Hochvakuumtechnik, Berlin, 1936. (for ρ vs temp.).

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	** α (0-100°C)	** ρ Microhm-Cm			References
			20°C	500°C	1200°C	
Tungsten	3410 ± 20	-	5.5	-	-	(20), 460
Tungsten	-	4.54×10^{-3}	5.75	-	-	(21), 159
Tungsten	-	-	5.0	-	-	(27), 246
Tungsten	3400	4.82×10^{-3} (20°- 100°C)	5.58	-	-	(31), (Re-2)
Tungsten	abt. 3400	5.1×10^{-3} (0-170°C)	5.5	-	33. @ 1000°C 67 @ 2000°C (39.8 @ 1200°C)	(33), 25 (33), 25 (33), by interpolation of data.
Tungsten	-	(4.29×10^{-3}) (27°-127°C)	(5.64) (@ 27°C)	19.47 @ 527°C	41.85 @ 1227°C	(35) 13; Data of Forsythe & Worthing
Tungsten	3410	-	5.65 @ 27°C	21.35 @ 627°C	39.50 @ 1227°C	(37) Regarding Tungsten.
Tungsten	-	4.82×10^{-3} (20-100°C)	5.48 @ 0°C	-	-	(38), 1

Element	M.P. (°o)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Uranium	1133	2.45×10^{-3}	29	54	(55) (@ 893°C)	(1), (I-U-1)
Uranium	-	3.4×10^{-3}	29.0	-	-	(2), 673
Uranium	-	-	(28.8)*** (@ 0°C)	-	-	(3), 533, purity 99.93% Uranium.
Uranium	-	-	29.6 to 32.2 (@ 0°C)	-	-	(3), 533, Purity 99.86% to 99.90% Uranium.
Uranium	-	(2.70 to) (2.82)	26.2 to 27.5 @ 25°C	-	-	(3), 533, Swaged wires, & annealed.
Uranium	-	-	(29. ***) (°C)	-	-	(3) 634 selected by editor of ref.(3)
Uranium	1132.3 ± 0.8	-	30.	-	-	(4), 49,47, 1226

TABLE 1.1 (Cont'd)

Element	M.P. (°C)	** α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Uranium	-	-	60 @ 18°C	-	-	(6), 21
Uranium	-	-	60.	-	-	(7), 81
Uranium	1133 ± 1	(2.36 x 10^{-3})	(30 @35.5°C)	(52.8)	-	(8), 388-390
			(29.1 @20°C)	-	-	(8), 390
Uranium	1850	-	60 (18°C)	-	-	(20), 460

Element	M.P. (°C)	* α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Vanadium	1847	3.33 x 10^{-3}	22	-	-	(1) (I-V-1)
Vanadium	-	2.8 x 10^{-3}	26	-	-	(2), 673
Vanadium	-	3.4 x 10^{-3}	24.8	-	-	(3) 592,593
Vanadium	1900 ± 25	-	24.8 to 26.0	-	-	(4) 47,49,1227
Vanadium	-	-	26.	-	-	(6) 21
Vanadium	-	-	26.	-	-	(7) 81
Vanadium	1900 ± 25	-	24.8	-	-	(8) 439
Vanadium	1900	-	24.8	-	-	(16) 61
Vanadium	1734 ± 50	-	-	-	-	(20) 460
Vanadium	-	3.4 x 10^{-3}	25	-	-	(38) 1

Element	M.P. (°C)	** α (0-100°C)	** ρ Microhm - Cm			References
			20°C	500°C	1200°C	
Zirconium	1857	3.64 x 10^{-3}	46.5	113	120	(1), (I-Z-1)
Zirconium	-	4.4 x 10^{-3}	41.0	-	-	(2), 673
Zirconium	-	4.4 x 10^{-3}	45.0	-	-	(3), 610; deduced Foote Zr. Rod; = Iodide process product.
Zirconium	1852	-	40.	-	-	(4), 47,49,1228; 1229
Zirconium	-	-	41. @ 0°C	-	-	(6) , 21
Zirconium	-	-	41	-	-	(7) , 81
Zirconium	1845 ± 25	-	41 (estm.)	122	115 (estm.)	(8) , 464, 465 (8) , 465, B form, from = 863°C
Zirconium	-	-	41. @ 0°C	-	-	(20), 460
Zirconium	-	-	41.7 @ 0°C	-	-	(27), 246
Zirconium	1830	-	40 to 45	-	-	(32), Bulletin No. 5A.0.1

TABLE 1.2

RESISTIVITY VS. TEMPERATURE (20,500, 1200°C) OF SELECTED PURE ELEMENTS

(Maximum and Minimum Recorded Values)

For Selected:

(1) Reference Temperatures

(2) Pure Elements

(3) Data from Table (1)

Element	$P_{20^\circ c}$ = microhm-cm		$P_{500^\circ c}$ = microhm-cm		$P_{1200^\circ c}$ = microhm-cm or P_t	
	Min.	Max.	Min.	Max.	Min.	Max.
Cr.	13.0	21.0	32.3	-	66.5	-
Co.	6.45	9.7	32.20	-	91.9	-
Cu.	1.4	1.72	4.55	4.86	-	-
Au.	2.20	2.44	6.5	6.8	12.1 @949°c 11.8 @900°c	32.71 (liquid Au.)
Hf.	30.	38.5	96	-	138 @ 977°c	-
Ir.	4.9	6.08	15.1	-	-	-
Fe.	9.71	10.	38.8	56.	111.7	122
Mo.	4.68	6.36	16.5	18.	31.8	37.8
Ni.	6.84	7.8	34	38.3	51.2	-
Nb.	12.5	20.	35	-	50 @893°c 38.96 @600°c	-
Os.	9.5	9.83	-	-	-	-
Pd.	10.8	12.5	26.8	28.7	44.8	-
Pt.	10.6	11.4	26.3	27.9	46.5	48.4
Re.	18	21.0	51.0	52.6	83	83.8
Rh.	4.7	4.93	14.6	-	-	-
Ru.	6.7	14.4	35	-	52.5	-
Ag.	(1.51)*	1.72	4.41	4.8	7.6 @900°c	19.4 for Ag. (liquid) @ 1200°c
Th.	13.0	20	49	-	71	-
Ti.	42.	80	124	135	149	-
Ta.	12.4	15.5	33	35	58	61.5
U.	26.2	60	52.8	54	-	-
V.	22	26	-	-	-	-
W.	5.5* 5.0	6.5	17.	19.47	38.	41.85 *preferred
Zr.	40	46.5	113	122	115	120

Where (a) (Value)* = derived or calculated value

(b) ______* = preferred value

TABLE 1.3

RESISTIVITY VS. TEMPERATURE (20, 500, 1200°C) CERTAIN PRECIOUS METAL ALLOYS

For Selected:

(1) Reference Temperatures;
(2) Precious Metal Alloys; and
(3) Reference Sources.

Alloy	20°c	500°c	1200°c	Ref.
10% Rh-Pt	19.1	-	51.5	(10)
20% Rh-Pt	20.75	-	48.3	(10)
40% Rh-Pt	17.45	-	44.8	(10)
10% Ir-Pt	25.	-	-	(11)
25% Ir-Pt	33.	-	-	(11)
30% Ir-Pt	33	-	-	(36)
4% Ru-Pt	30.	-	-	(36)
5% Ru-Pt	31.5	-	-	(11)
10% Ru-Pt	43.0	-	-	(11)
10% Ru-Pt	42.	-	-	(36)
8% Ni-Pt	27.0	-	-	(36)
4% W-Pt	36.5	-	-	(11)
8% W-Pt	62.0	-	-	(36)
5% M_O-Pt	64.0	-	-	(36)
20% Cu-Pt	82.5	-	-	(36)
40% Ag-Pt	42.0	-	-	(36)
4.5% Ru-Pd	23.5	-	-	(11)
10% Ru-Pd	36.0	-	-	(36)
40% Ag-Pd	42 to 43	-	-	(36) & (11)
40% Cu-Pd	35. (quenched)	-	-	(36) & (11)
40% Cu-Pd	3.50 (ordered)	-	-	(11)
In-Ru-Pt	39.0	-	-	(36),p.6,7.

TABLE 1.4

SELECTED PURE METALLIC ELEMENTS AND PRECIOUS METAL ALLOYS - MINIMUM RESISTIVITIES AT 20, 50, 1200°C

Pure Element	Minimum Resistivity; Microhm -cm				Reference to Data	Precious Metal Alloy	Minimum Resistivity; Microhm -cm			Reference to Data
	ρ20°C	ρ500°C	ρ n°C	ρ 1200°C			ρ 20°C	ρ 500°C	ρ 1200°C	
Au	2.20	6.5	12.1 at 949°C	32.71 (liquid)	Group No. I	10% Rh-Pt	19.1	32.4	51.5	Ref
Rh	4.70	14.6	-	-						(10)
Ir.	4.90	15.1	-	-	c.f. Tables No.'s (2), and (3)	20% Rh-Pt	20.75	31.5	48.3	Group IV
Pt	10.6	26.3	-	46.5		40% Rh-Pt	17.45	28.5	44.8	
Pd	10.8	26.8	-	44.8		10% Ir-Pt	25.	-	-	(11)
Ru	6.7	35.	-	52.5		25% Ir-Pt	33.	-	-	(11) Group V
Re.	18.	51.	-	83.		30% Ir-Pt	33	-	-	(36)
Cu	1.4	4.55	-	-	Group	4% Ru-Pt	30	-	-	(36)
Ag	1.51	4.4.	(7.6) (at 900°C)	-	No. II	5% Ru-Pt	31.5	-	-	(11) Group VI
Mo	4.68	16.5	-	31.8	c.f. tables	10% Ru-Pt	43.0	-	-	(11)
W	5.5	17.	-	38.	No's	10% Ru-Pt	42.0	-	-	(36)
Ni	6.84	34.	-	51.2	(2), & (3)	8% Ni-Pt	27.0	-	-	Ref. (37)
Os	9.5	-	-	-		4% W-Pt	36.5	-	-	(11) Group VII
Ta.	12.4	33	-	58.		8% W-Pt	62.0	-	-	(36)
Th	13.0	49.	-	71		5% Mo-Pt	64.0	-	-	(36)
Co	6.45	32.2	-	91.9		20% Cu-Pt	82.5	-	-	(36)
Fe	9.71	38.8	38.9 at 600°	111.7	Group	40% Ag-Pt	42.0	-	-	(26)
Nb	12.5	35.	50. at 893°C	-	No. III	4.5% Ru-Pd	23.5	-	-	(36) (11)
Cr	13.0	32.3	-	66.5	c.f. tables	10.% Ru-Pd	36.0	-	-	(36)
U	26.2	52.8	-	-		40% Ag-Pd	42	-	-	Group VIII
Hf.	30.	96.	138 at 977°C	-	No's. (2)	40% Cu-Pd	35.(quenched)	-	-	(37) & (1) (11)
Zr	40	113	-	115	(3)	40% Cu-Pd	3.50(ordered)	-	-	(36) & (11) (36)
Ti	42.	124	-	149		Ir-Ru-Pt	39.0	-	-	(36) Group (IX)
V	22	-	-	-						

Group No.	(ρ;u-ohm-cm); Minimum and Maximum; in group at temperature				Reference to Data
	20°C	500°C	n°C	1200°C	
I	2.20 18.0	6.5 51.	-	32.71 83.	Data in a above section
II	1.4 13.0	4.41 49.0	- -	31.8 71.0	
III	6.45 42.0	32.3 124.0	-	66.5 149.	

Group No.	(ρ;u-ohm-cm); Minimum and Maximum; in group at temperature				Reference to Data
	20°C	500°c	n°C	1200°c	
IV	17.45 20.75	28.5 32.4		44.8 51.5	Data in above section
V	25. 33.				
VI	30 43	- -	- -	- -	
VII	27. 82.5	-	-	-	
VIII	3.5 42.	-	-	-	

TABLE 1.5

SELECTED PURE ELEMENTS AND (Rh- Pt) ALLOYS:
MEAN AND MEAN RELATIVE RESISTIVITIES AT
293°K, 773°K, 1473°K

Pure Element	R* (293°K)	R* (773°K)	R* T°K (other)	R* (1473°K)	$\frac{(R_{773°K})}{(R_{293°K})}$	$\frac{R_T(\text{OTHER})}{R_{293°K}}$	$\frac{R_{1473°K}}{R_{293°K}}$	Remarks:
Au	2.32	6.65	11.8 @ 1173°K	32.71 (liquid Au.)	2.87	5.09	14.10	Used liquid Au. for Ref.
Rh	4.81	14.6	-	28.7	3.04	-	5.97	-
Ir.	5.49	15.1	-	29.7	2.75	-	5.41	-
Pt.	11.0	27.1	-	47.45	2.46	-	4.31	-
Pd.	11.65	27.75	-	41.8	2.38	-	3.83	-
Ru.	10.55	35.0	-	52.5	3.32	-	4.98	-
Re.	19.5	51.8	-	83.4	2.66	-	4.28	-
Cu.	1.56	4.71	-	-	3.02	-	-	-
Ag.	1.66	4.61	7.6 @ (1173°K)	19.4	2.78	4.58	11.69	Ag. liquid @ 1234°K
Mo.	5.52	17.3	-	34.8	3.13	-	6.30	-
W.	6.0	18.3	-	40.0	3.05	-	6.67	-
Ni.	7.32	38.1	-	51.2	4.93	-	6.99	-
Ta.	14.0	34.0	-	59.8	2.43	-	4.27	-
Th.	16.5	49.0	-	71.0	2.98	-	4.30	-
Co.	8.08	32.0	-	91.9	3.96	-	11.37	-
Fe.	9.86	47.4	-	116.9	4.81	-	11.86	-
Nb.	16.3	35.0	50.0 (@1166°K)	61.0	2.15	3.07 @1166°K	3.80	Ref. (2)
Cr.	17.0	32.3	-	66.5	1.90	-	3.91	-
U.	43.1	53.4	61.0 (@ 1406°K)	-	1.24	1.415	-	-
Hf.	34.3	96.0	138.0 @1250°K	156.5	2.80	4.02	4.56	-
Zr.	43.3	118.	-	118	2.73	-	2.73	-
Ti.	61.0	129.5	-	149.	2.12	-	2.44	-

RESISTIVITY = MICROHM - CM

Selected Precious Metal Alloys	$R_{293°K}$	$R_{(773°K)}$	R_T (other)	$R_{1473°K}$	$R_{778°K}/R_{293°K}$	$R_T/R_{293°K}$	$R_{1473}/R_{293°K}$	Remarks
10% Rh-Pt	19.1	32.4	-	51.5	1.70	-	2.70	Alloys included for comparative purposes
20% Rh-Pt	20.7	31.5	-	48.3	1.52	-	2.33	
40% Rh-Pt	17.45	28.5	-	44.8	1.62	-	2.57	

Where:

(1). Mark "*", value given, was obtained by Mean Value from preceding Tables and graphs, &/or used the only value available. Mean = $(\frac{\text{Max.} + \text{Min.}}{2})$;

(2). Additional Data for Nb;, $R_{873°K}$ = 38.96; and $(R_T/R_{293°K})$ = (38.69/16.3) = 2.39

(3). Values of R_T contained in above table were in some instances derived by interpolation &/or extrapolation as necessary to establish a value at $(T_{°K})$ as occasioned by the limitations of available data.

TABLE 1.6

SUPPLEMENTAL RESISTIVITY DATA VS TEMPERATURES FOR SELECTED PURE ELEMENTS

Electrical Resistivity = Microhm-cm at Temperature													
Pure Element	Remarks	1000°K(727°C)			Remarks	1200°K(927°C)			1400°K (1127°C); or (other)			Remarks	Reference Sources Page Number
		Min.	Max.	Avg or only value		Min.	Max.	Avg or only value	Min.	Max.	Avg or only value		
Gold	---	--	--	9.2	--	--	--	11.7	--	--	--	--	(1), (I-G-3)
Rhodium	---	--	--	--	--	--	--	--	--	--	--	10.8 microhm-cm ● 1000°C	(10), 1
Iridium	---	--	--	--	--	--	--	--	--	--	--	--	"
Platinum	---	--	--	36.8	Data Obtained from extrapolation of Linear function noted for Limited data, per Ref.(1)	--	--	46.5	--	--	--		(1), I-P-2
Palladium	Extrapolated value from projected curve.	--	--	31.		--	--	--	--	--	--	--	(1), I-P-1
Ruthenium	---			36.	--			43.			50.5	--	(1), I-R-4
Rhenium	---	64	70	67	--	72	78	75	80	87	84	--	(1), I-R-2
Copper	---	6.25	6.8	6.52	--	7.9	9.1	8.5	--	--	--	--	(1), I-C-7
Silver	Data Obtained is based on extrapolation of existing data. Ref. (1)	--	--	6.3	See Preceding remarks	--	--	7.57	--	--	--	--	(1), I-S-4
Molybdenum	---	21.5	23	22.3	--	26	28.5	27.3	30.2	35.5	32.9	--	(1), I-M-4
Tungsten	---	--	--	24	--	--	--	30.	--	--	36	--	(1), I-T-7
Nickel	---	40.7	45.4	43	--	46.7	51.7	49.2	--	--	--	--	(1), I-N-3
Tantalum	---	--	--	40.	--	--	--	46	--	--	55.		(1), I-T-1
Thorium	---	53.	63.	58	--	59.	71.	65	--	--	--	--	(I), I-T-4
Cobalt	(773°K)=32.2 Ref (3),p.117	--	--	53.5 at 1000°K 49.2 at 973°K Ref (3)	--	--	--	68. at 1173°K Ref. (3)	--	--	86.7 at (1373°K) Ref. (3).	--	(1), I-C-6 (3), 117
Iron	---	91	97	94		104	118	--	--	--	--	--	(1), I-J-2
Niobium	Maximum Values obtained by extrapolation of limited data	43.5	54.5	49	See Preceding remarks	51.	70	61	--	--	--	--	(1), I-N-4
Chromium	---	--	--	49.	--	--	--	61.	--	--	90.	--	(1), I-C-5
Hafnium	---	118	142	130	--	--	--	133	--	--	--	--	(1), I-H-1
Uranium	See remarks to follow	52.	62.5	57.3	See remarks to follow	53.	62.	58	--	--	--	2 Crystallographic phase changes are encountered in Temperature Range.	(1), I-U-1
Zirconium	See remarks to follow	110	144	127	See remarks to follow	108	130	119	112	128	120	A Crystallographic phase change is encounted in temperature range indicated.	(1), I-Z-I
Osmium	---	--	--	--	--	--	--	--	--	--	--	--	--
Titanium	---	140	183	162	--	140	182	161	132	176	154	Phase Change of Alpha to Beta in temperature range Noted.	(1), I-T-6
Vanadium	---	--	--	--	--	--	--	--	--	--	--	--	--

NOTE: Average Values employed in above Table are = Mean Value = $\frac{\text{Maximum} + \text{Minimum}}{2}$

TABLE 1.7

MEAN RESISTIVITY AND RELATIVE RESISTIVITY AT 293°K, 1000°K, 1200°K, 1400°K, FOR SELECTED PURE ELEMENTS

Supplemental Data: Relative Resistances Vs. Temperature

Pure Element	R_T @ T(°K); (Mean Value)				$R_T/R_{293°K}$ @ R_T(°K)				Pure Element
	293°K	1000°K	1200°K	1400°K	293°K	1000°K	1200°K	1400°K	
Au.	2.32	9.2	11.7	-	1	3.97	5.04	-	- Au.
Rh.	4.81	-	-	-	1	-	-	-	- Rh.
Ir.	5.49	-	-		1	-	-	-	- Ir.
Pt.	11.0	38.8	46.5	-	1	3.53	4.23	-	- Pt.
Pd.	11.65	31.0	-	-	1	2.66	-	-	- Pd.
Ru.	10.55	38.	43.	50.5	-	3.60	4.08	4.79	- Ru.
Re.	19.5	67.	75.	84.0	1	3.44	3.85	4.31	- Re.
Cu.	1.56	6.52	8.5	-	1	4.18	4.45	-	- Cu.
Ag.	1.66	6.3	7.57	-	1	3.80	4.56	-	- Ag.
Mo.	5.52	22.3	27.3	32.9	1	4.04	4.95	5.96	- Mo.
W.	6.0	24.	30.	36.	1	4.0	5.0	6.0	- W.
Ni.	7.32	43.	49.2	-	1	5.87	6.72	-	- Ni.
Ta.	14.0	40.	48.	55.	1	2.86	3.43	-	- Ta.
Th.	16.5	58.	65	-	1	3.52	3.94	3.93	- Th.
Co.	8.08	53.5 68	68. 1173°K	86.7 1373°K	1	6.62	8.42 1173°K	10.72 1373°K	- Co.
Fe.	9.86	94.	111.	120.	1	9.53	11.3	12.2	- Fe.
Nb.	16.3	49.	61.	-	1	3.01	3.74	-	- Nb.
Cr.	17.0	49.	61.	90.	1	2.9	3.6	5.3	- Cr.
U.	43.1	57.3	58.	-	1	1.33	1.35	-	- U.
Hf.	34.3	130.	133.	-	1	3.79	3.88	-	- Hf.
Zr.	43.3	127.	119.	120.	1	2.93	2.75	2.77	- Zr.
Ti.	61.0	162.	161.	154.	1	2.66	2.64	2.52	- Ti.
Os.	-	-	-	-	1	-	-	-	- Os.
Va.	-	-	-	-	-	-	-	-	- Va.

TABLE 1.8

RESISTIVITY AND RELATIVE RESISTIVITY OF SELECTED PURE ELEMENTS
(Derived from Smooth Curves of Figures 1, 2, 3)

Resistivity, u - ohm - cm; R_T at T (°K)												Relative Resistances; $\frac{R_T}{R_{293°}}$, at T (°K)										
Element	293°	473°	673°	773°	873°	1000°	1200°	1473	X°	Y°	Remarks	$\frac{R_{293}}{R_{293}}$	$\frac{R_{473}}{R_{293}}$	$\frac{R_{673}}{R_{293}}$	$\frac{R_{773}}{R_{293}}$	$\frac{R_{873}}{R_{293}}$	$\frac{R_{1000}}{R_{293}}$	$\frac{R_{1200}}{R_{293}}$	$\frac{R_{1473}}{R_{293}}$	$\frac{R_{X°}}{R_{293°}}$	$\frac{R_{Y°}}{R_{293°}}$	Remarks
Re	19.5	32.5	46.5	53.	59.5	66.	75.	86.5	-	-	-	1.00	1.87	2.38	2.72	3.05	3.38	3.85	4.44	-	-	-
Ru.	10.5	19.7	30.5	34.	37.0	40.	44.5	50.	-	-	-	1.00	1.88	2.90	3.24	3.52	3.81	4.24	4.76	-	-	-
Pt.	11.0	18.5	25.2	28.5	31.5	35.2	41.	48	-	-	-	1.00	1.88	2.29	2.59	2.88	3.20	3.73	4.36	-	-	-
Pd.	11.65	18.0	24.4	27.2	30.	33.5	38.4	44.5	-	-	-	1.00	1.55	2.09	2.33	2.58	2.88	3.30	3.82	-	-	-
Ir.	5.5	9.9	13.2	15.	-	-	-	(29.7)	-	-	( ), Value Obtained by Extrapolation	1.00	1.64	2.40	2.73	-	-	-	(5.40)	-	-	-
Rh.	4.8	8.5	12.5	14.5	-	-	-	(29.)	-	-	( ), Value obtained by Extrapolation	1.00	1.77	2.60	3.02	-	-	-	(6.04)	-	-	-
Au.	2.32	4.0	5.7	6.7	7.7	9.2	12.	33 AU. liquid	1336°K, M.P.(Au) Extrapolated R=14	-	M.P. (Au.); 1336°K	1.00	1.72	2.46	2.89	3.32	3.97	5.17	14.2	6.03 at $\frac{R_{1336}}{R_{293}}$	-	Au; M.P. at 1336°K
U.	43.	45.2	49.7	53.2	56.2	57.8	58.	(70)	-		( ), R value Estm. at 1473K for U (liq.); by Extrapolation 933°K 1033°K Under remarks for U	1.00	1.05	1.16	1.24	1.35	1.34	1.35	1.63	-	-	Slight-Breaks in Resistivity Curve at 2 Phase Changes. (Sluggish reaction)
Th.	16.5	27.8	40.	48.	51.4	57.8	85.	88.	-	-	-	1.00	1.68	2.42	2.79	3.12	3.50	3.94	4.12	-	-	-
Ta.	14	22.	30.2	34.2	38.	42.7	50.	59.5	-	-	-	1.00	1.57	2.18	2.44	2.71	3.05	3.57	4.25	-	-	-
Ni.	7.2	15.5	33	38.5	39.3	43.	49.	53.	Curie Pt. at 623°K $R_{623}=30$	-	-	1.00	2.15	4.58	5.07	5.46	5.97	6.81	7.36	$\frac{R_{623°}}{R_{293°}}$ =4.17	-	Curie Pt. at 623°K
W.	5.5	9.5	14.8	17.7	20.7	24.5	30.8	40.	-	-	-	1.00	1.73	2.69	3.22	3.78	4.45	5.60	7.27	-	-	-
Mo.	5.5	9.0	13.7	16.2	18.6	21.7	27.2	35.	-	-	-	1.00	1.64	2.49	2.95	3.38	3.95	4.95	6.36	-	-	-
Au.	2.32	4.0	5.7	6.7	7.7	9.2	12.	33 Au.(Liq)	-	-	-	1.00	1.72	2.48	2.89	3.32	3 97	5.17	14.2	6.03 at $\frac{R_{1336}}{R_{293}}$	-	Au; M.P. at 1336°K
Ag.	1.66	2.5	4.0	4.7	5.3	6.15	7.5	19.5; Ag.(liq)	-	-	-	1.00	1.51	2.41	2.83	3.19	3.70	4.52	11.7	-	-	-
Ti.	61.	88.	116.7	130.5	144.2	159.	161.5	154.	R=165 at 1156°K	-	$\alpha \leftrightarrow \beta$ at 1155°K	1.00	p.44	1.91	2.14	2.36	2.61	2.65	2.52	2.70 at $\frac{R_{1155}}{R_{293}}$	-	$\alpha \rightarrow \beta$ at 1155°K
Zr.	43.3	70.6	102.	111.5	124.7	130.	114.	122.	R=133 at 1136°K	-	Phase Change at 1136°K	1.00	1.63	2.36	2.57	2.86	3.00	2.63	2.82	3.07 at $\frac{R_{1136°K}}{R_{293°K}}$	-	Phase Change at 1136°K
Hf.	34.3	61.3	90.	103.5	116.2	130.	151.7	179.7	-	-	-	1.00	1.79	2.62	3.02	3.39	3.79	4.42	5.24	-	-	-
Fe.	9.86	24.2	47.5	60.7	75.2	94.	111.	122	R=114 at 1183°K	R=101.5at 1043	$\alpha \leftrightarrow \gamma$ at(1183°K) $R_{1183}=114.0$ Curie Pt. at 1043°K	1.00	2.45	4.82	6.16	7.63	9.53	11.25	12.37	11.6 at $\frac{R_{1183}}{R_{293}}$	10.3 at Curie Pt.i.e. $\frac{R_{1043}}{R_{293}}$	$\alpha \rightarrow \gamma$ at 1183°K
Nb.	16.3	27.3	37.	41.7	46.2	51.7	(61)	(72)	-	-	( ) values obtained by Extrapolation	1.00	1.49	2.02	2.26	2.52	2.63	(3.33)	(3.93)	-	-	( ) See preceding remarks
Cr.	14.3	20.	27.7	32.	41.2	42.7	52.7	67.5	-	-	-	1.00	1.40	1.94	2.24	2.88	2.99	3.69	4.72	-	-	-
Co.	6.5	13.7	24.	31.3	36.7	53.5	72.5	95.	-	-	-	1.00	2.11	3.69	4.62	5.65	8.23	11.2	14.6	-	-	-

TABLE 1.9

SELECTED PROPERTIES OF CERTAIN PURE LIQUID METALS

M.P. $\leqq$1200°C
(B.P.) $\geqq$1200°C

			RESISTIVITY = MICROHM -cm AT TEMPERATURE										VAPOR PRESSURE = MM HG: AT TEMPERATURE										
ELEMENT (SYMBOL	M.P. °C °K	B.P. °C °K	M.P. (T_1=°C)	(T_2=°C)	(T_3=°C)	(T_4=°C)	(T_5=°C)	(T_6=°C)	(T_7=°C)	(T_8=°C)	(T_9=°C)	B.P. (T_{10}=°C)	M.P. (T_1=°C)	(T_2=°C)	(T_3=°C)	(T_4=°C)	(T_5=°C)	(T_6=°C)	(T_7=°C)	(T_8=°C)	(T_9=°C)	B.P. (T10=°C)	REFERENCES Sources for Data)
Al	660°C 933°K	2485°C 2758°K	20. 660°C	21. 700°C	22.5 800°C	23.5 900°C	--	--	--	--	--	--	10^{-8} 660°C	--	--	10^{-5} 900°C	--	--	1 (1450°C)	10 (1790°C)	100 (2110°C)	760 (2485°C)	(4); (14); (2); (66)
Sb	630°C 903°K	1380°C 1653°K	110. 830°C	111. 700°C	114. 800°C	118. 900°C	124. 1000°C	--	--	--	--	--	$\leqq 10^{-1}$ 630°C	<1 700°C	<1 800°C	1 (886°C)	10 (1033°C)	40 (1141°C)	100 (1223°C)	200 (1288°C)	--	760 (1380°C)	(2), 616; (14)
Ba	714°C 987°K	1640°C 1913°K	--	--	--	--	--	--	--	--	--	--	<1 (714°C)	--	--	--	--	--	1 (985°C)	10 (1180°C)	100 (1450°C)	760 (1640°C)	(2), 616; (4)
Bi	271°C 544°K	1560°C 1833°K	--	128.9 300°C	134.2 400°C	145.2 600°c	158.5 800°C	--	--	--	--	--	< 1 (271°C)	--	--	--	--	--	1 (892°C)	10 (1054°C)	100 (1274°C)	760 (1560°C)	(4); (2), 639
Ca	838°C 1111°K	1645°C 1918°K	--	--	--	--	--	--	--	--	--	--	<1 (838°C)	--	--	--	--	--	1 (917°C)	10 (1097°C)	100 (1355°C)	760 (1645°C)	(2), 614; (4)
Ce	804°C 1077°K	3470°C 3740°K	125. Estm. just below melting point.	--	--	--	--	--	--	--	--	--	--	$2x10^{-6}$ (1057°C)	--	--	$8x10^{-3}$ (1427°C)	--	--	--	--	760 (3470°C)	(1),I-C-4;(4); See also-D.H.Ahmann, Iowa State College J. Sci. 27,120(1953); and L.Brewer, Paper No. 3, National Nuclear Energy Series IV-19B,L.L.Quill (Ed.)McGraw Hill (1950)
Cu	1083°C 1356°K	2595°C 2868°K	Est. 10 just below m.p.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1 (1628°C)	10 (1879°C)	100 (2207°C)	760 (2595°C)	(2), 614; (4); (1), I-C-7
Eu	826°C 1099°K	1490°C 1763°K	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	760 (1490°C)	(4)
Ga	2978°C 302.8°K	2250°C 2524°K	25.9 29.75°C	28.4 46.1°C	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1 (1374°C)	10 (1603°C)	100 (1770°C)	760 (2250°C)	(4) (2), 614
Ge	937°C 1210°K	2670°C 2943°K	1500 Estm. just below m.p.	--	--	--	--	--	--	--	--	--	$<10^{-4}$ (937°C)	--	--	--	--	--	1 (1730°C)	10 (1980°C)	100 (2295°C)	760 (2670°C)	(2), 614; (4); (1), I-G-2.
Au	1063°C 1336°K	2970°C 3243°K	Est. 14. at m.p. c.f. Fig. (1)	31.34 1100°C	32.76 1200°C	34.17 1300°C	35.56 1400°C	37.00 1500°C	--	--	--	--	$\ll 1$ (1083°C)	--	--	--	--	--	1 (1870°C)	10. (2155°C)	100. (2520°C)	760 (2970°C)	(4); (14), 41; (2), 614
In	156°C 429°K	2080°C 2353°K	29.1 157°C	30.0 200°C	36.2 300°C	--	--	--	--	--	--	--	$\lll 1$ (156°C)	--	--	--	--	--	1 (1241°C)	10 (1452°C)	100 (1735°C)	760 (2080°C)	(4)-Melting Point (2),615-Resistivity & vapor pressure

25 Elements

REMARKS: **There appears to be only limited available data on the electrical resistivity properties of 7 pure liquid metals of the total group of 25 elements.**

Available data on the v.p.'s of metals of this group, indicates that 20 elements can be properly described.

TABLE 1.9

SELECTED PROPERTIES OF CERTAIN PURE LIQUID METALS (Continued)

M.P. ≦ 1200°C
(B.P.) ≧ 1200°C

ELEMENT (SYMBOL)	M.P. °C °K	B.P. °C °K	RESISTIVITY = MICROHM -cm . AT TEMPERATURE										VAPOR PRESSURE = MM HG: AT TEMPERATURE										REFERENCES Sources for Data)
			M.P. (T_1=°C)	(T_2=°C)	(T_3=°C)	(T_4=°C)	(T_5=°C)	(T_6=°C)	(T_7=°C)	(T_8=°C)	(T_9=°C)	B.P. (T_{10}=°C)	M.P. (T_1=°C)	(T_2=°C)	(T_3=°C)	(T_4=°C)	(T_5=°C)	(T_6=°C)	(T_7=°C)	(T_8=°C)	(T_9=°C)	B.P. (T_{10}=°C)	
La	920°C 1193°K	3470°C 3743°K	127. Estm. just below m.p.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1 (2140°C)	10 (2457°C)	100 (2907°C)	760 (3490°C)	(4); (66), 198; (1), I-L-1.
Pb	327°C 600°K	1750°C 2023°K	94.6 327°C	98.0 400°C	104.6 500°C	107.2 600°C	116.4 800°C	125.7 1000°C	--	--	--	--	$\ll 1$ (327°C)	--	--	--	--	--	1 (976°C)	10 (1164°C)	100. (1424°C)	760 (1750°C)	(4); (2), 615
Li	180°C 453°K	1372°C 1645°K	--	45.2 230°C	--	--	--	--	--	--	--	--	<1 (180°C)	--	--	--	--	--	1 (723°C)	10 (881°C)	100. (1097°C)	760 (1372°C)	(4); (2), 615
Mn	1225°C 1498°K	2150°C 2423°K	--	--	--	--	--	--	--	--	--	--	$\lessapprox 1$ (1225°C)	--	--	--	--	--	1 (1292°C)	10 (1505°C)	100 (1792°C)	760 (2150°C)	(2), 615; (4)
Nd	1019°C 1292°K	3087°C 3360°K	143. Estm. just below m.p.	--	--	--	--	--	--	--	--	--	$\lll 1$ (1019°C)	--	--	--	--	--	1 (1777°C)	10 (2097°C)	100 (2527°C)	760 (3087°C)	(4); (66), 199; (1), I-N-1
Pr	919°C 1192°K	3020°C 3293°K	143. Estm. just below m.p.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	760 (3020°C)	A. H. Danne, AECD-3209 Dec. 14, 1950
Sm	1072°C 1345°K	1630°C 1903°K	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	760 (1630°C)	(4); (67), 29 (V.P. 1×10^{-2} mm of Hg at 600°C)
Ag.	961°C 1234°K	2210°C 2483°K	7.8-8.0 Estm. just below m.p. See also Fig (2)	17.0 1000°C	18.2 1100°C	19.4 1200°C	20.5 1300°C	--	--	--	--	--	<1 (961°C)	--	--	--	--	--	1 (1330°C)	10 (1551°C)	100 (1854°C)	760 (2210°C)	(4); (2), 614 and 639; (1), 1-S-4;
Sr	768°C 1041°K	1367°C 1640°K	98. Estm. just below m.p.	--	--	--	--	--	--	--	--	--	>1 (768°C)	--	--	--	--	--	1 (742°C)	10 (897°C)	100 (1107°C)	760 (1360°C)	(4); (66), 199
Tl	303°C 576°K	1467°C 1740°K	74.	--	--	--	--	--	--	--	--	--	$<1\text{x}10^{-7}$ 303°C	--	--	--	--	--	1 (837°C)	10 (997°C)	100 (1207°C)	760 (1467°C)	(4); (66), 199; (1) I-S-5
Sn	232°C 505°K	2450°C 2723°K	47.6 232°C	49.0 300°C	51.4 400°C	54.0 500°C	56.8 600°C	62.7 600°C	68.6 1000°C	--	--	--	$\ll 1$ 232°C	--	--	--	--	--	1 (1600°C)	10 (1825°C)	100 (2115°C)	760 (2450°C)	(4); (14); (2), 616
U	1132°C 1405°K	3927°C 4200°K	70. Estm. at m. p. (Ref. c.f. Fig. (2)	--	--	--	--	--	--	--	--	--	10^{-8} (1132°C)	--	--	--	--	--	1 (2447°C)	10 (2797°C)	100 (3267°C)	760 (3927°C)	(4); (66), 199
Yb	824 1097°K	1530°C 1803°K	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	760 (1530°C)	(4)

25 Elements

REMARKS: There appears to be only limited available data on the electrical resistivity properties of 7 pure liquid metals of the total group of 25 elements.

Available data on the v p.'s of metals of this group, indicates that 20 elements can be properly described.

TABLE 1.10

AVAILABILITY OF DATA ON RESISTIVITY VS. TEMPERATURE FOR PURE LIQUID METAL (MP ≦ 1200°C, B.P. ≧ 1200°C)

Relative Order of Elements (B.P.s)	B.P. (°C)	M.P. (°C)	Liquid Range (°C)=(B.P.-M.P.)	(ρ) Data Available in Temperature Range	(ρ) Data, Unavailable in Temperature Range
Sr.	1367	768	599	---	768° - 1367°C
Li.	1372	180	1192	---	---
Sb.	1380	630	750	630°C - 1000°C	1000°C - 1380°C
Tl.	1467	303	1164	---	303°C - 1467°C
Eu.	1490	826	664	---	826°C - 1490°C
Yb.	1530	824	706	---	824°C - 1530°C
Bi.	1560	271	1289	300°C - 800°C	800°C - 1560°C
Sm	1630	1072	558	---	1072°C - 1630°C
Ba	1640	714	926	---	714°C - 1640°C
Ca	1645	838	807	---	838°C - 1645°C
Pb	1750	327	1423	327°C - 1000°C	1000°C - 1750°C
In	2080	156	1924	157°C - 300°C	300°C - 2080°C
Mn	2150	1225	925	---	1225°C - 2150°C
Ag	2210	961	1249	1000°C - 1300°C	1300°C - 2210°C
Ga	2250	29.78	2220	29.75°C - 46.1°C	46.1°C - 2250°C
Sn	2450	232	2218	232°C - 1000°C	1000°C - 2450°C
Al	2485	660	1825	660°C - 900°C	900°C - 2485°C
Cu.	2595	1083	1512	---	1083°C - 2595°C
Ge	2670	937	1733	---	937°C - 2670°C
Au	2970	1063	1907	1100°C - 1500°C	1500°C - 2970°C
Pr.	3020	919	2101	---	919°C - 3020°C
Nd	3087	1019	2068	---	1019°C - 3087°C
La	3470	920	2550	---	920°C - 3470°C
Ce	3470	804	2666	---	804°C - 3470°C
U.	3927	1132	2795	---	1132°C - 3927°C

TABLE 1.11

TYPICAL CHARACTERISTIC PROPERTIES OF SELECTED PURE METALLIC ELEMENTS

			ELECTRICAL						CRYSTAL				THERMAL					
		M.P. (°C)	Temperature Coefficent of Resistance=α*	Resistivity, (ρ_T), 1)Minimum 2)Average = Microhm-cm					Crystal Lattice Type				Vapor Pressure (mmg.Hg)					B.P. (°C)
Element	Symbol	(Ref. 4)	(0-100°C)	20°C	500°C	T=°C	1200°C	Ref.	20°C	500°C	1200°C	Remarks	20°C	500°C	T=°C	1200°C	T=°C	Ref. 4
Gold	Au	1063	$4x10^{-3}$	2.20 2.32	6.50 6.65	12.1at949°C 11.8at900°C	- 32.71 (liquid)	Table IV Table V	F.C.C.	F.C.C.	Liquid	Ref.(25),553	$2x10^{-58}$	$1.3x10^{-16}$	-	$1.2x10^{-4}$		2970
Rhodium	Rh	1963	$4.57x10^{-3}$	4.70 4.81	14.6 14.6	- -	- (28.7)	Table IV Table V	F.C.C.	F.C.C.	F.C.C.	Ref.(4),51 Ref.(26),554 Ref.(3),315 Ref.(2),193,196, 212	-	-	$1x10^{-5}$ 1672°C	-		4500
Iridium	Ir	2454	$4.17x10^{-3}$	4.90 5.49	15.1 15.1	- -	- (29.7)	Table V	F.C.C.	F.C.C.	F.C.C.	Ref.(25),553 Ref.(4)50,1196 Ref.(3)315	-	-	$1x10^{-5}$	-	-	5300
Platinum	Pt	1769	$3.9x10^{-3}$	10.6 11.0	26.3 27.1	- -	46.5 47.75	Table IV Table V	F.C.C.	F.C.C.	F.C.C.	Refs.(3)(4)&(25)	-	-	-	$1x10^{-9}$	-	4530
Palladium	Pd	1552	$4.02x10^{-3}$	10.8 11.65	26.8 27.75	-	44.8 44.8	Table IV Table V	F.C.C.	F.C.C.	F.C.C.	Refs.(3)(4)&(25)	-	-	$1x10^{-5}$ at 1156°C	-	$1x10^{-3}$ at 1400°C	3960
Ruthenium	Ru	2500	$5.07x10^{-3}$	6.7 10.55	35.0 35.0	-	52.5 52.5	Table IV Table V	H.C.P. (alpha)	H.C.P. (alpha)	(alpha → (beta →	beta at 1035°C)Ref (3), 316 gama at 1190°C)Ref (17)(53)	-	-	$1x10^{-5}$ at 1910°C	-	-	4900
Rhenium	Re	3180	$4.37x10^{-3}$	18.0 19.5	51.0 51.8	-	83.0 83.4	Table IV Table V	H.C.P.	H.C.P.	H.C.P.	Ref.(3)357 Ref.(4),1220 Rcf.(25),554	-	-	$1.1x10^{-6}$ at 2223°C	-		5900
Copper	Cu	1083	$5.5x10^{-3}$	1.4 1.56	4.55 4.71	- -	- -	Table IV Table V	F.C.C.	F.C.C.	F.C.C.	Refs(3)(4)&(25)	-	$4.7x10^{-14}$	-	$3x10^{-4}$	-	2595
Silver	Ag	961	$4.33x10^{-3}$	1.51 1.66	4.41 4.61	- 7.6at900°C	- 19.4 (liquid)	Table IV Table V Table V	F.C.C.	F.C.C.	F.C.C.	Refs(3)(4)&(25)	$2.93x10^{-41}$	$2.82x10^{-10}$	$2.34x10^{-3}$ at961°C	$5x10^{-2}$ to $16x10^{-2}$		2210
Molybdenum	Mo	2610	$4.7x10^{-3}$	4.68 5.52	16.5 17.3	-	31.8 34.8	Table IV Table V	B.C.C.	B.C.C.	B.C.C.	Refs.(3)(4)&(25)	- -	- -	- -	-	$1.6x10^{-6}$ at1727°C	5560
Tungsten	W	3410	$5.1x10^{-3}$	5.5 6.0	17.0 18.3	-	38.0 40.0	Table IV Table V	Cubic (A15) B.C.C.(25°C)	B.C.C.	B.C.C.	Refs.(3)(4)&(25), 554	-	-	-	-	$1.56x10^{-12}$ at1727°C	5930
Nickel	Ni	1453	$6.9x10^{-3}$	6.84 7.32	34.0 36.1		51.2 51.2	Table IV Table V	F.C.C.(A1)	F.C.C.	F.C.C.	Refs.(4),1217; & (26) 553	-	-	-	$4.1x10^{-5}$	-	2730
Remarks		(Ref.) (4)	From Table No. (1)	See also mean Resistivity Values vs. Temperature, from Figures 1, 2, 3, 5, 6, and 7 and Table 12.									See Table XII for Reference Source and Authority for Data					

F.C.C. = Face Centered Cubic
B.C.C. = Body Centered Cubic
H.C.P. = Hex. C.P. = Hexagonal Close-Packed
Cubic (A15) = (β-W)
A1 = (Copper); A2= (Tungsten Type); A3 = Magnesium Type

NOTES

$$*\alpha = \frac{1}{R_{0°C}} \cdot \frac{R_{100°}-R_{0°C}}{100}.$$

TABLE 1.11

TYPICAL CHARACTERISTIC PROPERTIES OF SELECTED PURE METALLIC ELEMENTS (Continued)

			ELECTRICAL						CRYSTAL				THERMAL					
		M.P. (°C) (Ref.4)	Temperature Coefficent of Resistance = α*	Resistivity, (ρ_T), 1) Miminum 2) Average = Microhm-cm					Crystal Lattice Type				Vapor Pressure (mmg.Hg)					B.P. (°C) Ref. 4
Element	Symbol		(0-100°C)	20°C	500°C	T=°C	1200°C	Ref.	20°C	500°C	1200°C	Remarks	20°C	500°C	T=°C	1200°C	T=°C	
Tantalum	Ta	2996	$3.83x10^{-3}$	12.4 14.0	33.0 34.0		58.0 59.8	Table IV Table V	B.C.C.(A2)	B.C.C.	B.C.C.	Refs.(3)(4)&(25)	-	-	-	-	$1.8x10^{-6}$ at 2283°C	5425
Thorium	Th	1750	$3.96x10^{-3}$	13.0 16.5	49.0 49.0		71.0 71.0	Table IV Table V	F.C.C.	(allotropic change at 225°C) F.C.C.	F.C.C. to 1400°C	Ref.(3) 444 Ref.(4) 1225	-	-	-		$1.5x10^{-7}$ at 1443°C	3850
Cobalt	Co	1495	$7.8x10^{-3}$	6.45 8.08	32.2 32.2		91.9 91.9	Table IV Table V	H.C.P. (Beta)	Beta → Alpha at 417 °C	F.C.C. (alpha)	Ref.(3) 115 Ref.(2),195,212	-	-	-	$3x10^{-5}$	-	2900
Iron	Fe	1536.5	$6.51x10^{-3}$	9.71 9.86	38.8 47.4	-	111.7 116.9	Table IV Table V	B.C.C. (Alpha)	B.C.C.	B.C.C. → F.C.C. at 910°C	Ref.(4),1210-11 Ref.(6),424-5	-	-	-	$6x10^{-5}$	-	3000
Niobium	Nb	2468	$3.95x10^{-3}$	12.5 16.3	35.0 35.0	38.96at600°C 50at893°C	- (61.0)	Table IV Table V	B.C.C.	B.C.C.	B.C.C.	Ref.(4),(3)					$1x10^{-5}$ at 2193°C	4927
Chromium	Cr	1895	$5.88x10^{-3}$	13.0 17.0	32.3 32.3	- -	66.5 66.5	Table IV Table V	B.C.C. (alpha)	B.C.C. (alpha)	B.C.C. (alpha)	Ref.(2), Vol. 1, 195	-	-	-	$3x10^{-4}$	-	2665
Hafnium	Hf	2222	$4.43x10^{-3}$	30.0 34.3	96.0 96.0	 128 at877°C	 (156.5)	Table IV Table V	H.C.P. (alpha)	H.C.P.	H.C.P.	H.C.P. → B.C.C. at 1950°C Ref (3) 184	See Ref.(41) or Table No. 7		Reference Source does not identify units of pressure. (Assumed atmosphere).			5400
Uranium	U	1132	$3.4x10^{-3}$	26.2 43.1	52.8 53.4	- (61.0) at 1406°C	- -	Table IV Table V	(alpha)	Alpha $\xrightarrow{660°C}$ Beta $\xrightarrow{760°C}$ Gamma $\xrightarrow{1132°C}$ M.P. (Orthorhombic)(Tetragonal)(B.C.C.)		Ref(3)391(4)1226	-	-	-		$1x10^{-5}$ at1676°C	3818
Zirconium	Zr	1852	$4.4x10^{-3}$	40.0 43.3	113 118	 -	115 (118)	Table IV Table V	H.C.P. (alpha)	H.C.P. (alpha)	Alpha $\xrightarrow{863°C}$ Beta H.C.P. B.C.C.	Ref.(2),609	-	-	-	-	$5x10^{-7}$ at1676°C	3580
Osmium	Os	2700	$4.2x10^{-3}$	9.5 9.5	-	-	-	Table IV Table V	H.C.P.	H.C.P.(?)	H.C.P.(?)	Ref.(3)317	-	-	-	-	$1x10^{-5}$	5500
Titanium	Ti	1668	$4.5x10^{-3}$	42.0 61.0	124.0 129.5	 -	149 149	Table IV Table V	H.C.P. (alpha)	H.C.P. (alpha)	Alpha $\xrightarrow{882°C}$ Beta H.C.P. B.C.C.	Ref.(3)462 Ref.(4)1225	-	-	-	$9x10^{-7}$	-	3260
Vanadium	V	1900	$3.4x10^{-3}$	22.0	-	-	-	Table IV	B.C.C.	B.C.C.	B.C.C.	Ref.(3) 573 Ref.(4)1227	-	-	-	$4x10^{-8}$	-	3400
Remarks		(Ref.) (4)	From Table No. (1)	See also mean Resistivity Values vs. Temperature, from Figures 1, 2, 3, 5, 6, and 7 and Table 12.					F.C.C. = Face Centered Cubic B.C.C. = Body Centered Cubic H.C.P. = Hex. C.P. = Hexagonal Close-Packed Cubic (A15) = (β-W) A1 = (Copper); A2 = (Tungsten Type); A3 = Magnesium Type NOTES				See Table XII for Reference Source and Authority for Data					

$$* \quad \alpha = \frac{1}{R_{0°C}} \cdot \frac{R_{100°} - R_{0°C}}{100}$$

TABLE 1.11

TYPICAL CHARACTERISTIC PROPERTIES OF SELECTED PURE METALLIC ELEMENTS (Continued)

MECHANICAL

		Modulus of Elasticity In Tension (million, psi)				Tensile Strength (psi) (Annealed)					Elongation-(annealed) (% in 2 inches)					Hardness	Creep Characteristics (Annealed State)			
Element	Symbol	20°C	500°C	T=°C	Ref.	20°C	500°C	1200°C	T = °C	Ref.	20°C	500°C	1200°C	T=°C	Reference	(annealed)	20°C	500°C	1200°C	Reference
Gold	Au	11.6	-	-	(4)	17,700 19,000				(2) 803;(40)	25 45				(2) (40)	20 V.P.N. & 50 V.P.N.	See Special Table, i.e., Table No. (6)			
Rhodium (hard wire)	Rh	42.5	-	-	(4)	138,000				(40)	35				(2)(40)	100 V.P.N.				
Iridium	Ir	76.	-	-	(4)	80,000				(40)	9				(40)	220 V.P.N				
Platinum	Pt	21.3	-	-	(4)	20,000 to 24,000				(2); (40)	30 to 40				(2) (40)	37. V.P.N				
Palladium	Pd	16.3	-	-	(4)	20,000 to 25,000				(2); (40)	30 to 40				(40)	37, 40 V.P.N.				
Ruthenium	Ru	60.Aoorox.	-	-	(4)	78,400				(4), 1221						220 V.P.N.				
Rhenium	Re	66.7 68	61 at 400°C	55.5 at 800°C		(43)	72,000 150,000	115,000	60,000	(4), 803 (42),6,7	24 to 19	10	3			135 K.H.N. 250 V.H.N.				
Copper	Cu	16.	-	-	(4)	30,000- 31,200				(4), 1204 (2), 727	60					42 B.H.N. 51 V.P.N.				
Silver	Ag	11	-	-	(4)	18,000				(40)	52- 60				(40)	26 V.P.N.				
Molybdenum	Mo	46 to 47	41	39 at 1000°C	(50) (4)	112,000 135,000 (75,000)	35,000 (51) 38,000		20,000 at 1,000°C(51) 35,000at650°C	(2),803;(51); (4),1216.	5-20 72 Ref,315				(53)	147 B.H.N. 165 V.P.N				
Tungsten	W	50 to 59	55	50 at 1000°C	(50) (4)	100,000	170,000 175,000	57,000 to 65,000	50,000 to 75,000 at 1000°C(51)	(40),(51),(2)	8					290 B.H.N.				
Nickel	Ni	30	-	-	(4)	46,000				(2), 1217	30					69 V.H.N.				
Remarks		See also Discussion Text				See also Discussion Text Notes					See also Discussion Text						Typical creep properties elements selected from Table XI, are presented in Table XIII.			

TABLE 1.11

TYPICAL CHARACTERISTIC PROPERTIES OF SELECTED PURE METALLIC ELEMENTS (Continued)

MECHANICAL

		Modulus of Elasticity In Tension (million, psi)				Tensile Strength (psi) (Annealed)					(Elongation-(annealed)(% in 2 inches)					Hardness	Creep Characteristics (Annealed State)			
Element	Symbol	20°C	500°C	T=°C	Ref.	20°C	500°C	1200°C	T=°C	Reference	20°C	500°C	1200°C	T=°C	Reference	(annealed)	20°C	500°C	1200°C	Reference
Tantalum	Ta	27.3	25	22 at 1000°C	(50)	32,000 72,000	18,000	7,500		(2), (47)&(40)	73 28-37	53	70	-	(47) (4),1223	70 B.H.N. 125 V.H.N.			See Special Table, i.e., Table No. (6)	
Thorium	Th	10.0	2.5		(8) p 309	31,700				(4), 1225	34					32 to 42 V.H.N.				
Cobalt	Co	30	-	-	(4)	37,000 to 137,000				(4), 1201 (2), 803	1-2				(40)	48-B.H.N.				
Iron	Fe	28.5	-	-	(4)	27,700 to 29,900				-	36 to 41				(4)	49 V.H.N.				
Niobium	Nb	12 to 15.1	6.5	13.6 at 870°C	(50) (51) (4)	30,000 58,000	32,000 at 500°C 29,400 at 538°C	6,000	9,000 at 1000°C 10,000 at 1093°C	(4), (49) (2), (45)	60.5 46	59 at 500°C 50 at 538°C	- -	75 at 1000°C 79 at 1093°C	(48)	80 V.H.N.				
Chromium	Cr	36	(31.8)	37 at 800°C	(4)	12,000	40,6000	-	26,000 at 800°C	(4)	0	30	-	47 at 800°C	(4)	70-90 B.H.N.				
Hafnium	Hf	20	-	-	(3)	64,000	33,700			(4), 1206	23	43			(4)	190 dph at 30 Kg load				
Uranium	U	24	-	-	(4)	56,000 to 134,000			12,000 at 600°C	(4), 1226 (2) 803 (3) 526	4 to 20				(4), 1226 (2),803	150 B.H.N. (annealed) Alpha U. rolled				
Zirconium	Zr	13.7	-	-		31,000-36,000				(2), 803	30-40				(2); 803	75-80 V.P.N.				
Osmium	Os	81	-	-	(4)											350 V.P.N.				
Titanium	Ti	16.8	-	-	(4)	34,000	15,000 at 410°C	-	13,300 at 538°C	(4), 1225	54	39 at 410°C		30 at 538°C		80 to 100 V.H.N.				
Vanadium	V	18 to 20.5	-	-	(46) (4) (45)	78,000 31,600 Ref. 47	-	-	7,700 at 1024°C	(4), 1227	25 17	-		37 at 1024°C	Ref.(4), 1227; Ref.(46)	48 RA 64 V.H.N.				
Remarks		See also Discussion Text				See also Discussion Text Notes					See also Discussion Text						Typical creep properties elements selected from Table XI, are presented in Table XIII.			

TABLE 1.11

TYPICAL CHARACTERISTIC PROPERTIES OF SELECTED PURE METALLIC ELEMENTS (Continued)

CHEMICAL - (OXIDATION)											
		Oxidation Characteristics (Dry Air and/or Dry O_2)					Prevention of Oxidation				
Element	Symbol	20°C	500°C	1200°C	T=°C	Reference	20°C	500°C(*)	1200°C(*)	TC=°C	Remarks
Gold	Au	None	None	None	None	(40), 244		None required			
Rhodium	Rh	Practically None	Rh oxidized to $Rh_2 0_3$ above (red heat) (500-550°C)	Rh Oxide Decomposes to metal & oxygen above 1100°C	-	(3), 320 (40), 244	None Req'd	Protection req'd in the range of -500 to 1100°C	None Req'd	-	-
Iridium	Ir	Practically None	Superficially oxidizes to Ir 0_2	Oxide dissociates above 1140°C with volatile sub-oxide	1100°C 1140°C; oxide Ir 0_2	(3); (59) (40), 244	None Req'd	Protection req'd from 500°C to 1140°C	None Req'd but there is a weight loss due to volatile sub-oxide resulting from dissociation of higher oxide		
Platinum	Pt	Not oxidized	Not oxidized	Not oxidized	None up to 1400°C	(3), 320 (40), 244		None required	None Req'd.		
Palladium	Pd	Not oxidized	Superficially oxidizes up to 700°C	at 875°C; oxide dissociates.	-	(3), 320 (40), 244	None Req'd	Abt.(500-875°C) Requires protection	None req'd but there may be a weight loss of Pd		-
Ruthenium	Ru	Practically None	Superficially oxidized	Stable oxide $Ru0_2$ formed	-	(3), 320	None Req'd	Require protection	Required Protection	(See notes (*)at bottom of table)	
Rhenium	Re	Polished Surface of Compact (Re) is Stable in air at R.T.	Above 350°C Re is converted to $Re_2 0_7$ (oxide)	Rate of oxidation would be very rapid at 1200°C	-	(3), 357	None Req'd		Requires Protection		See footnote below table
Copper	Cu	Practically none in (air or 0_2)	at 100°C $Cu_2 0$ at 200°C to 600°C } mixed oxides of $Cu_2 0$+Cu0	Accelerated rate or rapid oxidation	-	(40),205	None Req'd		Requires Protection		See footnote below table
Silver	Ag	Dry air practically none	Oxidation (dry air) 200°C	600°C, very rapid diffusion of oxygen.	-	(40), 244	None Req'd		Requires Protection		See footnote below table
Molybdenum	Mo	(In air or 0_2) Practically none at 20°C slow oxidation at 200°C	at 400°C ready formation of MoO_3	Very rapid oxidation; $M_o 0_3$ & $M_o 0_2$ form eutectic,M.R=778°C	at 200°C onset of slow oxidation	(40), 316	None Req'd		Requires Protection		See footnote below table
Tungsten	W	Slight tarnish in air above 300°C	Rapid oxidation	Very rapid oxidation to WO_3	Slight tarnish in air (0_2) at 300°C	(40), 263	None Req'd	Protective Atmos; inert, CO_2; H_2; or vac. Requires Protection			(41), 26 See footnote (1)
Nickel	Ni	Practically None	Slow oxidation at 400°C Ni0 protective film	Rapid oxidation	-	(40), 226	None Req'd		Requires Protection		See footnote below

An excellent detailed discussion of the kinetics and mechanism of low to moderate temperature, Oxidation characteristics of the above metals has been provided by J. R. Evans, Ref. (56); 18-74, 777-84.

(*) Footnotes

(1) All metals above can be adequately protected from oxidation by:
  (a) Ultra-high vacuum environment, or
  (b) By an ultra pure inert gas (argon, helium, etc.) with dew-point of the order of liquid nitrogen; free of all organic vapors; and other undesirable trace impurities.
(2) Additionally, an ultra pure H_2 environment is also satisfactory for the protection of W, & Mo.
(3) Tungsten may also be protected by an ultrapure/carbon dioxide atmosphere at temperatures of about 1200°C
(4) See also Discussion Text.

TABLE 1.11

TYPICAL CHARACTERISTIC PROPERTIES OF SELECTED PURE METALLIC ELEMENTS (Continued)

CHEMICAL - (OXIDATION)										
		Oxidation Characteristics (Dry Air and/or Dry O_2)					Prevention of Oxidation			
Element	Symbol	20°C	500°C	1200°C	T=°C	Reference	20°C	500°C (*)	1200°C (*) TC=°C	Remarks
Tantalum	Ta	Practically None	Weak oxidation at 400°C	400°C-600PC weak oxidation	700°C rapid oxidation	(40),336	None Req'd		Requires Protection	See footnote below
Thorium	Th	Pure Th, Relatively Inert Impure Th. oxidizes	Oxidizes	Oxidizes rapidly	-	(3), 442, & 447	None Req'd (ultra pure)	Required Portection 20°C through 1200°C		See footnote below
Cobalt	Co	Oxidation begins at 300°C in presence of 0_2,air or water vapor	Rapid oxidation	Very rapid oxidation oxides are $Co0$, Co_20_3, Co_30_4	-	(3), 120 121	None Req'd	Required ultra-high purity inert gas (helium, argon, etc.) or ultra-high vacuum environment. Requires Protection		See footnote below
Iron	Fe	Practically None	Oxidation proceeds from abt. 320°C $Fe0 \rightarrow Fe_30_4 \rightarrow Fe_20_3$	Rapid oxidation	-	(3), 180 (57), 24, 25	None Req'd (ultrapure)	Requires Protection 320°C to 1200°C		See footnote below
Niobium	Nb	Practically None	Oxidation rate changes from parabolic to linear at 400-430°C	Rapid Oxidation	Oxide is not adherent	(40),354	None Req'd	Requires portection from about 400°C through 1200°C		See footnote below
Chromium	Cr	Superficial film (Protective film)	Parabolic rate at 950-1050°C spurt in oxidation rate and at 4800A° thickness; and at 1050°C and 42,000 A° thickness 2nd spurt in rate			(57),30	None Req'd	Requires protection from 720°C through 1200°C		See footnote below
Hafnium	Hf	Practically None	at 750°C; still air; corrosion rate = 120 mg/sq dm/hr	at 950°C; (still air) corrosion rate = 385 mg/sq dm/hr	-	(3), 186	None Req'd	Required equivalent protection as (Cr)		See footnote below
Uranium	U	Oxidizes at R.T. in air (parabolic rate) up to 140°C	Linear rate 140°C to 240°C	Combustion occurs at 260°C in air or oxygen	-	(3), 544	Requires protection over the full temperature range			See footnote below
Zirconium	Zr	Practically None	400°C oxidizes	Rapid Rate	-	(3), 616	Requires equivalent protection of Cr, and Hf.			See footnote below
Osmium	Os	Practically None	At Temperatures greater than 200°C, $Os \rightarrow OsO_4$	Wt loss due to Volatility of ($Os \rightarrow OsO_4$)	-	(3), 320 (41)	None Req'd	Requires protection; (if wt loss is of concern) for Temp. range 200 to 1200°C		See footnote below
Titanium	Ti	Practically None	Oxidizes according to parabolic rate law		-	(3), 466	None Req'd	Requires protection - Abt. 200° C through 1200°C		See footnote below
Vanadium	V	Practically None	Oxidizes in stages from $V_2O_3 \rightarrow V_2O_4 \rightarrow V_2O_5$		-	(3), 596	None Req'd	Requires equivalent protection of Cr, Zr & Hf for range of about 200°C to 1200°C		See footnote

An excellent detailed discussion of the kinetics and mechanism of low to moderate temperature, Oxidation characteristics of the above metals has been provided by J. R. Evans, Ref. (56); 18-74, 777-84.

NOTES

(*) Footnotes

(1) All metals above can be adequately protected from oxidation by:
  (a) Ultra-high vacuum environment, or
  (b) By an ultra pure inert gas (argon, helium, etc.) with dew-point of the order of liquid nitrogen; free of all organic vapors; and other undesirable trace impurities.

(2) Additionally, an ultra pure H_2 environment is also satisfactory for the protection of W, & Mo.

(3) Tungsten may also be protected by an ultrapure/carbon dioxide atmosphere at temperatures of about 1200°C

(4) See also Discussion Text.

TABLE 1.11(Cont'd.)

Comparative Oxidation Rates of Selected Refractory Metal Elements (Reference State). VS. Temperature

Refractory Metal, Element	Temperature (°C)	Period, (Hours)	Oxidation Rate, (Micrograms/cm^2 hour.) Approx.	Atmosphere	Reference Number Page
Cr.	300				(13);13
	500				(13);13
	700	0 - 3	15. 3.5	1.0 atm(Air) 0.1 atm(O_2)	(13);13 (13);13
	900	0 - 3	165. 17	1.0 atm(Air) 0.1 atm(O_2)	(13);13 (13);13
	1100	0 - 3	1,100 265	1.0 atm(Air) 01. atm(O_2)	(13);13 (13);13
Cb(Nb)	300	1 - 2	5	0.1 atm(O_2)	(13);13
	500	0.3 - 2.0	700	0.1 atm(O_2)	(13);13
	700	0 - 16	1,150	1.0 atm(Air)	(13);13
	900	3.6 - 16 0 - 16	20,000 29,000	1.0 atm(Air) 1.0 atm(Air)	(13);13 (13);13
	1100	3.6 - 16 0 - 16	22,000 31,000	1.0 atm(Air) 1.0 atm(Air)	(13);13 (13);13
Mo	400	1 - 2	5	0.1 atm(O_2)	(13);13
	450	1 - 2	35	0.1 atm(O_2)	(13);13
				0.1 atm(O_2)	(13);13
	700	-	-	-	-
	900	-	-	-	-
	1100	-	-	-	-

TABLE 1.11 (Cont'd.)

Comparative Oxidation Rates of Selected Refractory Metal Elements (Reference State). VS. Temperature - Cont.

Ta	300	1 - 2	2.8	0.1 atm(O_2)	(13);13
	400	1 - 2	10.8	0.1 atm(O_2)	(13);13
	700	0 - 16	1,650	1.0 atm, (Air)	(13);13
	900	0 - 16	15,500	1.0 atm, (Air)	(13);13
	1100	0 - 16	≈31,000	1.0 atm, (Air	(13);13
V	400	1.6 - 2.0	10.8	0.1 atm, (O_2)	(13);13
	500	1.6 - 2.0	25.	0.1 atm(O_2)	(13);13
	600	1.6 - 2.0	100.	0.1 atm(O_2)	(13);13
	900	-	-	-	-
	1100	-	-	-	-
W	400	1 - 1.3	10.1	0.1 atm (Air)	(13);13
	500	1 - 1.3	86	0.1 atm (Air)	(13);13
	700	0 - 0.3	≈5,300	1.0 atm (Air)	(13);13
	900	0 - 0.3	≈40,000	1.0 atm (Air)	(13);13
	1000	0 - 0.3	≈130,000	1.0 atm (Air)	(13);13

TABLE 1.12

SELECTED ELEMENTS: VAPOR PRESSURE VS TEMPERATURE

Element	Constants of Vapor Pressure Equation *				Temperature Range (°K)	Specific Temperature		Vapor Pressure at Specific Temperature		Other Source - Data Vapor Pressure (mm. Hg.) at Selected Temperatures; and from Selected Reference.
	A	B	C	D		(°C)	°K	Log_{10}(P,mm:Hg)	P=mm. of Hg.	
Gold	19,820 19,280	10.81 12.38	-0.306 -1.01	-0.16 --	298 - 1336 1336 - 3240	20° 500 1063 1200	293 773 1336 1473	-57.7498 -15.87414 - 5.141822 - 3.908815	1.78×10^{-58} 1.34×10^{-16} 7.2×10^{-6} 1.23×10^{-4}	1.9×10^{-8} at 1000°K, Ref (1); (I-G-3) 1.1×10^{-5} at 1273°K, Ref (1); (I-G-3)
Rhodium	-	-	-	-	-	-	-	-	-	at 1954°K;, v.p.= 1×10^{-5}, mm of Hg, (after Dushman) at 2244°K; , v.p. = 1×10^{-3}, , (after Dushman) at 2422°K;, v.p.= 1×10^{-2}, , (after Dushman)
Iridium	-	-	-	-	-	-	-	-	-	at 2266°k; v.p. = 1×10^{-5}; at 2427°K, v.p. = 1×10^{-3} at 2829°K, v.p. = 1×10^{-2} (mm of Hg); after Dushman
Platinum	27,100 25,000	9.40 8.44	- -	- -	298 - 2042 2042 - 4000	20 500 1200	293 773 1473	-83.09100 -25.658 -18.998	8.1×10^{-84} 2.2×10^{-26} 1×10^{-9}	at 1879°k; v.p. = 1×10^{-5}) ( ) at 2177°K; v.p. = 1×10^{-3}) mm of Hg (After Dushman) at 2363°K; v.p. = 1×10^{-2}) ( )
Palladium	-	-	-	-	-	-	-	-	-	at 1429°K; v.p. = 1×10^{-5}, mm of Hg, (after Dushman) at 1678°K; v.p. = 1×10^{-3}, mm of Hg, (after Dushman) at 1839°K; v.p. = 1×10^{-2}, mm of Hg, (after Dushman)
Ruthenium	-	-	-	-	-	-	-	-	-	at 2186°K; v.p. = 1×10^{-5}, mm of Hg, (after Dushman) at 2503°K; v.p. = 1×10^{-3}, mm of Hg, (after Dushman) at 2704°K; v.p. = 1×10^{-2}, mm of Hg, (after Dushman)
Rhenium	-	-	-	-	-	-	-	-	-	1.2×10^{-6} at 2500°K; Ref (1); (I-R-2)
Copper	17,870 17,650	10.63 13.39	-0.236 -1.273	-0.16 -	298 - 1356 1356 - 2870	20. 500 1083 1200	293 773 1356 1473	-51.1212 -13.3293 -3.44767 -2.625472	7.55×10^{-52} 4.68×10^{-14} 3.57×10^{-4} 2.37×10^{-3}	at 1356°K: (3.1×10^{-4}), Ref. Dushman; & 3.0×10^{-4} after Ref (1), (I-C-7) at 1473°K: 3.2×10^{-3} Ref. (1), (I-C-7)
Silver	14,710 14,260	11.66 12.23	-0.755 -1.055	- -	298 - 1234 1234 - 2400	20. 500. 961 1200	293 773 1234 1473	-40.407265 -9.550341 -2.594523 -0.793377	$x.91 \times 10^{-41}$ 2.82×10^{-10} 2.54×10^{-3} 0.161×10^{-2}	at 961°c; 1.78×10^{-3} mm of Hg; after Dushman: 4.5×10^{-2} mm Hg; at 1473°K; after Ref (1); (I-S-4)
Molybdenum	34,000	11.98	-	-0.755	2000 - 2600	20 500 1200 1727	293 773 1473 2000	- - - -5.805	$\lll 1.57 \times 10^{-6}$ $\ll 1.57 \times 10^{-6}$ $< 1.57 \times 10^{-6}$ 1.57×10^{-6}	at 2196°K; v.p. = 1×10^{-5} mm of Hg; after Dushman at 2568°K; v.p. = 1×10^{-3} mm of Hg; after Dushman at 2110°K; v.p. = 1.9×10^{-6} mm of Hg; Ref. (1), (I-M-4)
Tungsten	42,000	9.84	-0.146	-0.164	2000 - 3500	20 500 1200 1727	293 773 1473 2000	- - - -11.80595	$\lll 1.56 \times 10^{-12}$ $\ll 1.56 \times 10^{-12}$ $< 1.56 \times 10^{-12}$ 1.56×10^{-12}	at 2827°K; v.p. = 1×10^{-5} mm of Hg; (after Dushman) at 3289°K; v.p. = 1×10^{-3} mm of Hg; (after Dushman)
Nickel	22,100 18,000	10.75 8.17	- -	-0.131 -	1000 - 1728 1728 - 2500	20 500 1200	293 773 1473	-4.38439	$\ll 4.12 \times 10^{-5}$ $< 4.12 \times 10^{-5}$ 4.12×10^{-5} Abt 5×10^{-5}	at 1430°K; v.p. = 1×10^{-5} mm of Hg; (after Dushman) at 1644°K; v.p. 1 x 10^{-3} mm of Hg; (after Dushman)
Tantalum	-	-	-	-	-	-	-	-	-	at 2556°K; v.p. = 1.75×10^{-6} mm of Hg; after Ref (1), (I-T-1) at 2680°K; v.p. = 1×10^{-5} mm of Hg; after Dushman at 2837°K; v.p. = 6.5×10^{-4} mm of Hg; after Ref (1), (I-T-1)
Thorium	-	-	-	-	-	-	-	-	-	at 1716°K; v.p. = 1.5×10^{-7} mm of Hg; Ref. (1); (I-T-4) at 1959°K; v.p. 1×10^{-5} mm of Hg; after Dushman. at 2444°K; v.p. = 6.1×10^{-3} mm of Hg; Ref. (1), (I-T-4)

TABLE 1.12

SELECTED ELEMENTS: VAPOR PRESSURE VS TEMPERATURE (Continued)

	Constants of Vapor Pressure Equation *				Temperature Range (°K)	Specific Temperature		Vapor Pressure at Specific Temperature		Other Source - Data Vapor Pressure (mm. Hg.) at Selected Temperatures; and from Selected Reference.
Element	A	B	C	D		(°C)	°K	Log_{10}(P,mm:Hg)	P=mm. of Hg.	
Cobalt	22,210	10.817	-	-0.223	1000 - 1772	20 500 1200	2.93 773 1473	- - -4.48407	$\ll 3x10^{-5}$ $< 3x10^{-5}$ $3.28x10^{-5}$	at 1522°K; v.p. = 1×10^{-5} mm of Hg; after (Dushman) at 1767°K; v.p. = 1×10^{-3} mm of Hg; after (Dushman) 2.2×10^{-4} mm of Hg at 1473°K Ref. (1) 2.6×10^{-5} mm of Hg at 1473°K Ref. (1)
Iron	21,080 19,710	16.89 13.27	-2.14 -1.27	-	900 - 1812 1812 - 3000	20 500 1200	293 773 1473	-4.200854	$\ll 6x10^{-5}$ $< 6x10^{-5}$ $6.29x10^{-5}$	at 1367°K; v.p. = 1×10^{-5} mm of Hg; after (Dushman) at 1583°K; v.p. = 1×10^{-3} mm of Hg; after (Dushman) at 1473°K; v.p. = 1.52×10^{-4} mm of Hg; after Ref. (1) (I-J-2) at 1473°K; v.p. = 7.6×10^{-5} mm of Hg; after Ref (1), (I-J-2)
Niobium										1×10^{-5} mm of Hg at 2467°K; after Dushman 1×10^{-3} mm of Hg at 2812°K; after Dushman
Chromium	20,470	10.35	-	-	1100 - 1700	20 500 1200	293 773 1473	- - -3.547	$\ll 2.84x10^{-4}$ $< 2.84x10^{-4}$ $2.84x10^{-4}$	at 1473°K; v.p. = 6.1×10^{-4} mm of Hg; Ref. (1) (I-C-5) at 1473°K; v.p. = 2.7×10^{-4} mm of Hg at 1473°K; Ref (1) (I-C-5) at 1478°K, v.p. = 1.09×10^{-2} mm of Hg; after (Dushman)
Hafnium	30,200	9.46	-	-	See Reference Notes			-	-	after Ref. (41), 534, and Ref. (42), 72, 73
Uranium	-	-	-	-	-	-	-	-	-	1×10^{-5} mm of Hg: at 1734°K; after Dushman 1×10^{-3} mm of hg: at 2003°K; after Dushman 1.9×10^{-6} mm of Hg: at 1627°K; Ref (1)
Zirconium	31,070	10.215	-	-0.242	1000 - 2130	20 500 1200	293 773 1473	-11.120	$\ll 7.59x10^{-12}$ $< 7.59x10^{-12}$ $7.59x10^{-12}$	4.2×10^{-7} mm of Hg; at 1944°K, after Ref (1), (I-Z-1)
Osmium	-	-	-	-	-	-	-	-	-	at 2374°K; v.p. = 1×10^{-5} mm of Hg. (after Dushman) at 2724°K; v.p. = 1×10^{-3} mm of Hg. (after Dushman) at 2940°K; v.p. = 1×10^{-2} mm of Hg. (after Dushman)
Titanium	24,275 22,110	10.66 9.135	- -	-0.23 -	1200 - 2000 2000 - 3300	20 500 1200	293 773 1473	- - -6.050	$\ll 8.9x10^{-7}$ $< 8.9x10^{-7}$ $8.91x10^{-7}$	1.5×10^{-6} mm of Hg; at 1510°K; after Ref (1) (I-T-6) 1.5×10^{-5} mm of Hg; at 1800°K; after Dushman)
Vanadium	26,650	10.815		0.112	1000 - 2050	20 500 1200	293 773 1473	- - -7.389	$\ll 4x10^{-8}$ $< 4x10^{-8}$ $4.08x10^{-8}$	1.9×10^{-6} mm of Hg; at 1636°K; after Ref. (1) $1. \times 10^{-5}$ mm of Hg; at 1738°K; after Dushman

Note: Values of Vapor Pressure; referred to in the above table have been derived or taken from the tables of Vapour Pressure of Metals;
Ref. (2); C. J. Smithells, Metall Reference Book, Vol. II, Butterworths Scientific Publications, London, 1955; p 613.
Ref. (39) (Reference: S. Dushman; Scientific Foundations of Vacuum Technique, John Wiley & Sons, Inc., N.Y., 1940 edition, pp. 743-752, inclusive.
Ref. (40); Kohl, W. H.; Materials and Techniques for Electron Tubes; Reinhold Publishing Company, 1960 edition.
Ref. (41); Encyclopedia Brittanica, Vol. XI, pp. 72, 73; 1957 edition.

*VAPOR PRESSURE EQUATION; After Smithells; (Ref. (2), p. 613).

$$\text{Log}_{(10)} P = -\frac{A}{T} + B + C\,\text{Log}_{10}\,T + D_{(a)}$$

(a): Where the "T" term following "D", of original cited equation, has been found necessary to exclude, for the specific elements selected and "D" values given in original reference.

(b): P = mm. of Hg:

(c): T = degrees Kelvin = 273°K + degrees Centigrade.

TABLE 1.13

SELECTED CREEP DATA FOR PURE ELEMENTS

Element	Reference	Temperature °c	Stress (PSI)	Creep Rate (Micro-inch/in/hour)	Period
Copper (E.T.P.)	(4),1008	204°c 204°c	5000 9000	0.42 2.1	1000 hr. 1000 hr.
Hf.	(4),1205	250°c to 370°c	2300 Appx.	1.0	-
Mo.	(4),1216	1849 1849	1700 1000	3.8×10^{4} $3.8 \times 10^{+3}$	- -
Mo.	(4),1218	2000°c 2000°c	2200 1400	- $3.6 \times 10^{+5}$ $3.6 \times 10^{+4}$	- -
Mo.		2500°c 2500°c	850 560	$3.6 \times 10^{+4}$ $3.6 \times 10^{+3}$	- -
Nb. (Wrought)	(4),1202	500°c 500°c 500°c	27000 31000 33500	50.5 100.0 200.0	10 hr. stress period
Nb.	(4),1202	500°c 500°c 500°c	17500 20000 23000	5.0 10.0 20.0	100 hr. stress period
Nb.	(4),1202	500°c 500°c 500°c	11500 13500 16000	0.5 1.0 2.0	1000 hr. strese period
Nb.	(4),1202	1200°c	5200 rupture stress	-	1 hr. rupture life
Nb.	(4),1202	1200°c	4600 rupture strese	-	100 hr. rutpute life
	(4),1202	1200°c	4000 rupture stress	-	1000 hr. rupture life
Th. Bomb reduced and inert-atmosphere annealed.	(8),3/4	316°c	10000	11.84 <u>Minimum</u>	100 hrs.
U.	(8),400	500°c	2220	Min. secondary creep rate 18.0	2000 hr. test
U.	(8),400	500°c	1720	Min. secondard creep rate 9.0	1350 hr. test
Ta.	(4),1223	815°c 815°c	14000 13000	1×10^{5} 5×10^{4}	0.1 hr. 0.1 hr.
Ta.	(4),1223	815°c 815°c 815°c 815°c	12300 10000 11000 7000	1×10^{4} 5×10^{3} 1×10^{3} 50	1 hr. 1 hr. 10 hr. 100 hr.
Ta.	(4),1223	1093°c	12600	1×10^{5}	0.1 hr.
Ta.	(4),1325	1093	8200	1×10^{4}	1.0 hr.
Ta.	(4),1223	1371°c	2500 1500	1×10^{5} 1×10^{4}	0.1 hr. 1.0 hr.
Zr. annealed	(4),1229	260°c	14300	1×10^{3}	-
Zr.	(4),1229	260°c	13600	1×10^{2}	-
Zr.	(4),1229	260°c	11600	0.1	-
Zr. annealed	(4),1229	400°c	10000	29.0	-
Zr. annealed	(4)1229	400°c	5000 4000	10.0 4.3	- -
Ra.	(43)	1000°c	80000 Rupture Stress	-	1/2 minute to rupture
Re.	(43)	1000°c	60000 Rupture Stress	-	5 minutes to rupture
Re.	(43)	1000°c	50000 Rupture Stress	-	3.7 minutes to rupture

TABLE 1.14

SELECTED PURE ELEMENTS AND TYPICAL FABRICATION CHARACTERISTICS

	Working Temperatures		Strain Hardening Exponent = n	Forming Characteristics Suitable For:						Other Characteristics			
	Cold-(Range) °Centigrade	Hot-(Range) °Centigrade		Machining	Turning	Swaging	Forging	Drawing	Extrusion	Heat Treatment	Joining	Remarks	References
GOLD	Any	All, (below M.P.)		Material very soft and "gummy"; machining characteristic (considered to be approximately between pure Iron and pure Bismuth; (Based on Hardness).		Ideal-Cold	Ideal-Cold	Ideal-Cold	Cold	Annealing (Not usually required) at 300°C (575°F).	Braze with Silver Solders, no flux; any flame. Weld: Resistance, Oxyacetylene, or others.	Cold Weld; Pressure Weld; Hot-Cold Roll Weld	(4); 1185, 1186
RHODIUM	Room Temp. Ductility is obtained after sufficient reduction of area.	Greater than 800°C		Does not Lathe cut cleanly, but machining may profit by examples of Cu, Mo, etc.		Hot swaged until sufficient ductilityis obtained. Use Dry Lubricants.	Above 800°C	Hot Drawn or Hot Rolled		Anneal, (after material can be cold worked); at 775°C to 800°C	Resistance Welding; Heliarc Welding; Electron Beam welding; Brazes - (Au, Ag, Pd) Silver Solders - (Selected)	As degree of worked metal increases, the recrystallization temperature is lowered, and hot working temperatures decreased.	(3); 308 (8); 526
IRIDIUM	None	1200°C to 1500°C				Hot 1200 - 1500°C	Forged, (Difficulty), at 1200°-1500°C	Hot Rolled at 1200°-1500°C		Since there is no apparent cold working of this metal; the hot working range provtdes the annealing temperature.			(4), 1196 (19), 49 (3), 307,308 (17), 49
PLATINUM	R. T.	Cast Ingots are power forged from "White Heat" i.e. (1450°C) (-1550°C)		Machining characteristics in class between Cu. and possibly Mo.		Suitably formed by these Methods, cold or hot (Includes Pt. & Pd.)				Oxidizing atmosphere for annealing. 600°-700°C	Pt./or Pd. joined by (1) Hammer welding at 1200°C; (2) Welding with solder whose m.p. ≈ 1600°C; (3) fusion welds; (4) Electric Resistance welding; and soldering (pure Au Solder or other.	Pure Pt. is very soft	(4), 1190 (3), 307,308 (6), 1103 (17), 31
PALLADIUM										Anneal pure Metal at 800°C - 900°C	(1) Oxidizing oxyacetylene flame for soldertng Pd. with Pt. Solders (melting from 1100-1300°C); (2) Gas-air torch for low melting white Gold Solders; (3) High Frequency Induction melting.	Electron Beam welding would be an appropriate method.	(4), 1194 (3), 307 (6), 1103 (17), 41
RUTHENIUM	None	Above 1500°C (Ref. 4)				Possible, but not practical, except perhaps at 1500°C or above, (based on evidence of forgeability (difftcult)					Weld - Inert atm - arc - ; Electron Beam	"Ruthenium and Osmium have never been successfully worked." Ref (3), 308.	(3), 308 (4), 1221

TABLE 1.14 (Continued)

SELECTED PURE ELEMENTS AND TYPICAL FABRICATION CHARACTERISTICS

	Working Temperatures		Strain Hardening Exponent = n	Forming Characteristics Suitable For:						Other Characteristics			
	Cold- (Range) °Centigrade	Hot- (Range) °Centigrade		Machining	Turning	Swaging	Forging	Drawing	Extrusion	Heat Treatment	Joining	Remarks	References
RHENIUM	Excellent ductility at Room Temp.	Not desired	0.353	Machining characteristics are considered to be equivalent to Copper, Nb, Fe, Ag, etc. See details for Copper, below.		Primary Working Methods; at Room Temperature With reductions of Areas from 10% to 20% before Anneals are required.			Limited (by high rate of strain-hardening to possible but not practical	Annealing Temperature - 1700°C; Period 1 - 2 hours Also as low as 1250°C- Ref (41), 528	Weld - Inert atmosphere. arc - Electron Beam - Brazes - Select Solders - Select	Rhenium - work hardens more rapidly than any other known metal, consequently, more frequent anneals are required.	(4), 1220 (17), 55 (40), 530, 528
COPPER	R.T.	750°C to 950°C		For machine cutting, use carbide tipped tools: a top rake of 20-30 degrees and a 5-8 degrees side clearance angle; cut at 250 to 300 feet/Min.; coolants free of sulphur.		Very suitable to these forming methods after break-down of cast structure. May be done cold or hot range. Avoid contamination by oxygen, sulfur, etc.			Cold	Annealing Range - (375°C - 650°C)	Rivet: Copper Rivets: Welding: Pressure, koldweld; Gas Shielded Arc: Silver - Brazes (A.S.T.M. B-260). Solders - all soft types.	Metal is tough and "Gummy" Data on machining may serve as a model for machining characteristics of similar "gummy-sticky" metals.	(40), 214 (4), 1203 (4), 1007 (4), 1008
SILVER	R.T.	Suitable above annealing Temp. but not neccessary		Can be machined satisfactorily, with sharp tools; tool design, feed, etc. for soft-gummy metal characteristics.		Very suitable to working by these forming methods and either at R.T., or above.				Annealing Temp. (for 50% cold worked metal) = 300°C Annealing Temp. (for > 50% cold worked metal < 300°C Complete anneal 1/2 hr at 900°C	Weld - Fusion methods; with care to avoid contamination by 0_2, Sulphur, etc. Pressure Weld - above R.T.	Metal is extremely ductile. Care must be exercised to prevent oxidation or contamination by Sulfur.	(4), 1182 (8), 528
MOLYBDENUM	Brittle below R.T. (21°C)	Forging temp. Range 1177°C - 1288°C with lower limit of 927°C		Can be satisfactory machined. Equivalent to hardened S.A.E. 1045 steel. Consult details of "Machining of Molybdenum" as supplied by Vendors &/or Mfgrs. (See Ref. 62)		See rolling, drawing and extrusion remarks.	Forged at 1177°C to 1288°C with min. at 927°C	Forged Billets rolled, extruded, drawn; by hot forming with glass as die lubricant; after French Ugine - Sejournet Process Ref. (3)		Annealed at 1000°C for not more than 3 minotes. or annealed at temp. greater than 725°C for larger periods, but less than the period for recrystallization.	Riveting or Brazing are common methods. Also resistance and/or inert gas welding process, but weld is brittle. Also by percussion, flash, and electron Beam weld methods. Good Inert Atmosphere Protection Required.	All sheet for forming operations must be heated to proper temperature relative to thickness of sheet and forming speed.	(61) (3), 283,284,285,311 (4), 1214
TUNGSTEN	Brittle at R.T.	Initial forging rolling & swaging of Sintered compacts is done at 1595°C to 1815°C		Machined with difficulty; but best results from practice indicates a cutting speed and depth of cut necessary to produce a coiled chip at a slight red heat (i.e. 450°C) or above the Brittle to ductile transition temp.		After initial forging, etc. of compact; the metal is hot worked from 800°C through series of reduction to lower temperature range of 400°C as degree of cold work reduces the recrystallization temperature				Anneal below recrystallization temperature, for recovery of Plasticity and additional reductions without recrystallization and embrittlement of metal. Stress relief annealing range (594°C - 1010°C) and a period of 20-30 minutes for the elevated temperature	Brazing is preferred method of joining, using pure copper, copper base, nickel base, or tantalum materials. Also hot riveting is an acceptable joining method. Tungsten-to-tungsten welds are brittle.	Ductility increases with degree of cold work or fibrous texture, contrary to behavior of most other metals. Room temperature brittleness is encountered.	(60) (4), 1226 (3), 496
NICKEL	R.T.	Range 1260°C to 871°C		Similar to mild steel but requirements of power are greater.		After break down of cast structure, (hot forged), the metal can be worked cold or hot throughout this range of forming operations.				Stress Equalization at 274°C to 344°C Stress Relief - at 538°C to 705°C Full Anneal at 815°C to 927°C	Weld methods include: Metal arc, inert gas metal arc, Submerged arc, oxyacetylene, resistance, electron Beam; Solder - Soft Types	Atmosphere control critical to avoid contamination by Sulphur and prevent oxidation.	(8), 229 (6), 1031,1033, 1034,1040

TABLE 1.14 (Continued)

SELECTED PURE ELEMENTS AND TYPICAL FABRICATION CHARACTERISTICS

	Working Temperatures		Strain Hardening Exponent = n	Forming Characteristics Suitable For:						Other Characteristics			
	Cold- (Range) °Centigrade	Hot- (Range) °Centigrade		Machining	Turning	Swaging	Forging	Drawing	Extrusion	Heat Treatment	Joining	Remarks	References
TANTALUM	R.T.	Preferred to work in lower Temp. Range to avoid Oxidation		"Sticky" characteristics of Tantalum require special cutting fluids (i.e. cutting oils dissolved in carbon tetrachloride or Trichloroethylene.)		-----Near Ideal - Maximum Reductions----- Before Anneals, ≈ 95%; for cold reductions; but requires special lubricants to prevent galling and welding in the dies.				Annealing - 1050°C to 1300°C-1400°C	Weldments by Resistance, arc, or other electrical methods; with provisions to prevent oxidation such as an inert atmosphere as in Heliarc welding.		(4), 1224 (59), (50) (3), 400-401
THORIUM	None	705°C to 955°C		Machining characteristics similar to mild steel		Can be cold worked to rather high reductions before annealing. (Forged at 749°C to 799°C for break-up initial cast structure).				Annealing- Bomb reduced - Th at 649°C to 749°C Iodide Th at 593°C to 699°C 1 hour at Annealing Temperature, followed by Slow cooling.	Welding results are erratic. Furnace Brazing methods unsuccessful. Spot welds for sheet 1/16" are sound. Resistance and Butt welds have been made (No data on Properties of welds).	Must protect metal from oxidation at all temperatures of working, by sheathing and/or inert atms.	(4), 1225 (8), 313,316
COBALT	Suitable at R.T.	Suitable		Machined, etc., after practice equivalent to Mild Steel.		Suitable cold after Swaged at 600°C	Suitable	Suitable for drawing to Fine wire-cold. Hot rolled at 1000°C in SAE 1020 sheath.	Suitable Hot or Cold. 4/1 Reduction Ratio obtained at 700°C with Metal Sheathed.	Annealing Time is lengthened due to Sluggish phase Reaction of Beta ⟶ Alpha at 417°C.	Weldment - All electric methods; and under protective inert Atmosphere Brazes - Similar to those for Nickel are suggested		(4) 1201 (8), 523,526
IRON	Suitable at R.T. for up to 97% reduction of area	Suitable, but not necessary, at 900°C		Metal is "gummy" and soft; with characteristics of seizing, galling, and work-hardening. To machine use equivalent Practice to tough Pitch copper.		Cold-suitable	After break-down of cast structure-cold-forge	Cold-Draw Pure Iron to very fine wire	Hot and/or Cold Suitability: Cold process preferred to prevent contamination.	Annealing Temperatures from 500°C - 900°C	Electron Beam Weld. Resistance-Weld Shielded Arc Weld Pure Iron Electrode Weld.		(4), 1212
NIOBIUM	Suitable at R.T.	Ingot Structure Break-down at 800°C - 1100°C	0.24	Machining characteristics similar to indicated pure Iron and tough Pitch Copper; corrected by depth of cut, cutting speed, and lubricants.		Required CARE in the selection of Dies and Lubricants for Cold-Swaging	Suitable Cold after break-down of cast structure.	Required care in selection of Lubricant and die material-Cold-forming operation	Remarks same as for Drawing-Cold	Maximum reduction between anneals. Recrystallization temperature for material 70 to 80% cold reduced, ≈ 1093°C with completion of Recrystallization in 1-hour.	Electron Beam welding; Brazing methods are currently experimental.	Problems of metal Seizure and Galling for extreme pressure forming methods.	(4), 1202 (4), 1203

TABLE 1.14 (Continued)

SELECTED PURE ELEMENTS AND TYPICAL FABRICATION CHARACTERISTICS

	Working Temperatures		Strain Hardening Exponent = n	Forming Characteristics Suitable For:						Other Characteristics			
	Cold- (Range) °Centigrade	Hot- (Range) °Centigrade		Machining	Turning	Swaging	Forging	Drawing	Extrusion	Heat Treatment	Joining	Remarks	References
CHROMIUM	"Ductile Chromium" per recent claims would indicate some ductility at R.T. or slightly greater	Con-ventionally: at 800°C - 1100°C and Sheathed.		Because of presence of sub-oxide formed at R.T. (skin); this metal is considered machineable after manner similar to Mo, W, etc.		Hot worked (at 800°C) in protective sheathing after conventional practice.				General lack of significant Room temperature and cold working processes reduces annealing to hot temperature working range.	Electron Beam method (Suggested) Solder-Silver solder with low melting point Silver brazing alloys; potassium fluoroborate reducing flame.		(4), 1201
HAFNIUM	Suitable at R.T. or greater and for limited reduction of area.	Con-ventionally at 1100°C; forging and extrusion, Ref (57) (927°C - 750OC)		Similar to Zirconium, with difficulties due to high rate of work - hardening, galling, build upon cutting edge, decreased tool life. Corrective measures are available.		Suitable at 1100°C for good finish-other finish - cold	Suitable at 1100°C for good finish but cold also.	Hot and/or cold best finish; perhaps hot-worked. 15-20% reduction per pass. 15 min. Reheat.	More difficult than Zr, but equal to Ti. Special Techniques.	Cold-worked Hafnium, should be annealed in Vacuo or an inert atmosphere at 700°C; for recrystallization. Heat Treatment - only for (Annealing and/or Stress Relief).	Electron Beam welding Butt welding with tungsten electrode.	Cold worked limited to about 7% reduction of area/pass; Anneal, after 30% reduction of area. Stress Relief at 800°C for 15 minutes.	(4), 1205 (3), 184 (58)
URANIUM	R.T.	at 500°C to 650°C		Conventional methods; using heavy cute and relatively high speeds. Lubricant is recommended to prevent serious burning of chips and/or work.		Cold and/or at 500°C to 600°C Reduction of (10-15% per pass for hot working are noted.	Successfully at 500°C to 650°C under Pro-tective atmos-phere.	Cold Drawn - Lubricant is critical factor, possible 20% Reduction per pass.	Extrusion are possible for Alpha, Beta, or Gamma, phases of U.	Common heat treatment and function is to obtain randomization of texture of wrought metal, by heating metal into the Beta phase (about 725°C) and quenching to R.T.	Welded by Heliarc and shielded arc consumable electrode process, (Electrode of U. wire). Braze and/or solder to silver or nickel plate on Uranium.	Anneal treatment, to eliminate hardening due to coldwork, at temperature of 770°C (Partial anneal at 150°C).	(8), 401 403,407-435 (4), 1226 (3), 521
ZIRCONIUM	R.T. Max. reduction between anneals of -30% to 50%	From 593°C to 1038°C	0.25 (annealed) 0.05, cold rolled	Possibly similar to Ti, Cu Niobium, etc. When ultra pure i.e. characteristics of seizing, galling and work hardening.		Hot and/or Cold reduction are feasible with the appropriate anneals for cold reduction working, and protective atmosphere or vacuo; 50×10^{-5} of Hg Extrusion at 800°C. Common practice to sheath Zr. In Iron or copper for hot working.				Annealing Temperature Range (500°C to 800°C)	Arc Welded, Heliarc Welded, Spot welded, Bent flat over small radius, riveted, cripped and Slotted (Used of protective atmosphere or Vacuo when required.		(4), 1228 (3), 614
OSMIUM	None	None		Not Workable Present state of the art indicates this metal to be unworkable: due in part to; (1) lack of purity (ease of forming oxide; (2) Structure, i.e. Hexagonal Close Packed.		Not Workable Present state of the art indicates this metal to be unworkable: due in part to; (1) lack of purity (ease of forming oxide; (2), Structure, i.e. Hexagonal Close Packed.					Shaped my melting and/or power metallurgical methods; will alloy as a hardener, for the precious metals. Therefore similar solders and Brazes are appropriate.	Osmium and Ruthenium are probably less developed in terms of required purity, then other precious metals.	(4), 1217 (3), 308 (17), 52

TABLE 1.14 (Continued)

SELECTED PURE ELEMENTS AND TYPICAL FABRICATION CHARACTERISTICS

	Working Temperatures		Strain Hardening Exponent = n	Forming Characteristics Suitable For:						Other Characteristics			
	Cold- (Range) °Centigrade	Hot- (Range) °Centigrade		Machining	Turning	Swaging	Forging	Drawing	Extrusion	Heat Treatment	Joining	Remarks	References
TITANIUM	Feasible Min. Bend Radius = (1t)	Preferred: at 871°C under Protective atmosphere		Use slow speeds, Heavy cuts, with adequate coolant to keep work cool and free of oxidation.		Feasible to Swage. Preferred at temp. above 260°C to 316°C to avoid cracking and spring back	Max. Temp. forging at 927°C	Max. Temp. for Rolling (871°C) Use special lubricants for Wire Drawing.	Similar to Stainless Steel. Tubes are formed by extrusion.	Annealing Temp. Range (593°C - 732°C) Stress Relief Temp. 538°C for 15 to 20 minutes, followed by air-cooling to R.T.	Arc-welded in a protective atmosphere. Spot welded. Resistance Seam welded. Flash welded. Brazing-Soldering In Development Stage.	Metal has characteristics of seizing and galling, which particularly affect machining characteristics.	(3), 479-480 (4), 1153 (8), 362,363
VANADIUM	Cold or R.T. reduction after breakdown of Cast (Structure)	1100 - 1150°C for initial break-down of cast structure. There after worked at 800°C - 1115°C.	Does not work harden appreciably	Free cutting metal, similar to copper. Use light lubricant with high cutting speeds and light Cut for good finish.		Suitable for all operations, either cold, or hot. Hot form operation requires inert atmosphere for protection from oxidation.				Recrystallization (Annealing) Temperatures $>$ 802°C to 1010°C. Grain Growth $\geqq$ 1010°C.	Electro-welding with adequate inert atmosphere protection. of weld zone. Heliarc with Argon shielding Soldering - (UNKNOWN)	Hot working requires shielding and/or inert atmosphere for protection against oxidation.	(4), 1227 (61) (3), 600

NOTES: (1) All fabrication processes, etc., are necessarily conducted under Environmental controls of extreme care, i.e. use of best techniques of inert atmosphere or vacuum to prevent contamination or alteration of purity of the specific elemental metal considered. Rare atmospheres employed should: have dew points of the order of liquid Nitrogen temperature; be free of all traces of organic vapors; be free of traces of N_2, and O_2, etc.

(2) All elements above, which appear unfeasible to form into desired shapes, by methods indicated, can be shaped by Powder-Metallurgical Methods and sintered to near final desired dimensions. Additional forming methods include (in principle), Electroforming, Vapor deposition, Vapor plating, etc.

(3) Electron Beam Welding Method of recent development, is considered a feasible Welding Method for most of the above pure elements.

TABLE 1.15

PRICES OF METALS

Alphabetical Order	$ per lb.
Aluminum	0.20
Antimony	0.29
Arsenic	0.70
Barium	13.50
Beryllium	100.00
Bismuth	2.25
Boron	318.00
Cadmium	2.00
Calcium	3.80
Cerium	12.00
Chromium	1.20
Cobalt	2.60
Columbium	59.00
Copper	0.30
Gallium	1360.00
Germanium	340.00
Gold	510.00
Indium	32.80
Iridium	2480.00
Iron	0.04
Lead	0.135
Lithium	10.00
Magnesium	0.27
Manganese	0.315
Mercury	2.50
Molybdenum	7.15
Nickel	0.60
Osmium	2040.00
Palladium	350.00
Platinum	1355.00
Rhenium	910.00
Rhodium	1820.00
Ruthenium	1165.00
Selenium	3.50
Silicon	430.00
Silver	12.40
Sodium	0.17
Strontium	22.50
Tantalum	41.20
Tellurium	1.50
Thallium	15.00
Tin	0.85
Titanium	6.00
Tungsten	15.00
Uranium	60.00
Vanadium	40.00
Zinc	0.10
Zirconium	10-15.00

Increasing Price Order	$ per lb.
Iron	0.04
Zinc	0.10
Lead	0.135
Sodium	0.17
Aluminum	0.20
Magnesium	0.27
Antimony	0.29
Copper	0.30
Manganese	0.315
Nickel	0.60
Arsenic	0.70
Tin	0.85
Chromium	1.20
Tellurium	1.50
Cadmium	2.00
Bismuth	2.25
Mercury	2.50
Cobalt	2.60
Selenium	3.50
Calcium	3.80
Titanium	6.00
Molybdenum	7.15
Cerium	12.00
Silver	12.40
Barium	13.50
Zirconium	10-15.00
Lithium	10.00
Tungsten	15.00
Thallium	15.00
Strontium	22.50
Indium	32.80
Vanadium	40.00
Tantalum	41.20
Uranium	50.00
Columbium	59.00
Beryllium	100.00
Boron	318.00
Germanium	340.00
Palladium	350.00
Silicon	430.00
Gold	510.00
Rhenium	910.00
Ruthenium	1165.00
Platinum	1355.00
Gallium	1360.00
Rhodium	1820.00
Osmium	2040.00
Iridium	2480.00

Increasing Price Order	$ per cu in.
Sodium	0.005
Iron	0.011
Magnesium	0.017
Aluminum	0.02
Zinc	0.028
Lead	0.055
Antimony	0.07
Manganese	0.084
Copper	0.10
Arsenic	0.145
Nickel	0.19
Lithium	0.19
Calcium	0.21
Tin	0.22
Chromium	0.31
Tellurium	0.338
Selenium	0.608
Cadmium	0.62
Bismuth	0.80
Cobalt	0.84
Titanium	0.97
Mercury	1.22
Barium	1.70
Strontium	2.11
Molybdenum	2.63
Zirconium	2.35-3.50
Cerium	2.94
Silver	4.70
Thallium	6.32
Beryllium	6.65
Indium	8.65
Vanadium	8.84
Tungsten	10.45
Columbium	18.26
Tantalum	25.40
Boron	26.90
Uranium	34.40
Silicon	36.00
Germanium	65.30
Palladium	152.00
Gallium	294.00
Gold	356.00
Ruthenium	513.00
Rhenium	695.00
Rhodium	820.00
Platinum	1050.00
Osmium	1665.00
Iridium	2020.00

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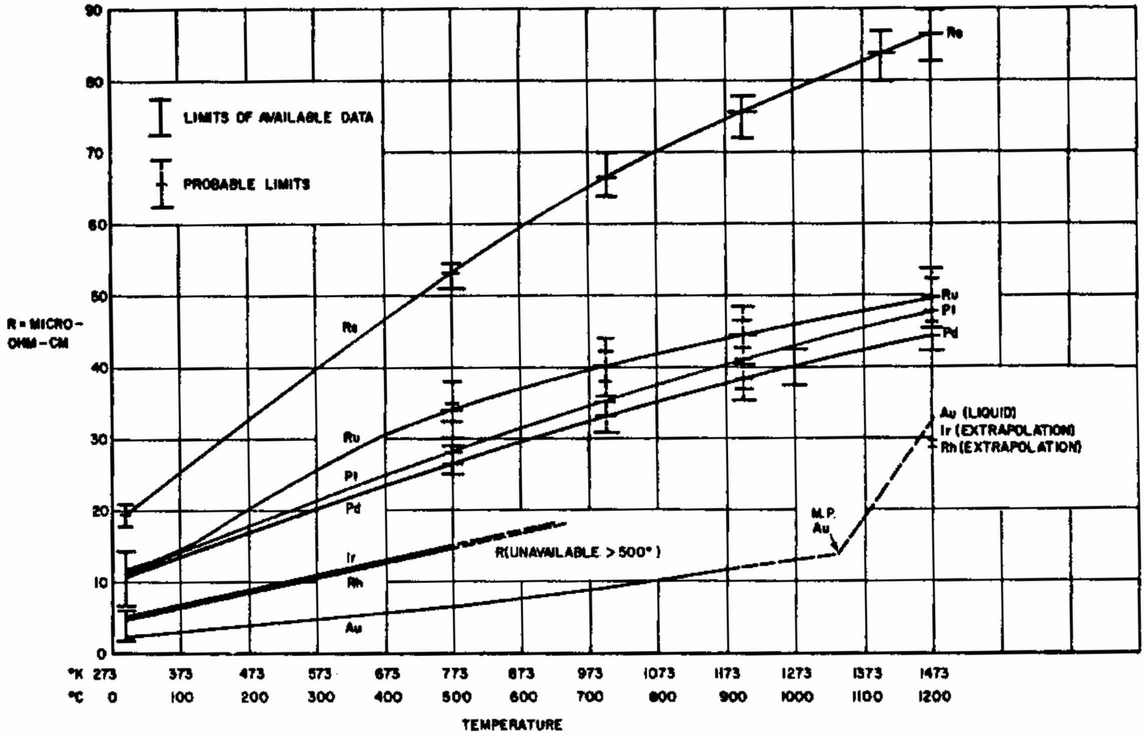


Figure 1. Resistivity of Selected Pure Elements vs. Temperatures

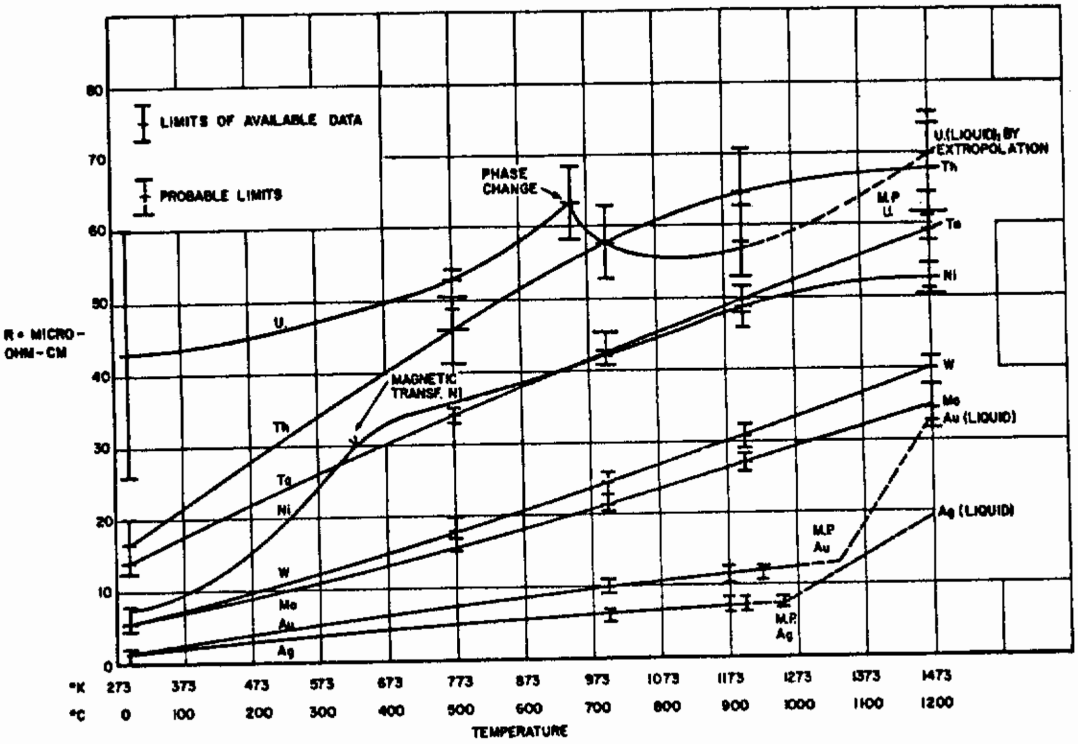


Figure 2. Resistivity of Selected Pure Elements vs. Temperatures

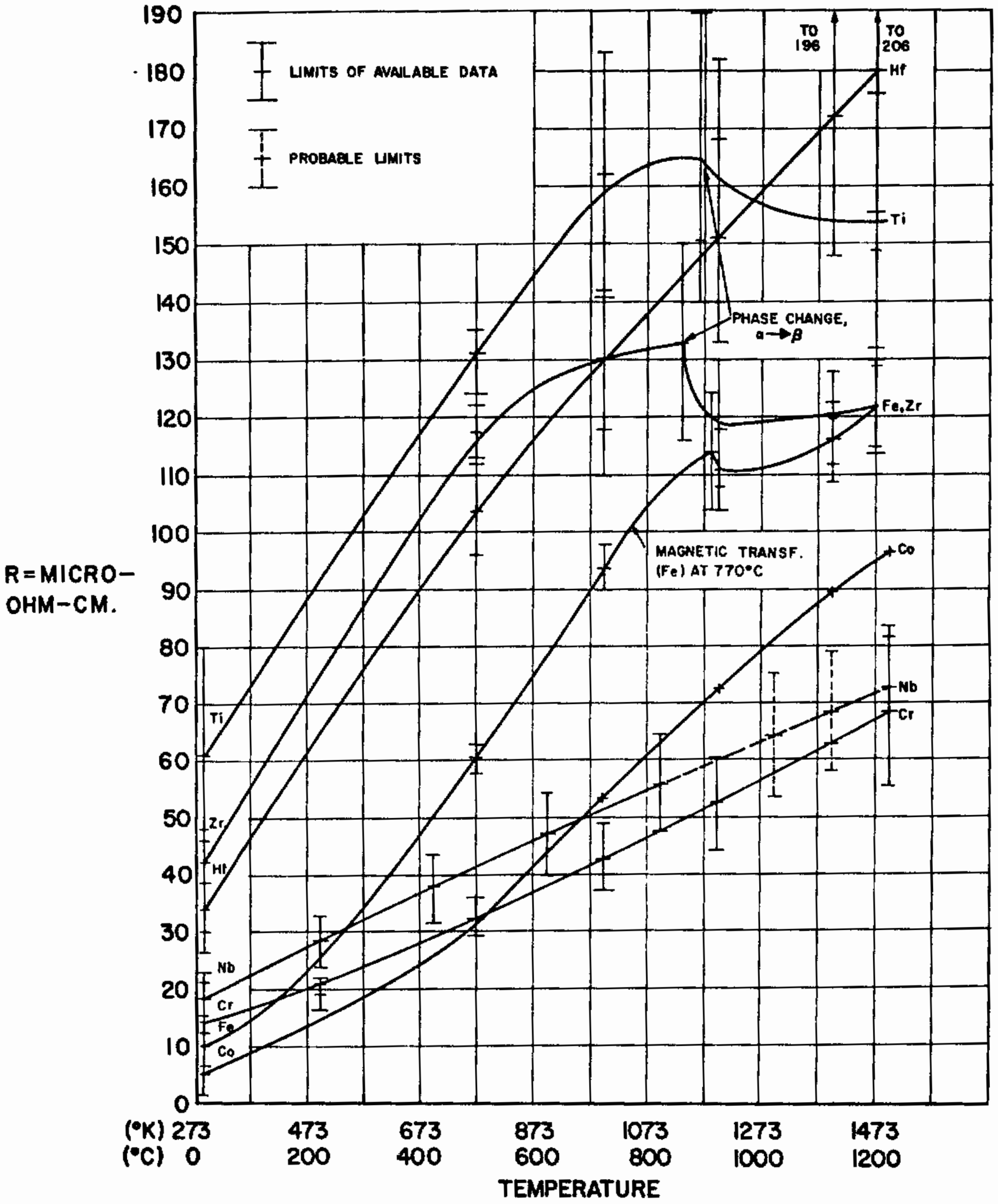


Figure 3. Resistivity of Selected Pure Elements vs. Temperatures

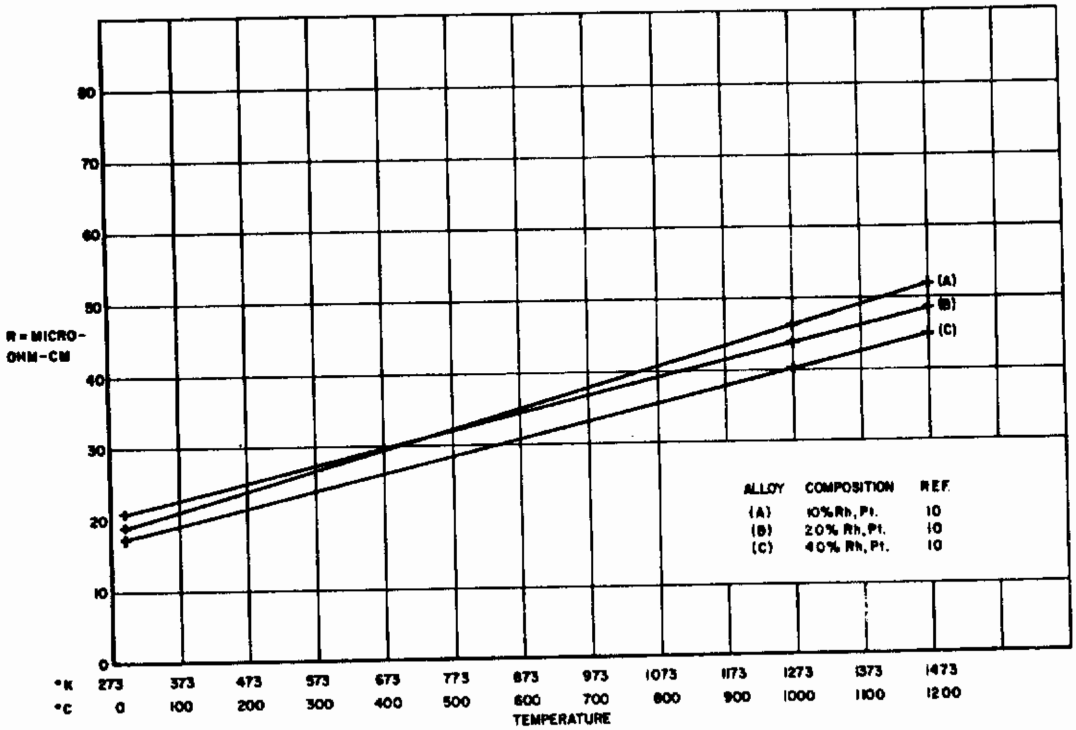
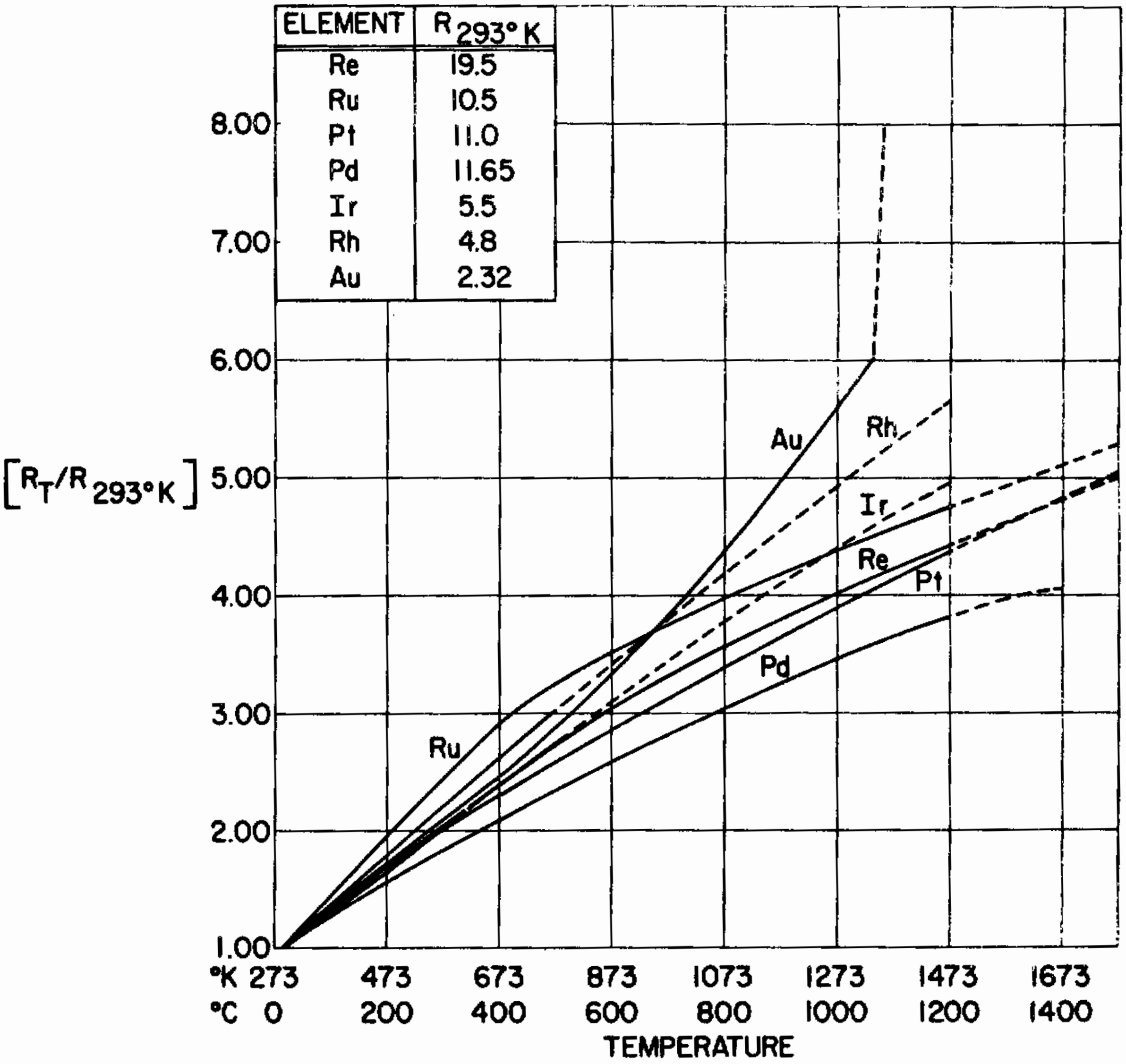


Figure 4. Resistivity of Selected Precious Metal Alloys vs. Temperature



ELEMENT	$R_{293°K}$
Re	19.5
Ru	10.5
Pt	11.0
Pd	11.65
Ir	5.5
Rh	4.8
Au	2.32

Figure 5. Relative Resistances of Selected Pure Metals vs. Temperatures

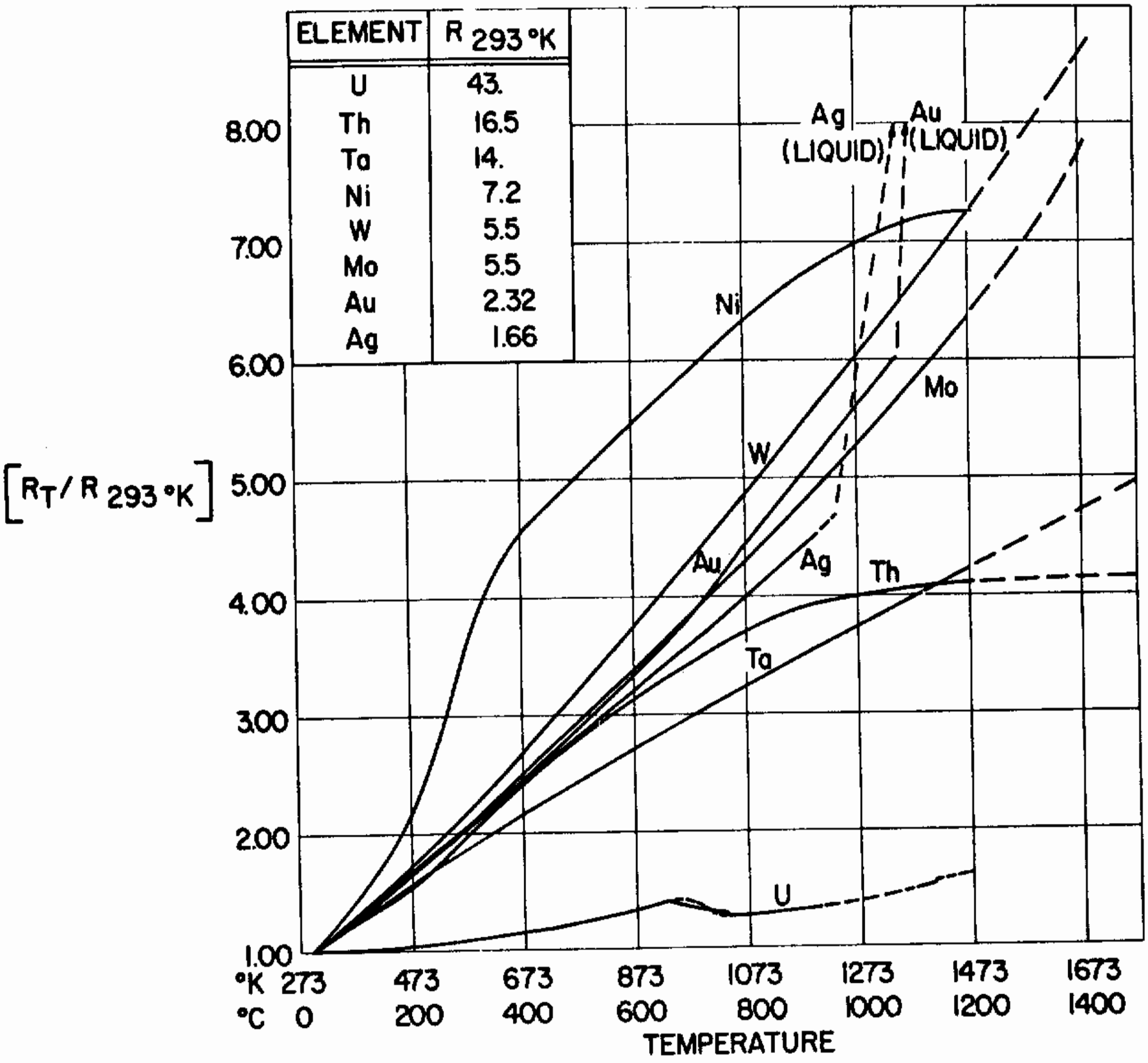


Figure 6. Relative Resistances of Selected Pure Metals vs. Temperatures

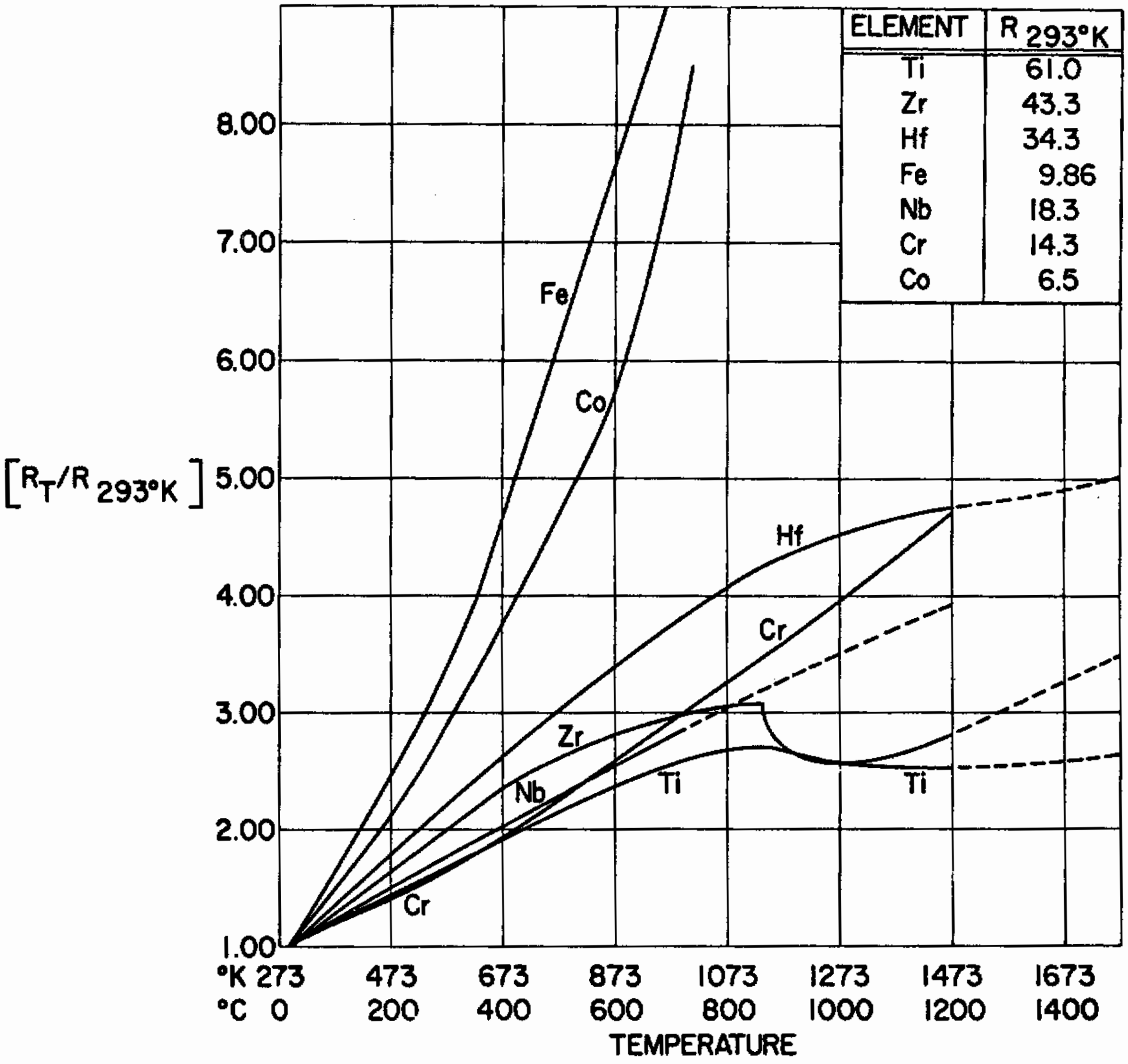


Figure 7. Relative Resistances of Selected Pure Metals vs. Temperatures

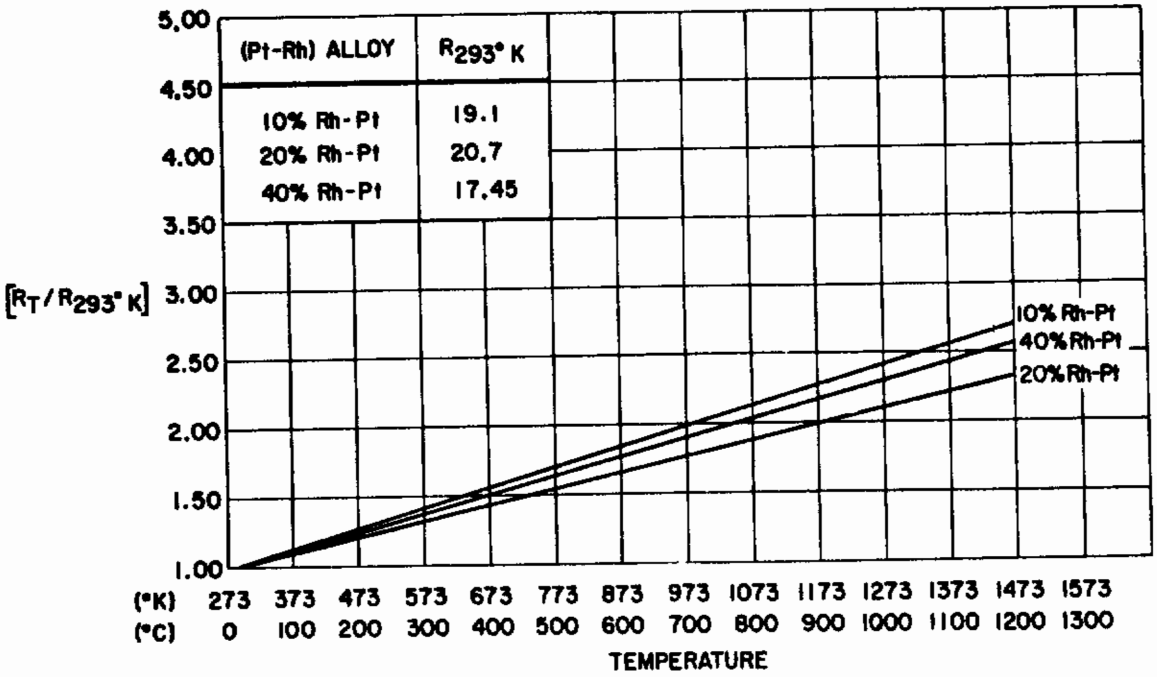


Figure 8. Relative Resistances of Selected (Pt-Rh) Alloys vs. Temperatures

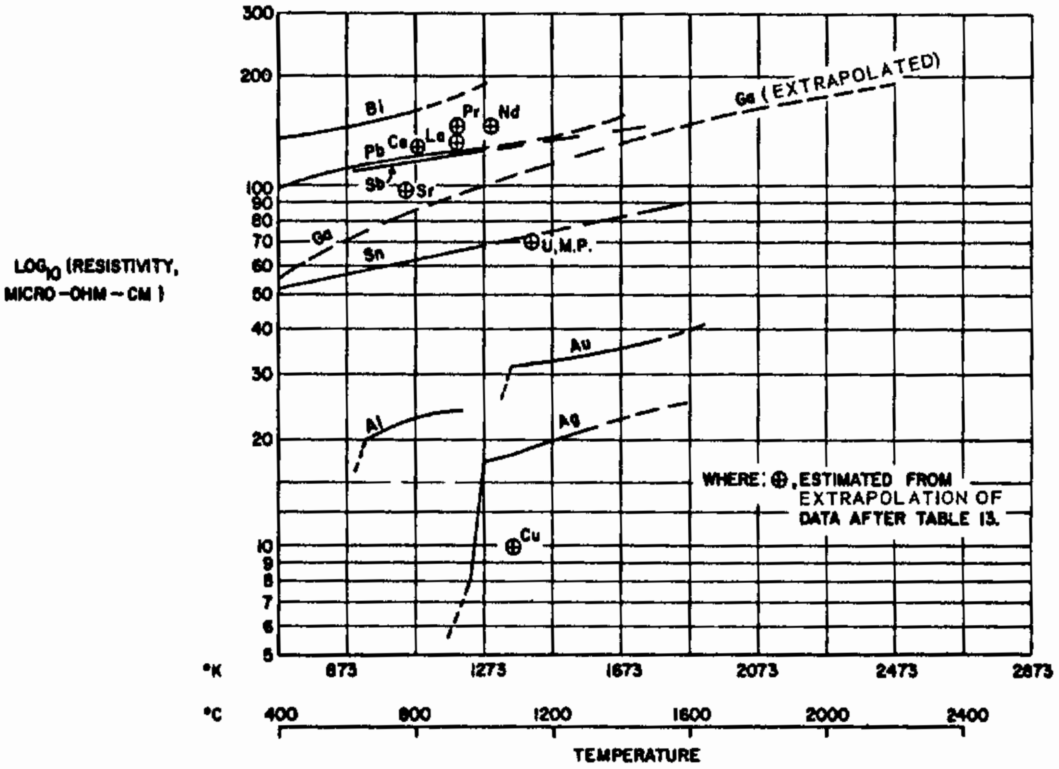


Figure 9. Electrical Resistivities of Selected Pure Liquid Metals

2. METALLIC ALLOYS AS HIGH TEMPERATURE CONDUCTORS

2.1 Introduction

2.1.1 General

In general, this study includes three types of conductors for high-temperature electrical conductor applications:

1. Pure metals
2. Metallic alloys
3. Metallic compounds

In the first section of this report, we showed that all pure metals were unsatisfactory in regard to one or more of three desirable qualities: (1) adequately high electrical conductivity; (2) adequately high oxidation resistance; and (3) adequate mechanical properties. General approaches to overcoming these limitations were discussed as follows:

a. Various systems for the mechanical support of high-conductivity, high-oxidation-resistant pure metals; and

b. General systems for the oxidation protection of mechanically supported pure metals.

In addition to the supported and oxidation-protected approaches to pure metals, there exists the possiblity of improving both the mechanical properties and the oxidation-resistance properties of pure metals of high conductivity by making suitable alloying additions, providing that the resistivity of the metal is not increased substantially beyond 25 microhm-cm at room temperature. This approach will be discussed in this section. The principal conclusion reached is that the most useful alloy systems for general use in the temperature range between 500°C and 1200°C are likely to be:

a. Those based on oxidation resistant metals Au, Pt, Pd, Rh and Ir (see preference scale for oxidation resistance in section 1.4.2) with alloying additions to improve their mechanical properties, but insufficient to cause the resistivity to exceed 25 microhm-cm room temperature;

b. Those based on Ag, Cu, Ru, Ni, Fe, Cr, Mo and W with alloying additions not only to improve their mechanical properties, but also to inhibit oxidation to reinforce or even eliminate the need for oxidation resistant coatings.

While the data compiled on metallic alloys in this report may seem extensive, it consists, however, of only a small fraction of the minimum amount of data required for proper analysis of possibly useful alloy systems. Due to a relative lack of interest in the electrical properties of metallic alloys in the past, especially at high temperatures, little basic data exists in this field. To quantitatively explore the areas in which no information exists, a thorough analysis has been made of Hansen's "Constitution of Binary Alloys." In table 2.1 are compiled the binary alloy systems in which either or both of the elements have a melting point of less than 1000°C, but which do not contain compounds of a melting point greater than 1000°C. A brief description is given of each system stating: (a) if compounds with melting points less than 1000°C exist; (b) if no compounds exist; (c) if the phase diagram is relatively simple or complex; and (d) if electrical data at room temperature or at elevated temperatures exist. The systems on which room-temperature resistivity data exists are underlined once. Those on which temperature variation data also exists are underlined twice. (For additional information on the binary systems presented, refer to "Constitution of Binary Alloys", 2nd Ed., McGraw-Hill Co. (1958) by Max Hansen, which was used as source material for this compilation.)

It will be observed from table 2.1 that some sort of electrical data exists in 40% of the systems considered; but this data is very seldom either for an extensive range of compositions or temperatures, and less often for both. Obviously, much work remains to be accomplished on the electrical properties of metallic alloys.

The relative scarcity of information concerning the electrical properties of alloys at room temperature, and more especially at elevated temperatures, is hardly surprising. First, the engineering interest in high-temperature conductors is only of recent origin except for studies on pure metals for resistance thermometers and alloys for resistors and switching contacts. The second reason is that scientific interest has been stimulated in the direction of low-temperature studies. This is because changes in resistance as a function of temperature at low temperatures is of much greater fundamental importance to the verification of solid-state theory of electron-phonon, and electron-impurity ion or electron-electron interaction. In addition, the temperature variation properties of metals above the Debye temperature is approximately in accordance with theory. This also applies to alloy not involving the transition metals. This is not the case for the absolute values of the resistivity, except in the case of the alkali metals. However, this latter discrepancy can only be removed by the interaction of theory and experiment; first, at low temperatures and second, at higher temperatures. Thus, low-temperature research is important to the elucidation of room-temperature and high-temperature conductivity data.

2.1.2 Theoretical

Resistance of Alloys; Dilute Solutions

Matthiessen's rule. The resistance of a metal which contains foreign atoms in solid solution is nearly always greater than that of the pure metal, the increase being, in many cases, considerable; if one atomic per cent of tin is added to copper (specific resistance at room temperature, 1.55 microhm-cm), the increase in its resistance is 2.6 microhm-cm.

As was first shown by Matthiessen (1), the increase in the resistance of a metal due to a small concentration of another metal in solid solution is, in general, independent of the temperature. This is shown in figure 10, where the resistance of copper, both in the pure state and with various small concentrations of other metals in solid solution, is plotted against temperature. Since the lines are parallel, the increase ρ_o is independent of temperature. (Mn is an exception.)

An alternative statement of Matthiessen's rule is that, if ρ is the resistivity of the alloy, $d\rho/dT$ is independent of concentration. Figure 11 shows $d\rho/dT$ plotted against the concentration for various metals in solid solution in gold. It will be seen that Co and Cr form exceptions to the rule.

The high resistance of alloys and Matthiessen's rule find a particularly simple explanation in the quantum theory of conductivity. An electron can move quite freely through a perfect lattice, which would consequently have no resistance. The resistance of a pure metal is due to the thermal agitation of the atoms, which destroys the periodicity of the lattice. When, moreover, a foreign atom is present in solid solution, the periodicity of the field within the lattice is broken at that point. Thus electrons may be deflected by that atom and a resistance will arise, even in the absence of any temperature agitation.

The resistivity of a metal may be written

$$\rho = \frac{m}{Ne^2}\frac{1}{\tau}, \tag{1}$$

where N is the (effective) number of electrons per unit volume, and $1/\tau$ the number of times per second that an electron is deflected. Let $1/\tau_o$ be the number of times per second that an electron is deflected by a foreign atom, and $1/\tau_T$ the number of times that it is deflected owing to the thermal oscillation of the atoms; then

$$\frac{1}{\tau} = \frac{1}{\tau_o} + \frac{1}{\tau_T}, \tag{2}$$

Thus we may write for the resistivity

$$\rho = \rho_o + \rho_T \tag{3}$$

where

$$\rho_o = \frac{m}{Ne^2}\frac{1}{\tau_o}, \qquad \rho_T = \frac{m}{Ne^2}\frac{1}{\tau_T} \tag{4}$$

ρ_o is equal to the resistance of the alloy at the absolute zero temperature, and is independent of temperature; ρ_T will be approximately proportional to the temperature, as for a pure metal.

Matthiessen's rule is satisfied if

1. The effective number of free electrons is unaltered by the addition of foreign atoms.

2. The thermal vibrations of the foreign atoms give the same scattering as those of the atoms of the solvent metal. Neither of these conditions will be fulfilled exactly, but we should expect the change of ρ_T due to the admixture of, say, 1% of the foreign metal to be of the order 1%, while the change in ρ_0 may be very much greater.

As we have seen, the resistance ρ_0 of an alloy at the absolute zero is due to the break-down in the periodicity of the field in the lattice. This may be due to two causes: the lattice may be distorted by the foreign atom, the neighbouring atoms being pushed out of position; or, even if this does not occur, the field within the foreign atom will be different from what it would be at that lattice point in the pure metal. The latter effect is, in general, the more important and is the only one which will be considered here. An estimate of the increase in the resistance due to distortion has not, at present, been made. It is then important to remember that the extra resistance is due to the difference between the fields in the two atoms.

Theoretical calculation of the increase ρ_0 in the resistance of a noble metal due to foreign atoms in solid solution

If it is assumed that ρ_0 is due to scattering by the foreign atoms, Mott (5 - chapter 7) has shown that

$$\rho_0 = \frac{m}{Ne^2} \frac{VX}{\Omega_0} A, \qquad (5)$$

where A is the effective area presented by each foreign atom (i.e. the collision cross section of the scattering imperfection), v is the electron velocity, and Ω_0 is the atomic volume. For A is obtained, subject to certain assumptions (5),

$$A = \int_0^{\pi} (1-\cos\theta) \left| \frac{2\pi m}{h^2} \int \psi_k^* U \psi_k dr \right|^2 2\pi \sin\theta \, d\theta \qquad (6)$$

where U is the difference between the potential in the dissolved and solvent atoms. In the perturbation method used in obtaining this equation, U was assumed to be small. The method is the same as Born's approximation in ordinary collision theory, which is known to give incorrect results for slow electrons and heavy atoms (2); for such problem, the exact method, due to Faxen and Holtsmark,(3) must be used. In our problem, therefore, the perturbation method should give fair results for pairs of atoms, such as copper and zinc, with nearly the same atomic numbers, but not for pairs such as copper and gold.

A method analogous to that of Faxen and Holtsmark, and applicable when both dissolved and solvent metals are monovalent, has been given by Mott(4). Let u(r) be the wave function for an electron in the lowest state in the solvent metal (i.e. the wave function satisfying the boundary condition $\partial u / \partial n = 0$ at the boundary of the atomic polyhedron(5 - chapter II). Let E_0 be the corresponding energy. The wave function of any other state k may be written (5), to a fair approximation, in the form

$$\Psi_k = u(r)e^{i(kr)} \quad , \qquad (7)$$

with energy

$$E_k = \hbar^2 k^2/2n + E_o \qquad (8)$$

Now consider one of the dissolved atoms: an atomic polyhedron may be drawn surrounding this atom, and a solution u'(r) of Schrodinger's equation obtained such that $\partial u'/\partial n$ vanishes over the surface of the polyhedron. Let E_o' be the corresponding energy. The wave function within the atomic polyhedron of the dissolved atom for energy E_k is then, to the same approximation,

$$u'(r)e^{i(kr)} \qquad (9)$$

where

$$k'^2 = \frac{2m}{\hbar^2}(E_k - E_o') = k^2 + \frac{2m}{\hbar^2}(E_o - E_o').$$

We consider now the wave function of an electron of energy E_k moving in the field of the lattice as a whole. The wave function must consist of terms of the type (equation 7) outside and of the type (equation 9) inside the atomic polyhedron of the dissolved atom. In other words, the wave-length $2\pi/k$ will be different inside and outside the dissolved atom.

Both the wave function itself and its gradient must be continuous over the boundary of the polyhedron. These boundary conditions are already satisfied by the functions u(r), u'(r). We have, therefore, only to consider the exponential terms in the wave functions, $e^{i(kr)}$ and $e^{i(kr)}$.

We wish to know the probability that an electron is deflected by the dissolved atom. We therefore require a wave function, which, at large distances from the dissolved atom, takes the form of an incident wave and a scattered wave. The problem is therefore the same as that which arises in investigating the scattering of a beam of free electrons by a field with potential:

$U = (E_o - E_o')$ within the atomic polyhedron

$= 0$ outside the atomic polyhedron.

The solution of this problem is well known; in the cases considered here $|E_o - E_o'| \ll 1/2mv^2$, so that the problem may be treated by Born's approximation. We obtain (5) for the effective scattering area presented by each foreign atom to the beam of oncoming electrons

$$A = 0.86\pi r_o \left(\frac{E_o - E_o'}{E_{max}}\right)^2 \qquad (10)$$

Here r_o is the 'atomic radius' and $E_{max} = 1/2mv^2$, the energy of the electrons with the maximum energy in the Fermi distribution. The increase in the resistance of a metal due to the admixture of 100x per cent of another metal in solid solution is thus given by equations (5) and (10).

The following table gives the observed(6) increase ρ_o in the resistance of copper, silver, and gold due to the admixture of 1 percent of these metals. We show also the atomic volumes. Ag and Au have the same atomic volume, and hence the same values of E_{max} and r_o. Equation 10 therefore predicts that ρ_o will be the same for 1 percent of silver in gold as for 1 percent of gold in silver. The table shows that this is in agreement with experiment.

Increase of Resistance in Microhm-cm

Due to	in Cu	in Ag	in Au
1 percent of Cu		0.068	0.485
1 percent of Ag	0.14		0.38
1 percent of Au	0.55	0.38	
Atomic volume, cm^3 per gm atom	7.1	10.3	10.3

Dependence of resistance on the properties of the solvent and dissolved metals (dilute solutions)

Norbury,(7) in a paper published in 1921, has summarized the experimental material available at that date. Of the work carried out since then, we shall frequently refer to that of Linde(8) on the resistance of dilute solid solutions in Cu, Ag, and Au.

Norbury(7) was the first to point out the connection between the increase in resistance ρ_o and the valencies of the solvent and dissolved metals. If the metals have the same valency, the resistance ρ_o due to one atomic percent of one metal dissolved in the other will be small; if the valencies are different, it will be large. Figures illustrating this are given in Norbury's paper. Linde(8) has found a numerical relationship between the increase of resistance of a noble metal due to the admixture of 1 percent of a foreign metal and the valency of the latter. This is illustrated in figure 12. If z + 1 is the number of electrons outside a closed d shell in the dissolved atom, and one the number in the solvent, Linde finds that ρ_o is proportional to z^2.

The results of Linde have a simple theoretical explanation(9). The core of a solvent atom carries a positive change (+ e). The core of the dissolved atom carries a positive charge (+ (z + 1) e), which is greater by ze than for an atom of the solvent metal. It is the field of this extra charge that must be regarded as causing the scattering of the electrons, and hence the resistance ρ_o. But, by the Rutherford scattering law, the intensity of the scattering is proportional to the square of the scattering charge, and hence to z^2. It follows that ρ_o is proportional to z^2.

To obtain a numerical estimate of the resistance we must know the field round the charge. It will not be correct to take the field of a bare positive charge ze, because (5 - Chapter II) the charge is screened by the surrounding electrons. An unscreened charge would actually give an infinite resistance as shown by equation (12). If we take for the potential

$$V(r) = \frac{ze^2}{r} e^{-gr}, \tag{11}$$

and assume that the electrons behave as if they were free, then the scattering probability may be calculated using Born's approximation, equation (6), and we obtain for the resistance due to 1 percent of the foreign metal in solid solution

$$\rho_o = \frac{1}{100} \frac{2\pi z^2 e^2}{mv^3} \left\{ \mathrm{Log} \left(1 + \frac{1}{y} \right) - \frac{1}{1 + y} \right\}, \tag{12}$$

where

$$y = q^2 \hbar^2 / 4m^2 v^2 .$$

v is here the velocity of the electrons. Agreement with experiment may be obtained by calculating v from the Sommerfeld equation (5 - Chapter II) and taking $1/q \sim 0.3$ Å.U. This is somewhat less than the value obtained by the Thomas-Fermi method (5 - Chap. II), which may perhaps be due to the errors inherent in that method.

Increase of resistance of pairs of metals

With two metals A and B which are mutually soluble in one another, it is interesting to compare the increase ρ_A in the resistance of A, due to one atomic percent of B in solid solution, with the increase ρ_B, due to one atomic percent of A dissolved in B. If the two metals A and B have the same atomic volume, the same crystal structure, and the same effective number of free electrons, we should expect ρ_A and ρ_B to be equal, as already stated in the discussion of Cu, Ag, and Au. The following table shows the extent to which this prediction of the theory is fulfilled:

Change in specific resistance ρ_o (microhm-cm) due to one atomic percent of the first-named metal dissolved in the second(5)

Ratio of atomic volume of first-named metal to second		ρ_o		ρ_o
0.54	Na in K	1.3	K in Na	0.95-1.1
0.70	Cu in Au	0.485	Au in Cu	0.55
0.70	Cu in Ag	0.068	Ag in Cu	0.14
1.01	Ag in Au	0.38	Au in Ag	0.38
1.17	Mg in Cd	0.40-0.45	Cd in Mg	0.5-0.6
0.97	Pd in Pt	0.55-0.60	Pt in Pd	0.7

The case of Mg and Cd is interesting, the metals having quite different corrected conductivities $\sigma/M\Theta^2$. The data (5) for the two elements are as follows:

	Mg	Cd
$\sigma/M\Theta^2$	1.25	0.47
Atomic volume $cm^3 \times 10^{24}$	23.2	19.8

The fact that ρ_0 is the same for both seems to be good evidence that the higher resistance of pure cadmium is not due to the effective number of free electrons, but to some other cause, e.g., the size and scattering power of the ions.

If we compare a monovalent with a divalent metal, we find, using the limited data available, that the increase is greater in the divalent metal, as the following table shows(5):

	Microhm-cm		Microhm-cm
Mg in Ag	0.8-1.3	Ag in Mg	3.0-3.5
Cd in Au	0.64	Au in Cd	1.7-1.9

It has been suggested that this is due to the same cause as the drop in the conductivity in passing from a monovalent to a divalent metal, namely the smaller 'effective number of free electrons' in a divalent metal.

Finally we consider alloys of the transition metals with copper or silver or gold. The following are some of the values(5):

Pd in Cu	0.89	Cu in Pd	1.27
Pd in Ag	0.436	Ag in Pd	1.4
Pd in Au	0.407	Au in Pd	1.0
Ni in Cu	1.25	Cu in Ni	1.0
Pt in Ag	1.59	Ag in Pt	(2.3)
Pt in Au	1.02	Au in Pt	1.55

In considering these values we must remember that, for dilute solid solutions of Cu, Ag, or Au in Pd or Ni, transitions from the s to the d band will not be possible for the following reason: the transition probability(5) is proportional to

$$\left| \int \psi_d \, U \, \psi_s \, d\tau \right|^2, \qquad (13)$$

where U is the perturbing potential. Now this perturbing potential is only finite within a foreign atom, i.e., one of Cu, Ag, or Au. But certainly in a silver atom, and almost certainly in one of Cu and Au, the d shell is full; the wave function of any empty d state will have very small amplitude within any of the dissolved atoms. Thus the quantity given by equation (13) will be small.

It follows that, so far as the resistance of dilute solid solutions is concerned, only the s electrons need be taken into account in calculating the resistance, and we should not expect any striking difference between the values given in the two halves of the table above.

One might perhaps explain the rather larger values of ρ_0 for a noble metal in Pd than for Pd in a noble metal by the small number (~ 0.55) of s electrons per atom in Pd compared with one in the noble metal. The similarity of the orders of magnitude of the numbers in the two columns of the above table shows, in any case, that the low conductivities of these transition metals are not due to an abnormally small effective number of free electrons. Iron may be an exception since there appear to be only 0.2 conduction or s electrons per atom. We should therefore expect the increase in the resistance of iron due to foreign atoms in solid solution to be abnormally high.

Resistance of alloys with concentration of both components comparable

In this discussion we shall assume that the alloy under consideration consists of a single phase, i.e., that all the small crystals of which it is built up have the same composition and crystal structure. This is not the case for any range of composition for Sn-Pb, Sn-Zn, Sn-Cd, Cd-Zn, which are insoluble in each other. Also in the brasses Cu-Zn, and in many other alloys, there are ranges of composition for which the alloy consists of a mixture of two phases.

As previously explained, we may, from the theoretical point of view, divide up the resistance of an alloy into two parts

$$\rho = \rho_0 + \rho_T. \qquad (14)$$

ρ_T is due to the thermal vibration of the atoms, as for a pure metal; ρ_0 is due to the fact that, in a disordered alloy, the lattice field is not periodic.

In alloys such as Ag-Au, which do not form any superlattice, ρ_0 is independent of temperature. (Certain alloys(10) such as CuNi (constantan), are exceptions). We may therefore equate ρ_0 to the resistance at the absolute zero of temperature. In alloys such as Cu-Au, however, the degree of order in the lattice depends on temperature, and hence ρ_0 depends on temperature(5).

A theory of the resistance of a completely disordered alloy is given in the next discussion. For a completely ordered alloy, ρ_0 should, in theory, vanish. Actually, the residual resistance found by extrapolation to the absolute zero is found to be much smaller than the disordered alloy(11).

For a partially ordered, alloy no theory has yet been given; the assumption made by Bragg and Williams(12) is purely for simplicity.

The term ρ_T in the resistance is, in general, linear in T. Hence we may write, assuming that no superlattice is in process of formation,

$$\rho_T \simeq T \frac{d\rho}{dT} \tag{15}$$

Resistance of a totally disordered alloy(13):

We shall suppose that the structure remains unchanged through the whole range of composition, and that no superlattice is formed (examples Ag-Au, Pd-Pt). Let the alloy consist of two kinds of atom, A and B, present in the ratio x: (1-x), and suppose that in the crystal the potential energy of an electron in the neighbourhood of an atom of A is $V_A(r)$ and in the neighbourhood of B is $V_B(r)$. As we have seen, an electron can move quite freely through a periodic field, and will only be scattered when deviations from periodicity occur; the greater the deviations from periodicity the greater will be the probability of scattering. For dilute solid solutions (x small), we have supposed previously each A atom to represent a break in the periodicity of the perfect lattice of B atoms; but in the present case, where x and (1-x) are comparable, it is clearly necessary to take for our perfect lattice the periodic field which resembles most closely the actual field, and to regard deviations from periodicity as arising both in A and B atoms.

We therefore take for our periodic field the field for which the potential in each atom is

$$V = xV_A + (1-x)V_B. \tag{16}$$

In each A atom the divergence from this potential is

$$V-V_A = (1-x)(V_B - V_A), \tag{17}$$

and in each B atom

$$V-V_B = x(V_A - V_B). \tag{18}$$

The probability per unit time that an atom will be scattered by any one atom A atom will therefore(5) be proportional to

$$(1-x)^2 \left| U \right|^2, \text{ with } U = \int \psi_k^* (V_B - V_A) \psi_k \, dr, \tag{19}$$

and by any B atom $x^2 \left| U \right|^2$.

Since there are x of the A atoms and (1-x) of the B atoms, the total probability of scattering is proportional to

$$\left[x(1-x)^2 + (1-x)x^2\right]\left|U\right|^2 = x(1-x)\left|U\right|^2. \qquad (20)$$

It follows that, if the atomic volume, crystal structure, and number of free electrons remain constant throughout the range, the resistance ρ_0 of the alloys at the absolute zero depends on the composition according to the formula

$$\rho_0 = \text{const } x(1-x). \qquad (21)$$

Figure 13(a) shows measurements of the resistance of Ag-Au and of Pd-Pt. In both cases the curves lie very close to the theoretical form given by equation (21). Figure 13(b) shows a similar curve obtained when the resistances of the two pure metals (In and Pb) differ considerably.

The form of the curve of ρ_0 (resistance extrapolated to the absolute zero) plotted against atomic composition for alloys of the ferromagnetic and strongly paramagnetic metals(5) Ni, Pd, Pt with Cu, Ag, and Au is strikingly different from that of the curves illustrated in figure 13(a) and (b). A typical example is shown in figure 13(c). The type of curve may be explained as follows(14):

In these alloys, the d band in the transition metals is incomplete for all percentages of the noble metal up to about 60 percent. It has been explained that the resistance of a transition metal is mainly due to transitions in which the electron jumps from the s to the d band, but that isolated atoms of Cu, Ag, or Au dissolved in the metal cannot cause such transitions, because within the dissolved atom the d states are full. But, for nearly equal compositions, both kinds of atom act as scattering centers. Taking, for instance, the case of Ag-Pd, and denoting by 1-x the atomic proportion of Pd in the alloy, we see from equation (17) that the perturbation in the mean periodic field (equation (16)) represented by any Pd atom is proportional to x, and thus the scattering probability to x^2. The transition probability from an s state to a d state due to the (1-x) Pd atoms will therefore be (5)

$$(1-x)x^2 N(E_{max}) \left| \int \psi_d \, (V_A - V_B) \, \psi_s \, dr \right|^2 , \qquad (22)$$

where N(E) is the density of states in the d band.

We may take the variation of N(E) to be the same as the variation of the paramagnetic susceptibility with concentration x. This is given approximately by(5 - Chapter 6)

$$\text{const.} \ (p - x)^2, \qquad p \simeq 0.6. \qquad (23)$$

Hence, finally, the probability that an s ⟶ d transition takes place, considered as a function of x, is proportional to

$$(p - x)^2(1-x)x^2. \tag{24}$$

The probability of an s-s transition will be proportional to x(1-x) as before, so that the resistance will be proportional to

$$A(p-x)^2(1-x)x^2+B(1-x)x, \tag{25}$$

where A and B are constants.

Figure 14 shows the form of this curve with arbitrary values of A and B. This figure should be compared with the experimental curves of figure 13(c).

We give, finally, a justification(5 - Chapter 7) of the assumption made throughout the discussions that the resistances due to disorder and to thermal agitation are additive (equation (14)). If an atom A in a disordered alloy is displaced a distance X from its mean position, the probability that an electron will be caused by that atom to make a transition from a state k to a state k' will be proportional to a term of the type

$$\left| \int \psi^*_{k'} \left(U - X \frac{\partial V_A}{\partial x} \right) \psi_k \, d\tau \right|^2 \tag{26}$$

we have assumed that this may be replaced by

$$\left| \int \psi^*_{k'} U \, \psi_k \, d \right|^2 + X^2 \left| \int \psi^*_{k'} \frac{\partial V_A}{\partial x} \, \psi_{k'} \, d\tau \right|^2 \tag{27}$$

Since U is approximately spherically symmetrical and $\partial V_A/\partial x$ is of the form f(r) cos θ, this is justified if we may assume for $\psi_k(r)$ the form $e^{i(kr)}$ u(r) with u(r) spherically symmetrical; for then it may easily be shown that the matrix element of U is real and that of $\partial V_A/\partial x$ imaginary. It must be remembered that the theorem is not exact.

Temperature coefficient of resistance of alloys

As has been stated, the quantity

$$\rho_T = T \frac{d}{dT} \tag{28}$$

is approximately equal to that part of the resistance of an alloy which is due to the thermal agitation of the atoms, that is, to the same cause as the resistance of a pure metal.

For pairs of metals with similar electronic structure, such as Ag-Au, Pd-Pt, we should expect ρ_T plotted against atomic composition to give approximately a straight line. Figure 15 shows this to be the case for Ag-Au. The deviations shown in the same figure for Pd-Pt may be compared with those for the paramagnetic susceptibility of the same series of alloys (5 - figure 85). According to magnetic theory(5 - Chapter 6 and 7), both ρ_T and the susceptibility are proportional to the density of states N(E) in the d band.

Figure 15(b) shows also ρ_T for the Au-Pd series of alloys; it will be seen that it falls sharply to a value comparable with that of pure gold at an atomic composition of about 50 percent Au. At a composition of 55 percent Au, the incomplete d shells in the Pd atoms become full. The form of the curve is, thus, direct evidence that the high resistance of a transition metal is due to the presence of incomplete shells, and hence lends support to the hypothesis that the resistance is due to electrons making transitions from the s band to the d band. (Rosenhall(15) has found that the addition of hydrogen to Pd-Ag alloys, which we know fills up the positive holes in the d band, also decreases the total resistance.)

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2.2 Technological Principals

2.2.1 General

The most important general requirements for high temperature conductors may be summarized as follows:

The alloying addition must be such as to produce an alloy with:

1. a sufficiently high electrical conductivity in the solid state at temperatures as high as required up to 1200°C and a smooth and sufficiently small conductivity variation with respect to temperature.

2. a high solidus temperature, and electrical annealing temperature to ensure electrical and mechanical stability.

3. Good oxidation resistance or capability of being protected from oxidation by an oxidation resistant coating.

4. Good mechanical properties at elevated temperatures including a low enough creep rate, high enough yield strength and sufficient ductility.

These requirements are, to some extent, always mutually conflicting. The problem of the alloying approach to high temperature conductors is essentially to optimize the above desirable characteristics relative to the specific requirements of a given application.

We briefly summarize the general principals which can be used by technologists to achieve the ends summarized in 1 to 4 above.

2.2.2 Electrical Properties

In the theoretical sections on alloys (2.1.2 and 2.4.1) the following rules governing the electrical properties of dilute substitution alloys have been presented, and discussed in detail.

I. Matthiesen's Rule: The increase in the resistance of a metal due to small quantity additions of a different metal is generally

$$\rho = \rho_o + \rho_T$$

where ρ_o is independent of temperature but ρ_T is dependent on temperature.

II. Linde's Rule: The resistivity increase in a noble metal due to small percentage (1%) of a foreign metal is proportional to the square of the valency of the foreign metal.

$$\Delta\rho = (k)\ (z)^2$$

III. Norbury's Rule: States that the atomic resistivity due to dilute alloy additions is proportional to the square of the difference of the atomic numbers of the solvent and solute elements

$$\Delta\rho = K_2 + K_1 (z_m - z_1)^2$$

where = resistivity increase due to the impurity addition

z_m = atomic number of the solvent metal

z_1 = atomic number of the solute metal

and K_1 and K_2 are constants for a given solvent for each period from which the solutes were taken

(The resistivity increase of transition metals dissolved in copper, silver or gold deviates from Norbury's Rule).

IV. Dellinger's Rule: The conductivity of a dilute alloy at a temperature (T_1) is proportional to the temperature coefficient of resistivity (α) for that alloy at temperature (T_1).

$$(T_1 \text{ alloy } 1) = B\alpha(T_1 \text{ alloy}_1)$$

V. The Mathiessen-Borelius Law: For a given ratio of the components in a binary alloy, the difference between the observed resistivity and that calculated from the resistivities of the components is temperature independent.

VI. Le Chatelier - Guertler's Rules:

1. The electrical conductivity and its temperature coefficient for heterogeneous mixtures of two phases varies linearly with the composition measured in volume percent.

2. The electrical conductivity and its temperature coefficient for solid solutions are always below those for the solvent metal, and, for continuous solid solutions, the conductivity is a U-shaped curve in the conductivity composition diagram.

(Data supporting these rules are discussed in the theoretical sections (2.1.2 and 2.3.1) on alloys.)

Conductivity temperature relations of alloys may differ markedly from those encountered for pure metals at temperatures above the Debye temperature. In particular, alloys involving the transition metals and alloys having crystallographic or magnetic transformations show such deviations. Such effects are sometimes sensitive to very small additions of the solute.

The only exception to the general rule that alloy additions increase the resistivity of the pure metal might be expected to be found for certain transition metals alloys. Instances of ρ_T being lowered by filling in the d-band have been discussed in section 2.1.2. However, except in the case where hydrogen was used to dope Pd-Ag alloy by Rosenhall(15) the total resistivity increase with alloying since the increase in ρ_o due to the alloying exceeds the decrease in ρ_T due to the filling in of the d-band. Little work has been done with polyvalent additons to transition metals. It is possible that ρ_T may be more substantially reduced by such additions since more electrons per atom should be available for filling in the d-band.

2.2.3 Oxidation Resistance

General

The oxidation resistant types of alloys (other than types involving protective coatings or scales) are dependent upon the degree of chemical inertness of the solvent metal for oxygen. An oxidation-resistance preference scale for solvent metals is naturally the same as that derived and discussed for pure metals in sections 1.3.4 and 1.4.2. This scale is as follows:

a. Au, Pt;

b. Pd, Ir, Rh, Os; Ag (above 200°C)

c. W, Ta, Nb, Re, Ri, Cu, Ni, Mo, Th, Co, Fe, V, Cr, Hf, Zr, U, and Ti.

The above scale, especially a and b, is also an approximate preference order of solvent metal for alloying for desirable combined characteristics of electrical conductivity and oxidation resistance (except for Ag).

Alloys which develop self-healing or other types of oxidation-resistant coatings or "scales" are less preferable than alloys based on the noble metals. Desirable oxidation-resistant scales (e.g., Al_2O_3, Cr_2O_3, ScO_2) have low conductivities which may approach values for dielectric materials. Such alloys, with or without the protective oxide coating, may serve as rigid structures with surface conductivity increased by a suitable coating of a noble metal.

Selection of specific hardening methods to be discussed, (which may include more than one in a combination) may also provide oxidation resistance.

Oxidation resistance of alloys may be conveniently classified into three general types:

Type I is that type of oxide formed which has a higher dissociation pressure than the partial pressure of oxygen in air at the oxidation temperature.

Type II is that type of alloy which exhibits a parabolic type of rate of oxidation.

Type III are those alloys of oxidation resistance characterized by a linear growth rate.

Specific examples of oxidation resistance governed by these three types of oxidation characteristics are now discussed.

Type I. Noble metal alloys having oxides which dissociate at modest to elevated temperatures are illustrative of Type I. Consider an Ag-Au alloy. This suffers selective oxidation of the silver at temperatures less than about 200°C. A superficial oxide of Ag, Ag_2O, will form. However, at higher temperatures, the oxide dissociates, leaving no superficial oxide film. The Ag may contain oxygen in solid solution at all elevated temperatures. Again consider an example of Pt-Pd alloy of high palladium content. This alloy may be preferentially oxidized, i.e., the Pd at temperatures less than about 790°C and greater than 400°C, to form a superficial oxide film of palladium oxide. At temperatures in excess of 790°C the oxide will dissociate in air, leaving only an amount of oxygen in solid solution in Pd according to the solubility limits at the specific temperature. From these specific examples it is apparent that all noble metal alloys are not oxidation-resistant throughout the range from low to maximum elevated temperatures. Exceptional alloys include Pt-Au alloys where the pure elements have very low dissociation temperature and may be considered to maintain desirable physical and electrical properties for a maximum temperature range. Alloys of the Pt-Rh types may also be classed with Pt-Au in its oxidation resistance.

Limits of high-temperature application of cladding non-oxidation-resistant base metals with noble metals or noble metal alloys of Pd and Rh to provide oxidation resistance are due to:

1. appreciable solubility of oxygen;

2. high rates of diffusion of oxygen; with consequence of oxygen penetration to the base metal or alloy with the formation of an oxide at the interface.

Generally, such cladding is useful only at moderate temperatures.

Type II. Oxidation characteristics for alloys may include the heat-resistant type of alloys such as:

1. 80-20, Ni-Cr, (Nichrome); and

2. 18-8, Cr-Ni-Fe, (stainless steel).

An essential condition for the validity of Type II oxidation (parabolic rate type of oxidation) is the formation of a dense and adherent oxidation-resistant coating or scale. This condition is often only fully obtained when the specific volume of the oxide formed is equal to or greater than the specific volume of the metal (or alloy).

The adherence of an oxide scale does not alone provide the protection required. The electrical characteristics of this scale determine whether the scale is protective. Low electrical conductivity types of coatings or scales restrict the flow of negatively charged oxygen ions, electrons, and positively charged metal ions which are characteristic in the transfer involved in the Wagner type of oxidation mechanism. It follows, both from experimental evidence and theory that the high electrical resistivity type of oxide coatings are protective in nature. Oxides of the following metals form protective coatings or scales:

Be, Zn, Al, Li, Ce, Pd, Cr, Mn, Fe, Ci, Ni, Pd, and Cu.

The relative degree of protection of the oxides of these elements may be considered as the inverse order of the electrical conductivity values. It has been established that copper oxides are relatively good conductors, and therefore the adherency of this type of scale does not provide the equivalent protection afforded by Al_2O_3 type scales. The best protective adherent-type oxide coatings or scales are therefore insulators or dielectrics.

Type III. The third type of oxidation characteristics of alloys is indicated by a linear rate for the progress of oxidation. The specific volumes of the oxides formed are smaller than the specific volumes of the respective metals of these oxides. The resultant scale is porous and crumbly with the rate of oxidation controlled only by the specific reactivity of the alloy (or metal) and the composition of the gaseous atmosphere, and by temperature. Typical examples for Type III would include many alloys of: magnesium, calcium, barium, and lithium.

Significantly, few or none of the alloys of oxidation characteristic Type III are included in this study. Previous selection of metals and alloys, based on melting point, has omitted this type of alloy from further consideration as high-temperature electrical conductors in the solid state. However, minor additions of certain of these elements to an alloy may be beneficial in terms of improved protection of the oxide scale.

Certain elements leading to Type III oxidation characteristics may have an important function as alloy additions in small amounts, generally less than 0.5 weight %. The additions of elements such as Ca, Th, Mg, and Ce, may result in ten-fold increase in the life expectancy of various heat-resistant types of alloys. Similar improvement in oxidation resistance has been found to be general with minor additions of alkaline earths and rare earth elements. The effectiveness of such minor alloying elements has been ascribed to the interference of ionic migration through the adherent oxide film.

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2.2.5 Hardening Methods

Hardening processes employed in metallurgical practice usually incorporate several methods of hardening. Hardening methods for metallic alloys may be generally classified as follows:

1. Dispersion
2. Internal oxidation
3. Precipitation or age-hardening
4. Substitutional type of solid solution
5. Interstitial solid solution type
6. Work-hardening
7. Selective crystal structure
8. Combinations of processes

The approximate order of preference of these methods for high-temperature conductor applications is 1,2,3,8,4,7,5,6.

Each generic type of hardening method will be characterized and the feasibility of its suitability for application to the problems of high-temperature electrical conductors briefly discussed in turn.

1. Dispersion-Hardening Method

Dispersion hardening consists of randomly dispersing an insoluble phase through a metal or alloy. The results are generally believed to be especially suited for the attainment of creep strength at elevated temperatures since the dispersed phase is metallurgically stable. This technique is thus well suited to the hardening of high-temperature electrical conductors.

Typical characteristics of dispersion-hardened alloys are discussed in references (1) through (25).

2. Internal Oxidation-Hardening Method

Internal oxidation-hardening process involves the preferential oxidation of a baser solvent by diffusion of oxygen into the solid. It is expedient to carry out this type of process at elevated temperatures since the kinetics are dominated by the rate of diffusion. The amount of solute is limited with oxidation condition adjusted such that oxygen diffuses inwardly to meet the solute, causing reaction to progress inward to form "subscale" rather than surface "scale." This type of reaction can be made to occur throughout the thickness of thin materials, thus producing a fine dispersion of oxide within the metal or alloy.

Internal oxidation of an alloy provides a means of obtaining very fine dispersions, stable in a suitable atmosphere, at temperatures well above those at which most age-hardening precipitates coalesce. The process offers a method of producing thin sheet and wire of outstanding creep resistance.

References (26) through (33) summarize the present state-of-the-art with respect to the theory and practice of alloys hardened by internal oxidation.

3. Precipitation or Age-Hardening Method

Precipitation or age-hardening is the hardening of an alloy caused by the precipitation of a constituent or second phase from a supersaturated solid solution. Increases of mechanical properties such as yield stress have been related to particle size, interparticle spacing, and coherence between matrix and precipitate, for selected precipitation type alloys(44). Peak yield stress was reached, in the case of a 2% cobalt in copper alloy, at an average particle radius of about 70 Å. Correlation of mechanical properties to the above parameters, however, is limited by the submicroscopic size of the precipitate which may be analyzed by magnetic methods, or the electron microscope or x-ray methods. The strengthening mechanism for alloy hardening has been attributed partly to internal stresses resulting from the coherence between matrix and precipitate.

This type of hardening process is generally limited for high-temperature application because of the reversibility of the aging or precipitation process. Also, the precipitated particles will grow in size when annealed at medium temperatures, with a cosequent loss of coherency and hardening of the alloy(38). At sufficiently high temperature, the matrix will be depleted of the finer precipitate with further growth into a coarser precipitated phase. Thus, in this type of alloy, hardening is not considered stable at the elevated temperatures considered feasible for either dispersion or internal oxidation-hardening methods. The latter method (with alumina or an equivalent insoluble phase as the dispersed phase) may be considered to be both high-temperature stable and irreversible.

Current theories and recent studies of precipitation hardening are presented in references (38), (42), and (45). Recent investigations of the precipitation type alloys: Cu-Ag; Sn-Be-Cu; Ni-Cr-Ti-Al; Zr-Fe; Ti-Cu; Co-Cu; Co-Ti; Co-Cu; Al-Ni; Co-Ta; Fe-Cu; Cu-Fe; and Cu-Ti are given in references (34) to (53).

Selected high-conductivity alloys from the preceeding list include: Cu-Ag; Ti-Cu; Co-Cu; Fe-Cu, and Sn-Be-Cu. However, these alloys are not oxidation-resistant types and are further restricted by the high-temperature phase instability of the precipitation type of hardening method.

4. Substitutional Types of Solid-Solution-Hardening

Substitutional solid-solution-hardening is identified as an alloying process where the solute atoms are located at some of the crystal lattice points of the solvent but with the distribution being random, as distinct from ordered-structures with a periodic distribution.

The strengthening mechanisms for this type of hardening process may include the following:

a. change in lattice parameters
b. lattice stress
c. interaction of solute atoms with the substructure in metallic lattice
d. effect of valence differences between solute and solvent
e. function of electron density (Suzuki's proposed chemical mechanism).

Typical examples of a continuous series of the substitutional type of alloys include:

Ag-Au
Ag-Pd
Ag-Cu (with several ordered structures)
Au-Pd
Au-Pt
Cu-Ni
Cu-Pd (with 2 superlattice structures in the binary system)
Cu-Pt (with similar superlattice structures to the (Cu-Pd) binary system)
Pt-Ir (with a suggested superlattice structure)
Ni-Pd
Ni-Pt
Pt-Rh

Binary constitutional diagrams for the above systems are included in the appendix of this report.

Noble metals included as one or both components of the previous binary alloys given, may be expected to provide good-to-excellent electrical properties and fair-to-excellent oxidation resistance combined with acceptable mechanical properties at elevated temperatures.

References (54 to 57) designate recent studies of the solid solution hardened type of alloys.

5. Interstitial Solid Solution Hardening Method

This classical method of hardening is the essential basis for the conversion of soft iron into hard steel by the addition of a relatively small amount of interstitial element (carbon 2%) and retention of solid solution with iron by appropriate treatment to insure a metastable state.

The interstitial solid solution type of alloy is identified by the solute atoms occupying positions between the atoms of the crystal lattice of the solvent. Solute atoms of this type are known as interstitial atomic elements and typically consist of oxygen, nitrogen, hydrogen, carbon, sulfur, phosphorus, tellurium, and selenium. The considerable influence of the interstitial elements, even in trace amounts, upon the physical and mechanical properties of pure metals and alloys, has occasioned the separation of this type of solid solution from the substitutional type. However, desirable interstitials are as hardeners or strengthening solutes at moderate temperatures for metals and alloys, the resulting increase of electrical resistivity and lack of elevated temperature hardness and strength stability limits the applications of this method to most high-temperature conductor applications.

Interstitial elements, such as oxygen, have a serious hardening effect on such transition element metals as Cr, Zr, Ti, Ta, V and Nb(58) with the resulting losses of ductility and working properties except at elevated temperatures. The additional disadvantages resulting from significant increase in electrical resistivity are particularly important in these cases.

6. Work-Hardening Method

The work-hardening method, also identified as "strain-hardening", is a mechanical process wherein an increase in hardness and strength results from plastic deformation at temperatures lower than the recrystallization range. A measure of this process is the work-hardening (or strain-hardening) exponent, "n", which is defined by

$$\sigma = \sigma_o \, \delta^n$$

where:

σ = true stress

σ_o = true stress at unit strain

δ = true strain

Available strain-hardening exponents for selected pure metals have been included in the table of fabrication characteristics of pure metals included in table 1.14 of section 1 in this report.

Feasibility of this hardening method for applications to high-temperature alloy conductors is restricted by the resulting lack of stability of hardness for extended periods and temperatures due to

a. the recrystallization range for the specific metal or alloy;

b. recrystallization temperature is lowered by the extent of energy absorbed during the cold-work process.

N. F. Mott, in his 1960 Institute of Metals lecture, "The Work Hardening of Metals"(59) has provided a recent review of theory of the process of work hardening.

7. Preferential Hardness Obtained from Crystal Structure

The origin for this type of hardening is based on the cumulative observations noted for metals (and alloys) that increasingly complex crystal structure results in increases of both tensile strengths and hardness for metals with nearly the same melting point. Investigations of hardness of metals at temperatures just above and below allotropic change points by W. Chubb (reference 60) has served to further establish previous observations and qualitative conclusions. Metals discussed in this investigation include: cobalt, iron, titanium, uranium, and zirconium. Of these metals, iron and uranium establish that both f.c.c. and complex tetragonal structures have significantly higher hardnesses than the less complex crystal structure present immediately below the elevated temperature allotropic phase change. Further evidence, obtained by linear extrapolation of the Log of Vickers hardness No. vs temperature for the more complex crystal structure, substantiates this conclusion in the cases of titanium and zirconium. Metals of near equal complexity of crystal structures have approximately the same slope of Log Vickers Hardness No. vs temperatures.

In contrast to the desirability of a complex crystallographic structure to obtain improved mechanical properties at elevated temperatures, there is the desirability of simplicity of crystal structure to obtain reproducible resistivity on temperature cycling for high-temperature conductor applications.

8. Combinations of Hardening Processes for Alloys

An illustration of a typical combination of hardening methods is the application of the substitutional solid solution method with an added second phase employed for additional hardening. Other more complex combinations probably represent the ultimate in hardening alloys as indicated by recent alloys of 700,000 psi ultimate tensile strengths. An illustrative example of a combination method is the work of Pelloux and Grant(61) on "Solid Solution and Second Phase Strengthening of Nickel Alloys at High and Low Temperatures."

2.2.6 Conclusion

Specific types of high-temperature conductor alloys recommended for mechanical property improvements of greater strengths and creep resistance by combinations of hardening methods, are listed in tables 2.6, 2.7 and 2.9.

The dispersion hardening method appears to offer the greatest advantages for obtaining uniformity of dispersed phase, greater degree of irreversibility of solution effects, and control of size, shape, and density of dispersion. However, the internal oxidation method is also a favorable hardening process for high-temperature conductors.

The desirable physical characteristics of the dispersed phases are discussed in references (1) to (25). These may be generalized as follows:

a. Volume % of dispersed agent ≈ 5% for intermetallics.

b. Weight % (case of Al_2O_3) is about 3 to 4%, with preferred volume % approximately 7.5.

c. Preferable size of dispersed agent ≈ 0.02 micron diameter.

d. Preferable grain size of matrix about 1 micron or A.S.T.M. grain size No. 16.

e. Density or spacing of dispersed particles should be of the order of 50 atomic spacings to effectively impede dislocation motion.

f. Maximum stability of dispersion agent and effectiveness as hardeners favors the selection of high melting-point, stable and insoluble types of oxides in preference to intermetallic compound types for dispersed agents.

An approximate preference order for specific oxides as disperse agents may be based on the free energy of formation at 727°C and 1227°C, and:

1. La_2O_3
2. Al_2O_3
3. ThO_2
4. V_2O_3
5. UO_2
6. CeO_2
7. Cr_2O_3
8. TiO_2
9. SiO_2
10. NbO_2
11. CaO
12. BeO
13. MgO
14. CeO

For temperature applications lower than 1200°C (such as 700°C) would favor the selection of insoluble types of intermetallic compounds of good-to-excellent conductivity and having essentially different crystal structure than the matrix metal. (See preceding discussion of the influence of a complexed, crystal structure as a second phase for increase in hardening.)

The manufacture of such dispersion-type hardened alloys, of interest for high-temperature electrical conductors, includes the following abreviated process functions:

a. Blending and mixture of matrix and dispersion agent powers.

b. Compaction or pressing of powders into desired geometrical shapes.

c. Sintering of compacts.

d. Hot swaging of sintered product to desired finished form.

Inadequate high-temperature mechanical properties of conventional types of electrical conductor metals and alloys may be improved by methods of hardening as indicated.

2.2.7 References for Section 2.2.5 and 2.2.6

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2.3 Compilation and Treatment of Data

The purpose of this compilation of data is to collect together and systematize the data on alloys which could be of use in high-temperature conductor applications. The electrical resistivity and its temperature coefficient as a function of temperature, oxidation resistance, various mechanical properties (young's modulus, yield strength, creep and rupture characteristics), thermal data (solidus temperature), crystal structure, and typical applications for the alloy are among the many relevent characterictics tabulated and evaluated. This work allows the design engineer to select the best available alloy for a given application in addition to providing the basic information on which technicaly profitable areas for future experimental work may be ascertained.

The sources used for the data research are:

1. Library of Congress, Washington, D. C.
2. Naval Research Laboratory Library, Anacostia, Washington D. C.
3. Department of Agriculture Library, Washington, D. C.
4. Department of Interior Library, Washington, D. C.
5. National Bureau of Standards Library, Washington, D. C.
6. Melpar, Inc. Library, Falls Church, Virginia.
7. Armed Services Technical Information Agency, Arlington Hall Station, Arlington, Virginia.

In table 2.1 of section 2.1.1, an indication was given of the immense scope of the field of binary alloy systems which are possible candidates as high-temperature conductors from the point-of-view of solidus temperature. The existence of extensive gaps in the knowledge of the electrical properties of alloys has been stressed in section 2.1.1.

The purpose of tables 2.2 to 2.5 and figures 16 through 29 is to present the basic data on alloys which are of use or may be of use as high-temperature conductors, either as the conducting material or as a mechanically suitable substrate of good oxidation resistance.

Tables 2.6 to 2.18 contain data of the electrical, oxidation, mechanical, and thermal properties of alloys selected for particular attention as high-temperature conductors. This data will now be presented in greater detail.

Current practice in high-temperature electrical conductor material has stressed the platinum-rhodium alloys. In table 2.2 is presented data on the resistivity at temperatures up to 1200°C and temperature coefficient from 0 to 100°C, M.P., and density for alloys of Pt, Rh, Ir and Pd with each other and with a number of other metals. (Curves illustrating the resistivity temperature behavior for standard Pt-Rh alloys are shown in figures 23, 24.)

In figure 16 is shown the resistivity behaviors of typical classes of alloys. These include high-conductivity alloys such as dilute alloys of copper and platinum and molybdenum; oxidation-resistant type low conductivity alloys; nickel-chromium alloys and various steels of intermediate values of resistivity and oxidation resistance. The curves of this figure present a summary of the resistivity temperature characteristics encountered in different types of alloys. The physical characteristics of these alloys are summarized in the table associated with and following the figure.

In table 2.3 are presented the basic electrical and thermal and, in some cases, the oxidation characteristics of metal alloys. The resistivity and temperature coefficient of resistivity data is presented at 20°C.

Most alloys presented in tables 2.3 have a solidus temperature in excess of 1200°C. However, resistivity data is available only at room temperature for the majority of these alloys. It is probable that many of the alloy systems presented would be useful in high temperature conductor applications either as conductors or oxidation resistant coating and would from stable substrates for highly conductive oxidation resistant coatings.

In table 2.4 is presented a number of miscellaneous alloys which are normally characterized by combinations of undesirable properties for high temperature conductors, e.g., low solidus temperature, very high resistance, little oxidation resistance, or absence of electrical resistivity data at room temperature or above. This data is included principally for completeness.

Table 2.5 presents a compilation of data on the resistivity of alloy systems from 0°C to 1200°C in steps of 100°C, and at 20°C. The average temperature coefficients of resistivity are also calculated and presented. The results for this table were obtained from smoothed curves of the original reference. In several instances, the curve fitting required interpretation from the phase diagram for the binary system concerned. An advantage of the system adopted is that the data is in a convenient form for the comparison of different systems at any temperature. The resistivity versus temperature, and temperature coefficient of resistivity data for the pure components A and B of the binary system are also given. This enables a convenient assessment of the effect of alloying on the resistivity relative to the pure components. The data is also in a form convenient for various basic studies of the effect of the rules presented in section 2.2.2. The data is also in convenient form for the computation of resistivity polynomials of the type

$$\rho = a + bT = cT^2 + dT^3 + eT^4$$

useful as an interpolation formula for the determination of points of inflection in the $d\rho/dt$ versus T curve. This procedure is useful as an aid in determining changes in electron scattering due to crystallographic and other transformations in conjuction with the phase diagrams and other supporting data.

In figures 10 to 15 of section 2.1.2 and figures 17 of section 2.4.1 are presented curves of the electrical characteristics as a function of temperature and composition for dilute and concentrated alloys. This data is discussed from a theoretical standpoint in sections 2.1.2 and 2.4.1.

The data of tables 2.2 to 2.5 have been critically reviewed and the alloys of table 2.6 and 2.7 were selected on the basis of (1) resistivity at 20° is less than approximately 22 micro-ohm-cm, (2) temperature variation of resistivity (0°-100°C), (3) solidus temperature, (4) oxidation-resistance characteristics, (5) crystallographic structure and complexity, and any phase transformations from room temperature to the solidus temperature, from which the mechanical behavior may be inferred. The information on these properties is summarized in columns of tables 2.6 and 2.7 in the concise from. (The phase diagrams available from Hansen on these selected alloy systems are given in the appendix to this report.) Table 2.6 contains resistivity data at 20°C and at the resistivity at the maximum temperature T_m at which data is available. The alloy of tables 2.6 and 2.7 are characterized by resistivity, at 20°C, of less than Pt - 20% Rh (22ohm-cm) and have been selected for further consideration in section 2.42 on the discussion of the technological aspects of the results.

The previous presentations of data have been principally concerned with electrical conductivity and its variation with temperature. Other information has been supplementary to the electrical properties. In the following tables, oxidation and mechanical properties are of primary concern.

Table 2.8 is devoted to data on the oxidation characteristics of alloys and their constitutents. The table is divided into three topics: (1) the comparative oxidation characteristics of certain pure refractory metals including oxidation rates as a function of temperature, time length of exposure, and chemical atmosphere, (2) the comparative oxidation characteristics in air at 980°C of certain binary alloys containing chromium additions for the inhibition of oxidation, and (3) comparative oxidation characteristics of precious metal alloys. These alloys include Pt-Rh, Pt-Pd, and Pt-Ir, and are useful as oxidation-resistant standards with which other high-temperature conductors can be compared. Useful data is presented on the comparative weight changes as a function of temperature (at 900°C and 1100°C) and time (20 hours and 200 hours) in oxygen atmospheres at 1 atmosphere pressure.

The next subject for data presentation is the mechanical properties of alloys. Table 2.9 is concerned with the typical mechanical and physical properties of noble metal alloys; tables 2.10 to 2.18 are concerned with properties of typical internal oxidation-hardened and dispersion-hardened alloys. These alloys are particularly interesting since they present the best prospects of greatly improving the mechanical characteristic of soft oxidation-resistant metals without large increases in electrical resistivity over the pure solvent metal. References to the application of this technique to hardening the best high-temperature oxidation-resistant pure metals (Au, Pt, Pd, Rh, Ir, Ru) or their alloys has not been reported. An extension of these methods of hardening to above metals probably represents the best single approach to the development of new high-temperature conductors of good electrical, oxidation-resistant, and mechanical properties. In the absence of actual data on these systems, typical results are given on numerous other similar systems in tables 2.10 to 2.18. These systems are also of interest as high temperature conductors for moderate temperature applications by themselves. The topics of tables 2.10 to 2.18 are as follows:

Table 2.10	Mechanical properties of a selected internal oxidation-hardened copper alloy.
Table 2.11	Selected mechanical properties of internally oxidized copper alloys.
Table 2.12	Selected mechanical properties of an internally oxidized aluminum-copper alloy.
Table 2.13	Selected mechanical properties of several internally oxidation-hardened alloys.
Table 2.14	Selected mechanical properties of internal oxidation-hardened alloy of silver.
Table 2.15	Selected mechanical and electrical properties of internal oxidation-hardened copper alloys.
Table 2.16	Selected mechanical properties for a typical dispersion-hardened copper alloy.
Table 2.17	Mechanical and electrical properties of several dispersion-hardened copper alloys.
Table 2.18	Mechanical and electrical properties of dispersion-hardened silver base alloys of equivalent volume composition of dispersion agents.

A summary of the typical characteristic of various coating methods using high conductivity oxidation-resistant noble metals or alloys are summarized in table 2.19. Paragraph 1.6 of section 1 is devoted to an elaboration of the vapor-plating technique. The technique of using an oxidation-resistant high-conductivity coating on a mechanically firm stable substrate, conducting cable, waveguide, or antenna is an attractive direct solution to many high-temperature conductor problems, provided the problem of adhesions and diffusion can be overcome.

Finally, in table 2.20 is presented some examples of established alloys of high electrical conductivity and high oxidation resistance. Further experimental data at elevated temperatures on alloys of this type are worthy of determination.

While the data on alloys presented in this section may seem extensive, a critical examination of the tables will show very clearly that extensive gaps exist in the knowledge of the electrical resistivity as a function of temperature up to 1200°C. This can be remedied only by the encouragement of extensive experimental work in the field of high-temperature conductors.

2.4 Discussion of Results

2.4.1 Theoretical

The results of earlier systematic experiments by Mattheissen and Vogt (1864) with alloys(1) led to the already discussed separation of the resistivity into a temperature dependent and a temperature independent part. The availability of purer metals as components and, in particular, the better possibility of making experiments at low temperatures, made it possible to test the validity of this hypothesis more accurately. Generally speaking, the Mattheissen rule holds(2) as long as the temperature independent part of the resistance is small compared to the temperature dependent part, and as long as the introduction of none of the components affects considerably the lattice of the solvent metal. The application of Matthiessen's rule, based on theoretical considerations are discussed in more detail by Jones(3).

Several authors have analyzed Matthiessen rule for practical applications. In particular for alloys, Borelius(4) and Linde(5) distinguished two formal expressions for Matthiessen rule. For very dilute alloys the Borelius interpretation of the Mattheissen rule is written as:

$$\frac{d\rho_1}{dT} = \frac{d\rho_2}{dT} \qquad (29)$$

that is, derivatives of resistivity with respect to temperature of two specimens of the same metal, which differ in purity, are equal.

For binary alloys equation (29) becomes

$$\left(\frac{d\rho_1}{dT}\right)_{\text{alloy}} = b_1\left(\frac{d\rho_1}{dT}\right) + b_2\left(\frac{d\rho_1}{dT}\right) \qquad (30)$$

in which b_1 and b_2 are the atom concentrations ($b_1 + b_2 = 1$) of the components 1 and 2. From (30) it follows

$$\rho_{\text{alloy}(T)} = \rho(0) + b_1\rho_1(T) + b_2\rho_2(T) \qquad (31)$$

or, for a given ratio of the components in a binary alloy, the difference between the observed resistivity and that calculated from the resistivities of the components, is temperature independent. This formulation is called by Borelius, the Matthiessen law. Both expressions (29) and (31) represent only a first approximation.

During the last twenty years resistivity measurements on alloys have become of growing interest, since experimental results have shown that crystallographic transformations, such as disorder-order transformations, can be detected rather sensitively by means of a determination of the resistivity. In particular, the reaction of alloys to cold-work and particle bombardment is reflected in their resistivity. Most of these experiments, however, have their main interest in the study of structural transitions in the solid state.

A general picture of the relation between the resistivity of binary metallic mixtures and the composition of the mixture is illustrated by figures 17 and 18 which are a representation of the LeChatelier-Guertler(6) rules. These rules are:

1. the electrical conductivity and its temperature coefficient of heterogeneous mixtures of two phases vary linearly with the composition, measured in volume percent (figure 17);

2. the electrical conductivity and its temperature coefficient for solid solutions are always below those of the solvent metal and for continuous solid solutions, the conductivity is a U-shaped curve in the conductivity-composition diagram (figure 18a).

As a function of temperature, $\rho(T)$ relations may occur which differ markedly from the normal linear relations found for pure metals for temperatures above 80°K. In particular, alloys with transition metals, and alloys having crystallographic or magnetic transformations, show such deviations. For small amounts of a solute in a solvent metal, forming dilute binary solid solutions, the interesting results found will now be discussed.

Dilute Binary Solid Solutions (influence of concentration and temperature).

Assuming additivity of the resistivity of the pure solvent and the solute metal, the observed resistivity ρ_{obs} can be written as

$$\rho_{obs} = \rho_m + \rho_i. \tag{32}$$

In most cases, it has been found that ρ_i is related to the concentration of the solute by a simple relation

$$\rho_i = c\,d\rho_i + c^2 d'\rho_i + \ldots \tag{33}$$

in which c is the amount of solute in atom percent (at %), $d\rho_i$ and $d'\rho_i$ resistivity values. This relation, found by Benedicks(7) for some copper-silver and copper-gold alloys, has been investigated systematically by Linde(5) for a great number of alloys with a noble metal as a solvent. The departure from linearity for concentrations of the order of a few atom percent is not negligable at room temperature. Thus, Linde defines the atomic resistivity increase, $d\rho_i$, as

$$d\rho_i = \lim_{c \to 0} \rho_i / c \tag{34}$$

For a number of copper base alloys, Linde's results are reproduced in figure 19.

For the special case where solvent and solute metal are in the same column of the periodic table $d\rho_i$ may be the same whether the metal M_I is dissolved in M_{II} or M_{II} is dissolved in M_I. For example, $d\rho_i \simeq 0.36 \times 10^{-7}$ ohm-cm for silver in gold as well as for gold in silver. For such cases, the Nordheim relation(8)

$$\rho_i \sim x\ (1-x) \qquad (35)$$

holds for $0 \leq x \leq 1$, where x is the fractional concentration of the solute. This relation is theoretically based on a first order perturbation calculation and holds when the electron concentration and structural properties of the base metal are not modified by alloying.

Besides Linde's work, we mention the earlier investigations by Norbury and Kuwada(9), the systematic investigations by Eucken and Schurenberg(10) on lead base alloys, by Robinson and Dorn(11) and by Gulyaev and Trusova(12) on aluminum base alloys. Furthermore, the investigations by Smith and Palmer (Cu-Al, Cu-Ni, Cu-Mn)(13) and by Nemilow (Pt-Ir, Fe-Pt)(14) give results on some special alloys.

Norbury found(15) for the resistivity increase of alloys consisting of elements of different valency, (except for alloys with a transition metal as one of the components), that the atomic resistivity increase changes proportionally with the squared difference of atomic number between solvent (Z_m) and solute (Z_i) metal. This rule has been checked by Linde for his data on copper, silver and gold base alloys, and by Robinson and Dorn for aluminium base alloys. The latter authors could represent Linde's and their own results by a relation

$$d\rho_i = K_2 + K_1\ (Z_m - Z_i)^2 \qquad (36)$$

where K_2 and K_1 are constant for a given solvent for each period from which the solutes are taken. They arrive at the conclusion that for aluminium as a solvent, a valency of 2.5 has to be taken for the ion valency in the metallic state.

The deviations which occur when Norbury's rule is applied to transition metals is shown in figure 20 in which for some gold base alloys Linde's values for $d\rho_i$ are inserted against $(Z_m - Z_i)2$ as abcissae. The general procedure for measuring the $d\rho_i$ values is to determine, at a given temperature, the resistivity of a specimen, and plot the results as a function of the concentration of the solute element. This value can be deduced from the weights of the materials during the manufacturing of the alloys. When small quantities are involved, this is a rather inaccurate method, its success depending on the method of melting and homogenizing of the alloys in solid state. For not too small quantities of the solute, the composition of the alloy can be found from micro-spectrographic analysis. Eucken and Schurenberg determined $d\rho_i$ from relative measurements at different temperatures of the resistance under the assumption that equation (32) holds for the temperature region they considered.

By differentiating (32) with respect to T, it follows that

$$\left(\frac{\partial\rho}{\partial T}\right)_{obs} = \left(\frac{\partial\rho_m}{\partial T}\right) + \rho_{i,T}\,\alpha_{d\rho,T} \tag{37}$$

in which the temperature coefficient for the atomic resistivity increase,

$$\alpha_{d\rho,T} = \frac{1}{d\rho_i}\,\frac{\partial d\rho_i}{\partial T} \tag{38}$$

is introduced. From Linde's measurements between 273°K and 373°K, linearity of $\left(\frac{\partial\rho}{\partial T}\right)_{obs}$ with ρ_i (see figure 21) is observed.

Apart from their magnitude, the negative values of $\alpha_{d\rho}$ for some of the transition metals as solute demonstrate the annomolous behavior of these elements.

Summarizing, it follows from the experimental data for dilate alloys that:

1. the resistivity increase, for concentrations of the solute less than a few atom percent, is in general, proportional to the concentration of dissolved component;

2. with the exception of transition metals as a solute, Norbury's rule is generally valid;

3. the resistivity increase is temperature dependent, with a positive coefficient of the order 10^{-4} degree $^{-1}$;

4. the resistivity increase of transition metals, dissolved in copper, silver, or gold, deviates from Norbury's rule, and negative, instead of positive, temperature coefficients may occur.

Hansen, Johnson, and Parks(16) have drawn attention to a forgotten experimental relation, found by Dellinger(17), between the conductivity and the temperature coefficient of resistance (at 273°K) for a dilute alloy. According to Dellinger, conductivity at 273°K for commercial copper wires should be proportional to the temperature coefficient of resistivity of the alloy:

$$\sigma_{(273)\text{alloy}} = \beta\,\alpha_{\text{alloy}(273)} \tag{39}$$

Considering Linde's data and those found by other authors Hansen et al(16) find a confirmation of this rule by plotting σ_{273} against α_{alloy} for a great number of alloys. They claim that, for a number of base metals, $\beta = 1/\rho_m \alpha/\rho$, the values for ρ_m and $\alpha\rho$ being taken at $T = 273^\circ K$. Using Linde's data, a plot of σ against $\alpha\rho$ has been reproduced in figure (22) in order to illustrate the accuracy of equation (39). Hansen et al. do not enter into the physical meaning of this effect. A simple calculation shows, that for the dilute alloys either the quantity $\rho_i \alpha_d \rho$ is much smaller than $\rho_m \alpha \rho$, or that the values for $\alpha_d \rho$ should hold only for $\rho_i \rightarrow 0$, or $c \rightarrow 0$. It follows from the figure that certainly for low values of σ_{alloy} and α_{alloy}, the relationship (39) is not valid, whereas the linearity of $(d\rho/dT)_{alloy}$ with ρ_i holds, as shown by Linde(5).

Concentrated binary solid solutions

For concentrations of solute metals exceeding, for instance, 5 at. % in some cases, and for higher concentrations in all cases, the deviation from the assumed normal additivity of the impurity resistance becomes so large that the applicability of Matthiessen's law is doubtful, and any theoretical interpretation, based on first or higher order perturbation fails. The concentrated alloys are, in general, of greater interest for solving technical rather than physical problems, as long as order-disorder and magnetic transformations are excluded from consideration.

We referred before to Hansen et al. who found equation (39) holding for dilute solid solutions. It is remarkable that for continuous solid solutions, for example silver palladium alloys(18), a σ_{alloy} vs. α_{alloy} plot gives a linear relation for all silver palladium solid solutions, split however into a silver-line and a palladium-line, defined by the coefficient $\beta = \sigma/\alpha$ for silver and palladium, respectively (see figure 21). For binary alloy systems in which the component metals are soluble in each other to a certain extent and which do not form an intermediate phase, the diagram consists again of two straight lines representing the properties of the primary solid solutions (as in the case of silver-palladium) and a third straight line joining the points for the saturated solid solutions(16). This is represented for the Cu-Co(19) and Cu-Ag(20) system in figure 22(a) and (b).

Most concentrated unordered alloys with a nonconductor as a component, are semiconductors. Exceptions are solid solutions of Zr-B($\rho_{273} = 30 \times 10^{-6}$ ohm-cm) as found by Glaser(21) and palladium-hydrogen alloys(22).

Further results for the resistivity and temperature coefficient of typical alloy systems are presented in figures 23 to 29. These include data on Pt-Rh standard alloys (figures 23 and 24); Fe, Ni, Co, Ag, Al, Pt, Cu, Au (figures 25, 26, 27); Cu-Ni alloys (figures 28 and 29).

2.4.2. References for Section 2.4.1

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2.4.3 Technological

In this section a brief discussion is given of the technological aspects of the data compiled in section 2.3 within the guidelines for the development of high-temperature conducting alloys set out in section 2.2.1.

The results of surveys on binary alloy systems presented in table 2.1 indicated extensive gaps in our knowledge of the resistance versus temperature characteristics of metallic alloy systems. It is certainly desirable to have these gaps eliminated by experimental work for alloys of the oxidation-resistant metals (Au, Pt, Pd, Ir and Rh) with elements of melting point in excess of 500°C. Alloys with metals which are easily oxidized (Al, Be, Ce, Hf, La, Mg, Nd, Sc, Si, Sm, Th, Ti, Y) are to be avoided unless internal oxidation hardening is to be deliberately applied. Systems of interest for further work, from table 2.1, are listed below. Those to which an asterisk has been added are those of more than average interest as potential high temperature conductor systems.

Ag-Au, Ag-Cu*, Ag-Pd*, Ag-Pt*, Al-Cu, Au-Co*, Au-Cr*, Au-Cu*, Au-Fe*, Au-Mo*, Au-Ni*, Au-Pd*, Au-Pt*, Au-Rh, Au-V, Co-Pd*, Co-Pt*, Co-Ru, Cr-Cu*, Cr-Ni*, Cr-Ti, Cr-W*, Cu-Ir*, Cu-Pd*, Cu-Pt*, Fe-Pt*, Ir-Pt*, Ir-Rh*, Mn-Pt, Mo-W*, Nb-W, Ni-Pd*, Ni-Pt*, Pd-Pt*, Pd-Rh*, Pt-Rd*, Pt-W*.

The alloy systems underlined by two lines are those for which some data is available on the temperature variation of resistivity although this data is usually incomplete. Systems underlined once are those for which data at room temperature only is available. The systems which are not underlined are those for which no significant room temperature resistivity data has been found. Most of the systems of particular interest (marked with asterisk) have simple phase diagrams and many are solid solutions with complete solid-solubility at all compositions, as may be seen by reference to table 2.1.

Most of the systems contained in table 2.2 on precious metal alloys are included in the previous list of alloys. The missing high temperature resistivity data in the systems of table 2.2 should be determined if possible.

Tables 2.6 and 2.7 analyze data on alloys selected from tables 2.3 to 2.5 with resistivities at 20°C of less than 22 microhm-cm. The systems of particular interest in tables 2.6 and 2.7 are:

Pt-Rh (5, 10, 20, 40 Wt. %)*, Ag-Pd (10, 30 Wt. %)*, Ag-Pt (2, 4, 30 Wt. %)*, Ag-Pd (30 Wt. %)*, Au-Pd (2.2, 20 Wt. %)*, Au-Pt (2, 4, 25 Wt. %)*, Au-Ag (40 Wt. %)*, Cu-Au (20 Wt. %)*, Cu-Si (1, 2 Wt. %), Cu-Ni (10 Wt. %)*, Cu-Pd (2, 3, 6, 7 Wt.), Cu-Pt (1 to 4 Wt. %), Cu-Al (14.5 to 19.3 Wt. %), Pd-Ni (6 to 83 Wt. %), Pd-Pd (10, 20, 90 Wt. %), Pt-Ir (5 Wt. %).

The oxidation resistance, resistivity, and crystal structure are also discussed in the tables 2.6 and 2.7.

Summarizing, the most useful alloy systems for general use in the temperature range between 500°C and 1200°C are likely to be:

1. Those based on oxidation-resistant metals, Au, Pt, Pd, Rh and Ir, with alloying additions to improve their mechanical properties, (dispersion hardening, internal oxidation-hardened, or substitutionally-hardened) but insufficient to cause the resistivity to exceed 25 microhm-cm at room temperature;

2. Those based on Ag, Cu, Ni, Fe, Cr, Mo and W with alloying additions (insufficient to cause the resistivity to exceed 25 microhm-cm at room temperature) in order to improve their mechanical properties, using the hardening methods given above, and also to inhibit oxidation.

The previous discussion has been concerned principally with the electrical properties of alloys. Table 2.8 is concerned with the oxidation characteristic of metals and alloys and substantiates the preference order for oxidation resistance given in sections 1.4.2 and 2.2.3.

The standard mechanical performance of Rt-Rh and other noble alloys have been presented in table 2.9.

The mechanical properties of internal oxidation-hardened alloys and dispersion hardened alloys is discussed in tables 2.10 to 2.18. The results of the data presented in these tables will now be discussed.

The creep characteristics of a typical internal oxidation-hardened alloy of copper plus 0.05 Wt. % Al is contrasted with that of pure copper in table 2.10 for five different thermal treatments prior to creep test. The data shows that the creep properties are most favorable for internal oxidation treatment at 850°C. The creep, after 80 hours at 69,400 psi, was 0.42×10^{-3}cm which was 5.6 times less than that of pure copper.

The mechanical properties of internally oxidized Cu-Si (0.2 and 0.25 Wt. % Si) and Cu-Al (0.09 and 0.23 Wt. % Al) are considered in table 2.11. Hardness, creep rupture at 450°C as function of oxidizing temperature and time are discussed. Internal oxidation leading to the formation of SiO_2 and Al_2O_3 was obtained by heating in air at 650°C or 750°C and the mechanical properties analyzed as a function of oxide particle size and inter-particle spacing. The percent improvement in the creep rupture test at 500 psi over pure copper was 280 for the 0.25 Wt. % Si alloy and 150 for the 0.23 Wt. % Al alloy.

Another Cu-Al (0.04 to 0.84 Wt. %) internally oxidization-hardened alloy is considered in table 2.12. The aluminum was internally oxidized to Al_2O_3 at 1000°C and the mechanical properties (yield strength and hardness) studied at 20°C as a function of wire diameter and grain size. Yield strength characteristics were also tested as a function of temperature from 27°C to 400°C for 20 mil wire internally oxidized at 1000°C. Under test, (400°C) the 0.84 Wt. % Al-Cu was 5.8 times higher in yield strength than copper.

Another investigation of the mechanical properties (hardness, tensile strength, and average yield strength from -190°C to 500°C) of internally oxidized copper-based alloys (copper + 0.20 Wt. % Al, 0.24 Wt. % Mg, 0.27 Wt. % Cr, 0.22 Wt. % Be) is presented in table 2.13. Internal oxidation at 900°C yields the best results. The maximum improvement in yield strength at 500°C over pure copper was 2.1 for Al alloy, 2.8 for the Mg alloy, 1.5 for the Cr alloy, and 1.5 for the Be alloy. Marked improvements in creep characteristics were also observed, as expected, from the yield strength results.

A study of mechanical properties of internally oxidized Ag-Al (0.14 Wt. %) is summarized in table 2.14. Tensile strength and yield strength versus annealing temperature was studied as a function of different thermal and mechanical treatments. During internal oxidation, the Al is oxidized to Al_2O_3 (AgO disassociates above 250°C, yielding metallic silver). The best mechanical results were obtained by internally oxidizing cold worked annealed alloy which was internally oxidized at 800°C for 1000 hours. The improvement in yield strength at 21°C for this internally oxidized Ag-Al (0.14 Wt. %) alloy, after annealing at 900° over pure silver, was 19.2.

A study of internally oxidized (at temperatures from 650 to 950°C) Cu-Si (0.01 to 0.59 Wt %) and Cu-Al (0.09 to 0.77 Wt. % Al) is summarized in table 2.15. The mechanical properties (ultimate tensile strength, yield stress at 0.2% elongation, reduction of area at rupture and creep rupture characteristics for an interpolated 100 hour rupture life) were studied in air and nitrogen as a function of temperature (450°C and 850°C). Measurements were also made on the electrical resistivity at 20°C. The internally oxidized alloys were studied after extrusion in terms of volume % dispersed oxide phase, oxide particle radius, and mean separation between particles. The best results were obtained for Cu-SiO_2 (0.21 Vol. % SiO_2 alloy internally oxidized at 750°C in air and having a mean particle radius of 0.026 micron and a mean distance between particles of 1.67 microns. The yield strength, ultimate strength, and % area reduction on rupture were 17.5, 1.2 and 5.8 times better than that of copper (plus 0.01 Wt. % Si). The best results with the Cu-Al alloys were obtained with 3.6 Vol. % Al_2O_3 internally oxidized at 750°C (mean particle radius 0.06 micron, mean particle separation 1.21 micron). Improvements in yield strength, ultimate strength, and % reduction in area at rupture over the 0.09 Al doped copper was 3.3, 2.1 and 2.3 respectively. The electrical resistivity for these samples after internal oxidation but prior to mechanical testing was 2.7 microhm-cm at 20°C.

These results on internal oxidation hardened copper and silver alloys indicate that this is an excellent method for the improvement of the mechanical properties of high-electrical conductivity dilute alloys. The alloys discussed are of interest in themselves as high-temperature structural conductors for use at temperatures up to 400° to 500°C. If the same techniques could be applied to the oxidation-resistant noble metals (especially Au and Pt), they should yield good mechanical, electrical, and oxidation-resistant properties at higher temperatures (up to 900°C for Au and higher than 1200°C for Pt).

Similar conclusions are arrived at for dispersion-hardened pure metals and dilute alloys. In this method of hardening, an insoluble phase (usually an oxide) is dispersed by means of powder metallurgical or other techniques to yield results which are also very favorable.

In table 2.16 is summarized an investigation on the mechanical properties of dispersion-hardened copper alloys using mechanically dispersed Al_2O_3 particles (size not given). An improvement in yield strength at room temperature of 3.8 over that of pure copper was obtained for 10 Vol. % Al_2O_3 - 90 Vol. % Cu alloys after annealing at 400°C for 1 hour. A creep rupture test on the material at 350°C gave a rupture life of 500 hours and a rupture stress of 15,600 psi which represents an improvement of 3.4 over results for untreated copper.

A further investigation on a sintered copper and 2.5 to 10 Vol. % Al_2O_3 alloy is presented in table 2.17. The copper particle sizes used were less than 74 but greater than 1 micron in diameter and the Al_2O_3 particles were 0.018 microns in diameter. The best results were obtained with 7.5 Vol. % Al_2O_3 with 1 micron diameter copper pressure sintered 900°C. Yield strength, (69,900 psi), % elongation and % area reduction at rupture were 8.8, 11 and 10 times better than that of copper. A 300% improvement in ultimate strength was obtained relative to copper. The electrical resistivity of this sample was 2.41 microhm-cm at 20°C. The general range of resistivity for this investigation was from 1.82 to 2.59 microhm-cm.

The final investigation reported on dispersion hardening is summarized in table 2.18. The mechanical properties of a base of silver plus dispersion-hardening additions of 15 Vol. % W, 15 Vol. % Mo, 15 Vol. % WC and 15 Vol. % Ni were compared to pure silver. The properties studied were hardness and bending properties (Young's modulus, fracture stress and deflection per unit of stress) measured at room temperature. The improvement in fracture strength for the Mo and WC additions was 2.8 and 2.4. The improvement in fracture strength for the W and Ni additions was 1.9. The materials were compiled and entered at 920°C (particle diameters of 2 and 10 microns). They were compacted and hot pressed at 1400°F and 1000 psi, coined at 60,000 psi at room temperature, and annealed and outgassed at 800°F.

The results of tables 2.19 on methods of plating noble metals for high-conductivity, oxidation-protective coatings and the results of table 2.20 on typical commercial high-conductivity oxidation-resistant alloys have been previously discussed in section 2.3.

2.5 Conclusion

The discussion of the results presented in this section has led to the conclusion that where expense is not a problem and performance up to temperatures of 800° to 1200°C is required, the best solution to the high temperature conductor problem is noble metals or noble metal alloys (Pt, Au ($T \sim 1000^{o}C$) Pd, Rh and Ir) which have been hardened by dispersion hardening or internal oxidation hardening. For temperatures up to 700°C, dispersion or oxidation-hardened copper and silver should provide conductors of much lower materials cost and ten times greater electrical conductivity than Pt-Rh alloys, provided suitable oxidation protection can be provided for those applications requiring long periods of exposure in oxidising atmospheres.

TABLE 2.1

BINARY ALLOYS WITH ONE CONSTITUENT OF M.P. GREATER THAN 1000°C, BUT WHICH FORM NO WELL - DEFINED COMPOUNDS OF M.P. GREATER THAN 1000°C

System (A) (B)	M.P.°C (A) (B)	Description	Resistivity Reference	Crystal Structure
Ag-Au	960.5-1063	alloy complete Sol Sol	TABLE 2.3 1, 2	
Ag-Be	960.5-1282	no compound - phase diagram complex — alloy forms at 90 wt% Be		
Ag-Cu	960.5-1083	no compounds - phase diagram simple	TABLE 2.3 3, 4	
Ag-Pd	960.5-1552	Alloy-complete Sol Sol	TABLE 2.3 5, 6, 7	
Ag-Pt	960.5-1769	Compound MP.<1000°C - phase diagram complex*	TABLE 2.3	f.c.c. Rhbdr f.c.c.
Ag-Si	960.5-1430	no compounds - phase diagram simple		
Al-Be	660-1284	no compounds - phase diagram simple		
Al-Cu	660-1083	no compounds - phase diagram complex - many eutectics & peritectics	TABLE 2.3	
Al-Si	660-1430	no compounds - phase diagram simple		
As-Au	-1063	no compounds - phase diagram simple		
As-Bi	-271.3	no compounds - phase diagram simple		
As-Cu	-1083	compound MP.<1000°C- phase diagram simple		>225°C cubic <225°C hex.
As-Ni	-1484	compound MP. <1000°C- phase diagram simple		
Au-Be	1063-1278	compounds MP. <1000°C- phase diagram complex		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P.°C (A) (B)	Description	Resistivity Reference	Crystal Structure
Au-Bi	1063-271.3	compound MP.<1000°C-phase diagram simple		Au_2Bi f.c.c.
Au-Cd	1063-321	compound MP.<1000°C-phase diagram complex	8	Tetr and Rhomb
Au-Co	1063-1495	no compound - phase diagram simple		
Au-Cr	1063-1880	no compound- phase diagram complex		
Au-Cu	1063-1083	continuous series of solid solutions at high temperature	TABLE 2.3 9 - 10	
Au-Fe	1063-1534	no compounds - phase diagram complex	TABLE 2.3	
Au-Ga	1063-29.7	compounds MP.<1000 - phase diagram simple		AuGa - rhomb $AuGa_2$ - cubic
Au-Ge	1063-936	no compounds - phase diagram simple		
Au-Hg	1063-38.9	compounds <1000-phase diagram complex		
Au-In	1063-155.4	compounds <1000-phase diagram simple		AuIn - Tricl $AuIn_2$- cubic
Au-Mo	1063-2620	no compounds - phase diagram not published		
Au-Na	1063-97.5	compounds <1000 - phase diagram simple		$NaAu_2$ - f.c.c. Na_2Au - Tetr
Au-Ni	1063-1453	no compounds - phase diagram simple	11, 12, 13	
Au-Pb	1063-327	compounds MP.<1000-phase diagram simple	TABLE 2.3	Au_2Pb - f.c.c. $AuPb_2$ - b.c.tetr

TABLE 2.1 (cont'd.)

System (A) (B)	M.P.°C (A) (B)	Description	Resistivity Reference	Crystal Structure
Au-Pd	1063-1541	continuous series of solid solutions	TABLE 2.3 14, 15	
Au-Pt	1063-1769	continuous series of solid solutions	TABLE 2.3 16, 17, 18	
Au-Rh	1063-1966	no phase diagram - Rh reported to raise the MP of (Ref. 19)		
Au-Sb	1063-631	compound MP<1000-phase diagram simple		$AuSb_2$-cubic
Au-Si	1063-1430	no compound - phase diagram simple		
Au-Sn	1063-232	compounds MP<1000 - phase diagram simple	19	AuSn -hex, $AuSn_2$-rhomb, $AuSn_4$ -rhomb
Au-Te	1063-451	compound MP<1000-phase diagram simple		
Au-Tl	1063-302	no compound - phase diagram simple		
Au-Zn	1063-419	compounds MP <1000 - phase diagram complex	20	Au_3Zn - f.c.c.
Au-V	1063-1710	no compound - phase diagram not complete		
B-Cu	1083	no compounds - phase diagram simple	21	
Be-Nb	1280-2500	no phase diagram - possible compound		
Be-Si	1280-1414	no compounds - phase diagram simple		
Bi-Cu	271-1083	no compound - phase diagram simple		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Bi-Ge	271-936	no compound - phase diagram simple		
Bi-Ni	271-1451	compounds MP < 1000 - phase diagram simple		NiBi - hex $NiBi_3$- hex
Bi-Rh	271-1966	compounds MP < 1000*- phase diagram complex		RhBi - hex
C-Ni	3550-1453	phase diagram complex - possible compound Ni_3C?		
Ca-Co	816-1495	no compounds - phase diagram complex and incomplete		
Ca-Cu	816-1083	compounds MP <1000- phase diagram complex	22	CaCu - hex
Cd-Cu	321-1083	compounds MP <1000- phase diagram complex		Cu_2Cd - hex
Cd-Pd	321-1549	compound MP <1000 - phase diagram complex		
Cd-Pt	321-1773	compound MP <1000 - phase diagram complex		
Cd-Rh	321-1966	similar to Cd-Pd		
Ce-Cu	715-1083	Compounds MP <1000 phase diagram simple		
Ce-Cr	715-1930	no compounds - no phase diagram established		
Ce-Mn	775-1245	no compounds - phase diagram complex		
Ce-Th	775-1845	complete sol-sol, - no phase diagram		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Ce-Ti	775-1720	no compounds - phase diagram incomplete		
Ce-U	775-1133	no compounds - no phase diagram established		
Co-Cr	1495-1860	no compounds - phase diagram complex		
Co-Cu	1495-1083	no compounds - phase diagram complex	23	
Co-Fe	1495-1534	no compounds - phase diagram complex	TABLE 2.3 24, 25, 26, 27	
Co-Ir	1495-2454	no compounds - phase diagram simple		
Co-Mg	1495-649	compound MP<1000 - phase diagram simple	28	
Co-Mn	1495-1245	no compound - phase diagram complex		
Co-Ni	1495-1452	continuous series of solid solution	TABLE 2.3	
Co-Os	1495-2700	continuous series of solid solutions		
Co-Pd	1495-1554	continuous series of solid solutions	29	
Co-Pt	1495-1773	continuous series of solid solutions	30	f.c.c.
Co-Re	1495-3167	continuous series of solid solutions		
Co-Rh	1495-1966	continuous series of solid solutions		f.c.c.

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Co-Ru	1495-	continuous series of solid solutions		
Co-Tl	1495-302	no phase diagram - no compounds reported		
Co-Zn	1495-4194	no compounds - phase diagram complex		
Cr-Cu	1550-1083	no compounds - phase diagram complex	TABLE 2.3	
Cr-Fe	1830-1539	continuous series of solid solutions	TABLE 2.3 31, 32	tetr
Cr-Mo	1830-2620	continuous series of solid solutions		
Cr-Ni	1840-1455	no compound - phase diagram complex	TABLE 2.3 33, 34	
Cr-Pb	1840-327	no compound reported-phase diagram complex		
Cr-Pu	1890-640	no compounds - phase diagram simple		
Cr-Re	1890-3440	continuous series of solid solution		
Cr-Sn	1840-232	no compounds - phase diagram simple		
Cr-Te	1840-452	no compounds reported-no phase diagram available		
Cr-Th	1880-1845	no phase diagram reported-simple eutectic system		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Cr-Ti	1880-1720	continuous series solid solutions (possible compound $TiCr_2$)		
Cr-U	1880-1133	no compound - phase diagram simple		
Cr-W	1880-3370	complete series of solid solutions at high temperatures		
Cr-Zn	1880-419	phase diagram not established-possible compound		
Cu-Fe	1083-1533	no compounds - phase diagram complex	TABLE 2.3 35	
Cu-Ga	1083-29.6	compound M.P. < 1000- phase diagram complex		$CuGa_2$-Tetr
Cu-Ge	1083-936	compound M.P. <1000- phase diagram complex		Cu_3Ge-h.c.p.
Cu-In	1083-155.4	compound M.P. <1000- phase diagram complex		
Cu-Ir	1083-2454	no phase diagram- electrical conductivity of copper-rich alloy	36	
Cu-La	1083-812	compounds M.P. < 1000- phase diagram simple		$LaCu_5$-hex
Cu-Li	1083-179	no compound - phase diagram simple		
Cu-Mg	1083-650	compound M.P. < 1000- phase diagram simple	37, 38	$MgCu_2$- f.c.c. Mg_2Cu - rhomb
Cu-Mn	1083-1244	complete series of solid solutions	TABLE 2.3 39	

TABLE 2.1 (cont'd)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Cu-Mo	1083-2620	no phase diagram	40	
Cu-Nb	1083-2500	no phase diagram-reported to be a simple eutectic system		
Cu-Ni	1083-1453	continuous series of solid solutions	TABLE 2.3 41	
Cu-Os	1083-2700	no phase diagram	41	
Cu-Pb	1083-327	no compound - phase diagram simple	TABLE 2.3 42, 43	
Cu-Pd	1083-1554	continuous series of solid solutions	TABLE 2.3 44, 45, 46	
Cu-Pr	1083-932	compound M.P. < 1000-phase diagram simple		
Cu-Pt	1083-1769	continuous series of solid solutions at high temperatures	TABLE 2.3 47, 48	
Cu-Rh	1083-1966	no compounds - phase diagram simple		
Cu-Sb	1083-630.5	compound M.P. < 1000-phase diagram complex		Cu_2Sb - Tetr CuSb - Hex
Cu-Si	1083-1430	compound M.P. < 1000-phase diagram complex	TABLE 2.3	
Cu-Sn	1083-232	compound M.P. < 1000-phase diagram complex	TABLE 2.3	
Cu-Ta	1083-2996	no compounds reported phase diagram not established		
Cu-Ti	1083-1660	compound M.P. < 1000-phase diagram simple		Ti_3Cu - tetr Ti_2Cu - f.c.c.

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Cu-Cl	1083-302	no compound - phase diagram simple		
Cu-V	1083-1870	no phase diagram - no compound reported		
Cu-Zn	1083-419	no compounds - phase diagram complex	TABLE 2.3 49	
Cu-Ir	1083-2454	reported to form a continuous series of solid solution		
Fe-Mn	1534-1245	no compound - phase diagram simple		
Fe-Mo	1534-2620	no compounds - phase diagram complex		
Fe-Ni	1534-1455	no compound - phase diagram simple	TABLE 2.3	
Fe-Pb	1534-327	no compound - phase diagram simple		
Fe-Pd	1534-1552	no compound - phase diagram simple		
Fe-Pt	1534-1773	continuous series of solid solutions at high temperatures	TABLE 2.3	
Fe-Rh	1534-1966	possibly forms a continuous series of solid solutions		
Fe-Sb	1534-630	compound M.P. < 1000 - phase diagram complex		$FeSb_2$ - hex
Fe-Sn	1534-232	compound M.P. <1000 - phase diagram complex		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P.°C (A) (B)	Description	Resistivity Reference	Crystal Structure
Fe-Te	1534-452	compound M.P.<1000- phase diagram incomplete		FeTe - hex
Fe-V	1534-1125	continuous series of solid solutions	50	
Fe-Zn	1534-419	compounds M.P. < 1000- phase diagram complex		
Ga-Mn	29.8-1244	no compounds - phase diagram complex		
Ga-Si	29.8-1430	no compounds - phase diagram simple	51	
Ga-Th	29.8-1845	no compounds - phase diagram simple		
Ge-Mn	955-1245	compounds M.P.<1000- phase diagram complex		
Ge-Si	940-1412	no compound - phase diagram simple		
Hf-Nb	1534-2500	no compounds - phase diagram not established		
Hf-Zr	1534-2230	continuous series of solid solutions		
Hg-U	38.9-1133	compound M.P. < 1000- phase diagram simple		
In-Mn	156-1245	compound M.P. < 1000- phase diagram complex		
In-Ni	156-1453	compound M.P. < 1000- phase diagram complex		
In-Si	156-1430	no compound - phase diagram simple		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
In-Ti	156-1800	no phase diagram-probable compound 1000		
Ir-Pt	2454-1769	continuous series of solid solutions	TABLE 2.3 52	
Ir-Rh	2454-1966	no phase diagram-probable continuous series of solid solutions		
La-Mn	820-1245	no compound - phase diagram simple		
Mg-Th	650-1700	compound M.P.<1000-phase diagram simple		MgTh - f.c.c.
Mn-Ni	1245-1453	continuous series of solid solutions at high temperatures	TABLE 2.3 53	
Mn-Pd	1245-1552	no compound? - phase diagram complex		
Mn-Pt	1245-1769	continuous series of solid solutions	54	
Mn-Rh	1245-1966	phase diagram incomplete		
Mn-Ru	1245-2450	phase diagram incomplete		
Mn-Sb	1245-630	compound M.P. <1000-phase diagram complex		Mn_2Sb - tetr
Mn-Sn	1245-232	compounds M.P. <1000-phase diagram complex		Mn_3Sn - hex Mn_2Sn - hex
Mn-Ti	1245-302	no compound phase diagram simple		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P.°C (A) (B)	Description	Resistivity Reference	Crystal Structure
Mn-Zn	1245-419	no compound - phase diagram complex		
Mo-Pt	2620-1773	possible intermediate phase - no phase diagram		
Mo-Ta	2620-2996	continuous series of solid solutions		
Mo-Ti	2620-1660	complete solid solubility	TABLE 2.3	
Mo-U	2620-1133	compound M.P. <1000- phase diagram complex		MoU_2? - tetr
Mo-V	2620-1710	continuous series of solid solutions		f.c.c.
Mo-W	2620-3370	continuous series of solid solutions		b.c.c.
Nb-Th	2400-1700	no compounds - phase diagram simple	55	
Nb-Ti	2410-1720	continuous series of solid solutions	TABLE 2.3 56	
Nb-U	2410-1133	no compounds - phase diagram simple		
Nb-V	2420-1860	continuous series of solid solutions		
Nb-W	2435-3370	continuous series of solid solutions		
Nb-Zr	2435-1860	no compounds - phase diagram simple		
Nd-U	840-1133	no compounds - no phase diagram		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Ni-Pb	1452-327	no compounds - phase diagram complex		
Ni-Pd	1453-1552	continuous series of solid solutions	Table 1, Report 3 57	
Ni-Pt	1453-1769	continuous series of solid solutions	Table 1, Report 2 47	
Ni-Ru	1453-2450	probable series of solid solution - no phase diagram		
Ni-S	1453-119	compounds M.P. < 1000- phase diagram complex		NiS_2 - cubic Others
Ni-Tl	1453-302	no compound - phase diagram simple		
Ni-Zn	1453-419.4	compounds M.P. <1000- phase diagram complex		
Os-At	2700-1773	no compound reported - no phase diagram		
Os-Re	2700-3167	continuous series of solid solutions		
Os-Zn	2700-419.5	no compounds no phase diagram		
Pb-Pt	327-1744	compounds M.P. <1000- phase diagram complex	58	Pt_3Pb - cubic PtPb - hex
Pb-Ru	327-2450	no compounds reported no phase diagram	TABLE 2.3	
Pd-Pt	1549-1773	continuous series of solid solutions	TABLE 2.3 59	
Pd-Rh	1549-1966	continuous series of solid solutions		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P.$^{\circ}$C (A) (B)	Description	Resistivity Reference	Crystal Structure
Pd-S	1549-119	compound & M.P. $<$ 1000 - phase diagram incomplete		Pd-S - tetr
Pd-Zn	1549-419	possible compounds - phase diagram not confirmed		
Pt-Re	1769-3180	no compound - phase diagram simple		
Pt-Rh	1769-1966	continuous series of solid solutions	TABLE 2.3 60, 61	f.c.c.
Pt-Tl	1769-302	compound M.P. $<$ 1000- phase diagram simple		PtTl
Pt-W	1769-3370	no compounds - phase diagram simple	TABLE 2.3	
Pu-V	640-1900	no compounds - phase diagram simple		
Si-Sn	1417-232	no compounds - phase diagram simple		
Ta-Ti	2996-1680	continuous series of solid solutions		
Ta-U	2996-1133	no compounds - phase diagram simple		
Ta-W	2996-3370	continuous series of solid solutions		
Th-Ti	1700-1660	no compounds - phase diagram simple		
Th-U	1675-1133	no compounds - phase diagram simple		

TABLE 2.1 (cont'd.)

System (A) (B)	M.P. °C (A) (B)	Description	Resistivity Reference	Crystal Structure
Th-V	1720-1845	no compounds - phase diagram simple		
Th-Zr	1700-1820	continuous series of solid solutions at high temperature	62	b.c.c.
Ti-U	1720-1133	no compounds - phase diagram simple		
Ti-V	1720-1900	complete series of solid solutions	63	
Ti-W	1720-3370	no compounds - phase diagram simple		
Ti-Zr	1720-1860	continuous series of solid solutions	TABLE 2.3 64	
U-V	1133-1900	no compound - phase diagram simple		
U-W	1133-3370	no compound - phase diagram simple		
U-Zr	1133-1840	continuous series of solid solutions		

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TABLE 2.2

SELECTED PRECIOUS METALS - ALLOYS

Composition	*** M.P. (°C)	Density - grams/cc	α(0-100°C)	ρ Microhm - Cm						Selected References
				0°	20	100	500	1000	1200	
10% Rhodium-Platinum	-	-	1.7×10^{-3}	-	19.	-	-	-	-	(36), 6,7
10% Iron-Platinum	1800	21.6	1.3×10^{-3}	-	24.5	-	-	-	-	(36), 6,7
20% Iron-Platinum	1815	21.7	0.85×10^{-3}	-	32.	-	-	-	-	(36), 6,7
25% Iron-Platinum	1845	21.7	-	-	32.5	-	-	-	-	(36), 6,7
30% Iron-Platinum	1885	21.8	-	-	33.0	-	-	-	-	(36), 6,7
4% Ruthenium-Platinum	1775	20.8	-	-	30.0	-	-	-	-	
10% Ruthenium-Platinum	1780	19.9	4.7×10^{-3}	-	42.0	-	-	-	-	
Iron-Ruthenium-Platinum	1890	20.8	-	-	39.0	-	-	-	-	(36), 6,7
8% Nickel-Platinum	1660	19.3	-	-	27.0	-	-	-	-	(36), 6,7
10% Ruthenium-Palladium	1580	12.0	-	-	36.0	-	-	-	-	
40% Silver-Palladium	1290	11.0	-	-	43.0	-	-	-	-	(36), 6,7
40% Gold-Palladium	1200	10.4	-	-	35.0	-	-	-	-	
5% Ruthenium 15% Rhodium-Platinum	-	-	0.7×10^{-3}	-	31.	-	-	-	-	

*** (Solids)

TABLE 2.2 (Cont'd)

Composition	*** M.P. (°C)	Density * grams/cc	α(0-100°C)	ρ Microhm - Cm						Selected References
				0°	20	100	500	1000	1200	
8% Tungsten-Platinum	-	-	0.28×10^{-3}	-	62	-	-	-	-	(36), 6,7
5% Molybdenum-Platinum	-	-	0.24×10^{-3}	-	64	-	-	-	-	
20% Copper-Platinum	-	-	9.8×10^{-5}	-	82.5	-	-	-	-	
40% Silver-Platinum	-	-	3×10^{-5}	-	42.0	-	-	-	-	

TABLE 2.2 (Cont'd)

Composition	M.P. (°C)	Density - grams/cc	α(0-100°C)	ρ Microhm - Cm						Selected References
				0°C	20°C	100°C	500°C	1000°C	1200°C	
10% Rhodium-Platinum	-	19.97	1.7×10^{-3}	-	19.2	-	-	-	-	(11), 293
20% Phodium-Platinum	-	18.74	1.4×10^{-3}	-	20.8	-	-	-	-	(11), 293
10% Iron-Platinum	-	21.53	1.3×10^{-3}	-	25	-	-	-	-	(11), 293
25% Iron-Platinum	-	21.66	0.6×10^{-3}	-	33.0	-	-	-	-	(11), 293
5% Ruthenium-Platinum	-	20.67	0.9×10^{-3}	-	31.5	-	-	-	-	(11), 293
10% Ruther ium-Platinum	-	19.94	0.8×10^{-3}	-	43.0	-	-	-	-	(11), 293
4% Tungsten-Platinum	-	21.3	-	-	36.5	-	-	-	-	(11), 293
4.5% Ruthenium-Palladium	-	12.0	1.3×10^{-3}	-	23.5	-	-	-	-	(11), 293
40% Silver-Palladium	-	11.3	2×10^{-5}	-	42.0	-	-	-	-	(11), 293
40% Copper-Palladium	-	10.6	0.32×10^{-3} 2.24×10^{-3}	-	35.0 quenched 3.5 ordered		- -	- -	- -	(11), 293 (11), 293
10% Rhodium-Platinum	1830	20.0	-	-	19.1	-	(32.4)	46.5	51.5	(10), Values of after conversion from ohms-circular-mil-foot
20% Rhodium-Platinum	1860	18.7	-	-	20.75	-	(31.5)	43.2	48.3	
40% Rhodium-Platinum	1920	16.6	-	-	17.45	-	(28.20)	39.9	44.8	
										Where (estm) by interpolation between (20°C & 1000°C)

TABLE 2.2 (Cont'd)

Alloy	20°c	500°c	1200°c	Ref.
10% Rh-Pt	19.1	-	51.5	(10)
20% Rh-Pt	20.75	-	48.3	(10)
40% Rh-Pt	17.45	-	44.8	(10)
10% Ir-Pt	25.	-	-	(11)
25% Ir-Pt	33.	-	-	(11)
30% Ir-Pt	33	-	-	(36)
4% Ru-Pt	30.	-	-	(36)
5% Ru-Pt	31.5	-	-	(11)
10% Ru-Pt	43.0	-	-	(11)
10% Ru-Pt	42.	-	-	(36)
8% Ni-Pt	27.0	-	-	(36)
4% W-Pt	36.5	-	-	(11)
8% W-Pt	62.0	-	-	(36)
5% M_O-Pt	64.0	-	-	(36)
20% Cu-Pt	82.5	-	-	(36)
40% Ag-Pt	42.0	-	-	(36)
4.5% Ru-Pd	23.5	-	-	(11)
10% Ru-Pd	36.0	-	-	(36)
40% Ag-Pd	42 to 43	-	-	(36) & (11)
40% Cu-Pd	35. (quenched)	-	-	(36) & (11)
40% Cu-Pd	3.50 (ordered)	-	-	(11)
In-Ru-Pt	39.0	-	-	(36),p.6,7.

TABLE 2.3 - BASIC DATA

Alloys I

(Resistivity at 20°C, Temperature Coefficient of Resistivity, Composition, Solidus Temperature)

Basic Data - Purer Alloys

Alloy (Pure)	Nominal Composition (Wt. %)	Solidus Temperatures (° C)	Temperature (° C)	Resistivity (ρ) (microhm-cm)	Temperature Coefficient of Resistivity (α)	Reference Number Page	Remarks
Ag-Cu	Cu-20 Ag-80	779	≈20° C	2.31	3.00×10^{-3}	(24);18 (16);202, 204	
	Cu-40 Ag-60	779	≈20° C	2.31	3.23×10^{-3}	(24);18 (16);202, 204	
	Cu-60 Ag-40	779	≈20° C	2.31	3.00×10^{-3}	(24);18 (16);202, 204	
	Cu-80 Ag-20	779	≈20° C	2.31	3.07×10^{-3}	(24);18 (16);202, 204	
	Cu-90 Ag-10	779	≈20° C	2.31	3.23×10^{-3}	(24);18 (16);202, 204	
Ag-Au	Au-20 Ag-80	970	≈20° C	5.39	1.32×10^{-3}	(16);202, 204 (24);5, 6, 7	
	Au-40 Ag-60	980	≈20° C	8.85	0.847×10^{-3}	(16);202, 204 (24);5, 6, 7	
	Au-60 Ag-40	1015	≈20° C	10.0	0.693×10^{-3}	(16);202, 204 (24);5, 6, 7	
	Au-80 Ag-20	1035	≈20° C	9.24	0.886×10^{-3}	(16);202, 204 (24);5, 6, 7	
Ag-Pt	Pt-10 Ag-90	963+	≈20° C	8.86		(16);202, 204 (34);43	
	Pt-20 Ag-80	≈970	≈20° C	17.7		(16);202, 204	
	Pt-30 Ag-70	≈1000	≈20° C	27.3		(16);202, 204 (24);43	

TABLE 2.3.1

Basic Data - Purer Alloys

	Pt-35 Ag-65	≈1029	≈20° C	30.		(16);202, 204 (24);43	
Ag-Pd	Pd-20 Ag-80	1075	≈20° C	10.0	0.50×10^{-3}	(16);202, 204 (24);41, 42	
	Pd-40 Ag-60	1230	≈20° C	21.5	0.384×10^{-3}	(16);202, 204 (24);41, 42	
	Pd-50 Ag-50	1285	≈20° C	32.3	0.153×10^{-3}	(16);202, 204 (24);41, 42	
	Pd-60 Ag-40	1330	≈20° C	41.6	0.057×10^{-3}	(16);202, 204 (24);41, 42	
	Pd-80 Ag-20	1425	≈20° C	30.8	$.577 \times 10^{-3}$	(16);202, 204 (24);41, 42	
Au-Pt	Pt-10 Au-90	1120	≈20° C	10.3		(24);226 (16);202, 204	
	Pt-20 Au-80	1180	≈20° C	12.3		(24);226 (16);202, 204	
	Pt-22 Au-78		≈20° C	13.1		(24);226 (16);202, 204	
	Pt-25 Au-75	1215	≈20° C	13.8		(24);226 (16);202, 204	
	Pt-30 Au-70	1240	≈20° C	19.2		(24);226 (16);202, 204	
	Pt-40 Au-60	1270	≈20° C	32.3		(24);226 (16);202, 204	
AuPd	Pd-20 Au-80	1340	≈20° C	11.5	0.73×10^{-3}	(24);224 (16);202, 204	

TABLE 2.3.1 (cont'd.)

Basic Data - Purer Alloys

	Pd-40 Au-60	1440	≈20° C	24.2	0.405×10^{-3}	(24);224 (16);202, 204	
	Pd-50 Au-50	1500	≈20° C	26.9	0.73×10^{-3}	(24);224 (16);202, 204	
	Pd-60 Au-40	1520	≈20° C	24.6	0.81×10^{-3}	(24);224 (16);202, 204	
Au-Fe	Fe-60 Au-30	1168	≈20° C	13.1		(24);204 (16);202, 204	
	Fe-70 Au-30	1168	≈20° C	19.3		(24);204 (16);202, 204	
	Fe-80 Au-20	1200	≈20° C	17.7		(24);204 (16);202, 204	
	Fe-90 Au-10	1430	≈20° C	19.3		(24);204 (16);202, 204	
Co-Ni	Co-20 Ni-80	≈1460	≈20° C	6.92		(24);485 (16);202, 204	
	Co-40 Ni-60	≈1468	≈20° C	8.85		(24);485 (16);202	
	Co-50 Ni-50	≈1475	≈20° C	9.62		(24);485 (16);202	
	Co-60 Ni-40	≈1480	≈20° C	10.4		(24);485 (16);202	
	Co-80 Ni-20	≈1488	≈20° C	11.5		(24);485 (16);202	
Cu-Au	Au-20 Cu-80	≈1050	≈20° C	6.54	$\frac{.84}{0.69} \times 10^{-3}$	(24);198 (16);202	

TABLE 2.3.1 (cont'd.)

Basic Data - Purer Alloys

	Au-30 Cu-70	≈1020	≈20° C	6.93	0.53	(24);198 (16);202	
	Au-40 Cu-60	≈980	≈20° C	9.23	$\frac{0.92}{0.49} \times 10^{-3}$	(24);198 (16);202	
	Au-50 Cu-50	≈960	≈20° C	11.15	$\frac{0.49}{1.91} \times 10^{-3}$	(24);198 (16);020	
	Au-60 Cu-40	≈925	≈20° C	12.5	$\frac{0.84}{0.49} \times 10^{-3}$	(24);198 (16);202	
	Au-70 Cu-30	≈895	≈20° C	13.5	$\frac{0.53}{1.07} \times 10^{-3}$	(24);198 (16);202	
	Au-80 Cu-20	≈889	≈20° C	12.5	$\frac{0.76}{0.61} \times 10^{-3}$	(24);198 (16);202	
Cu-Cr	Cr-5 Cu-95	≧1075	≈20° C	≈1.9	$+3.85 \times 10^{-3}$	(24);524 (16);202, 205	
	Cr-10 Cu-90	≧1075	≈20° C	1.9 Relative	$+3.85 \times 10^{-3}$	(24);524 (16);202, 205	
	Cr-15 Cu-85	≧1075	≈20° C	2.3 Relative	$+2.54 \times 10^{-3}$	(24);524 (16);202, 205	
Cu-Fe	Fe-10 Cu-90	1094	≈20° C	3.46		(24);580 (16);202	
	Fe-15 Cu-85	1094	≈20° C	3.84		(24);580 (16);202	
	Fe-20 Cu-80	1094	≈20° C	4.23		(24);580 (16);202	
	Fe-40 Cu-60	1094	≈20° C	5.38		(24);580 (16);202	

TABLE 2.3.1

Basic Data - Purer Alloys

	Fe-60 Cu-40	1094	≈20° C	7.32		(24);580 (16);202	
	Fe-80 Cu-20	1094	≈20° C	9.82		(24);580 (16);202	
Cu-Ni	Ni-10 Cu-90	≈1100	≈20° C	13.8	0.77×10^{-3}	(24);602 (16);203, 205	
	Ni-20 Cu-80	≈1130	≈20° C	20.	0.34×10^{-3}	(24);602 (13);203, 205	
	Ni-30 Cu-70	≈1165	≈20° C	40.	0.19×10^{-3}	(24);602 (16);203, 205	
	Ni-40 Cu-60	≈1210	≈20° C	49.6	0.077×10^{-3}	(24);602 (16);203, 205	
	Ni-58 Cu-42	≈1285	≈20° C	49.6	0.038×10^{-3}	(24);602 (16);203, 205	
	Ni-60 Cu-30	≈1290	≈20° C	49.6	0.27×10^{-3}	(24);602 (16);203, 205	
	Ni-80 Cu-20	≈1370	≈20° C	34.6 estm.	4.07×10^{-3}	(24);602 (16);203, 205	
Cu-Sn	Sn-10 Cu-90	≈825	≈20° C	13.1	$\times 10^{-3}$	(24);634 (16);203, 205	
	Sn-20 Cu-80	798	≈20° C	25.	$\times 10^{-3}$	(24);634 (16);203, 205	
	Sn-32 Cu-68	≈750	≈20° C	40.3	$\times 10^{-3}$	(24);634 (16);203, 205	
	Sn-40 Cu-60	≈680	≈20° C	8.77	$\times 10^{-3}$	(24);634 (16);203, 205	

TABLE 2.3.1 (cont'd.)

Basic Data - Purer Alloys

Fe-W	W-2 Fe-98	≈1530	≈20° C	17.5		(24);734 (16);203	
	W-10 Fe-90	≈1525	≈20° C	17.1		(24);734 (16);203	
	W-8 Fe-92		≈20° C	17.9		(24);734 (16);203	
Fe-Ni	Ni-10 Fe-90	≥1455	20° C	27.2	2.0×10^{-3}	(24);678 (16);203, 205	
	Ni-15 Fe-85	≥1455	20° C	31	1.38×10^{-3}	(24);678 (16);203, 205	
	Ni-20 Fe-80	≥1455	20° C	41	1.46×10^{-3}	(24);678 (16);203, 205	
	Ni-25 Fe-75	≥1455	≈20	62.	1.61×10^{-3}	(24);678 (16);203, 205	
	Ni-28 Fe-72	≥1455	20	79.2	1.46×10^{-3}	(24);678 (16);203, 205	
	Ni-34 Fe-67	≥1455	20	85.5	1.08×10^{-3}	(24);678 (16);203, 205	
	Ni-45 Fe-55	≥1455	20	47	3.15×10^{-3}	(24);678 (16);203, 205	
	Ni-55 Fe-45	≥1455	20	41	$\times 10^{-3}$	(24);678 (16);203, 205	
	Ni-60 Fe-40	≥1455	20	29.5	$\times 10^{-3}$	(24);678 (16);203, 205	
	Ni-70 Fe-30	≥1455	20	27.2	$\times 10^{-3}$	(24);678 (16);203, 205	

TABLE 2.3.1 (cont'd.)

Basic Data - Purer Alloys

	Ni-80 Fe-30	≥1455	20	21.7	x 10^{-3}	(24);678 (16);203, 205	
Fe-Cr	Cr-5 Fe-95	≥1507	20	25.6	3.3×10^{-3}	(24);527 (16);204, 205	
	Cr-10 Fe-90	≥1507	20	39.1	2.38×10^{-3}	(24);527 (16);204, 205	
	Cr-15 Fe-85	≈1507	20	47.2	2.42×10^{-3}	(24);527 (16);204, 205	
	Cr-18 Fe-82	≈1507	20	52	2.53×10^{-3}	(24);527 (16);204, 205	
	Cr-20 Fe-80	≈1507	20	44.2	2.30×10^{-3}	(24);527 (16);204, 205	
Ni-Cr	Cr-5 Ni-95	≈1450	20	43.9	0.77×10^{-3}	(24);542 (16);204, 205	
	Cr-10 Ni-90	≈1425	≈20	70.	0.33×10^{-3}	(24);542 (16);204, 205	
	Cr-15 Ni-85	≈1405	20	91.	0.19×10^{-3}	(24);542 (16);204, 205	
	Cr-20 Ni-80	≈1400	20	100	0.15×10^{-3}	(24);542 (16);204, 205	
Ni-Mn	Mn-5 Ni-95	≈1400	20	19.3		(24);938 (16);204, 205	
	Mn-10 Ni-90	≈1350	20	30.8		(24);938 (16);204, 205	
	Mn-15 Ni-85	≈1290	20	40		(24);938 (16);204, 205	

TABLE 2.3.1 (cont'd.)

Basic Data - Purer Alloys

	Mn-20 Ni -80	≈1240	20	77.		(24);938 (16);204, 205	
Pt-Ir	Ir-5 Pt -95	≈1770	20	18.5	1.92×10^{-3}	(24);872 (16);204, 205	
	Ir-10 Pt -90	≈1780	20	23.1	1.73×10^{-3}	(24);872 (16);204, 205	
	Ir-15 Pt -85	≈1800	20	26.9	1.00×10^{-3}	(24);872 (16);204, 205	
	Ir-20 Pt -80	≈1825	20	30.0	0.81×10^{-3}	(24);872 (16);204, 205	
	Ir-30 Pt -70	≈1900	20	32.7	0.61×10^{-3}	(24);872 (16);204, 205	
	Ir-34-35 Pt -66-65	≈1930	20	36.9	0.54×10^{-3}	(24);872 (16);204, 205	
Pt-Rh	Rh-5 Pt -95	≈1810	20	16.9		(24);1137 (16);204, 205	
	Rh-10 Pt -90	≈1840	20	21.5		(24);1137 (16);204, 205	
Pt-Pd	Pd-10 Pt -90	Solidus and Liquidus have not been determined	≈20	19.3	1.42×10^{-3}	(24);1121 (16);204, 205	
	Pd-20 Pt -80	"	20° C	23.1	1.15×10^{-3}	(24);1121 (16);204, 205	
	Pd-30 Pt -70	"	20° C	25.8	1.04×10^{-3}	(24);1121 (16);204, 205	

TABLE 2.3.1 (cont'd)

Basic Data - Purer Alloys

	Pd-40 Pt-60	"	20° C	26.9	1.04×10^{-3}	(24);1121 (16);204, 205	
	Pd-50 Pt-50	"	20° C	26.2	1.07×10^{-3}	(24);1121 (16);204, 205	
	Pd-60 Pt-40	"	20° C	24.2	1.15×10^{-3}	(24);1121 (16);204, 205	
	Pd-70 Pt-30	"	20° C	22.3	1.27×10^{-3}	(24);1121 (16);204, 205	
	Pd-80 Pt-20	"	20° C	19.3	1.54×10^{-3}	(24);1121 (16);204, 205	
	Pd-90 Pt-10	"	20° C	15.0	2.15×10^{-3}	(24);1121 (16);204, 205	

TABLE 2.3.2

- Alloys -

Alloy	Nominal Composition (Weight%)	Trade Name or Designation	Established Application - -and Oxidation Resistance	Form and Condition; Cast; Wrought; - Annealed Quenched	Solidus Temperature (°C)	Temperature (°C)	Resistivity, (Microhm-om)	Temperature Coefficient of Resistivity α	Reference Number Page
		Silver Alloys	**Electrical Contacts**						
Ag	100-Ag	--	High	Not Specified	960	20	1.627		(40);803
		Ag-Cu Alloys							
Ag-Cu	92.5 Ag 7.5 Cu	92.5-7.5		Not Specified	821	20	2.03		(40; 803
Ag-Cu	90 Ag. 10-Cu	90-10 "Coin-Silver"	Low	Not Specified Annealed	777 877	20 20	2.03 2.016		(40);803 (19);23
Ag-Cu	72 Ag 28 Cu	72-28	Low	Not Specified	777	20	1.96		(40); 803
		Ag-Cu-Ni-Alloys							
Ag-Cu-Ni	72-Ag 26-Cu 2-Ni	72-26-2	Low	Not Specified	777	20	2.88		(40);803
		Ag-Cd-Alloys							
Ag-Cd	85 Ag 15 Cd	85-15	Low	Not Specified	877	20	4.93		(40);803
		Ag-Pt-Alloys							
Ag-Pt	97 Ag. 3 Pt.				982	20	3.45		(40);803
		Ag-Pd-Alloys							
Ag-Pd.	97 Ag. 3 Pd	97-3			976	20	2.88		(40);803
Ag-Pd.	90 Ag. 10 Pd.	90-10			999	20	5.75		(40);803
AG-Pd	60 Ag. 40 Pd.	60-40		Not Specified	1227	20	21.5		(40);803

TABLE 2.3.2 (cont'd.)

- Alloys - Cont.

Ag-Pd	70 Ag 30 Pd.	70-30		Not Specified	1227	20	14.4		(40);803
Ag-Au	90 Ag. 10 Au	Ag-Au 90-10			971	20	4.31		(40);803
	90 Pt. 10 Rh	Pt. Alloys (Note)*	Electrical Contacts						
Pt.	Nominally 100 Pt.	--	High	Not Specified	1771	20	10.78		(40);803
Pt-Rh	90 Pt 10 Rh	Pt-Rh Alloy 90-Pt 10-Rh		Annealed	1845	20 0	19.45 21.14	0.0013 (0° to 100°C)	(19);23 (39);675
Pt-Ir	95 Pt 5 Ir	Pt-Ir Alloy 95-5 Free from oxide film at all temp. Ref. (32);79)	High	Not Specified	1777	20	19.20		(40);803
Pt-Ir	90 Pt 10 Ir	90-10	High	Not Specified Annealed	1782 1815	20 20 20	23.6 24.4 24.3	0.0012 (0° to 100°C)	(6);350 (40);803 (39);675 (19); 23
Pt-Ir	85 Pt 15 Ir	85-15	High	Not Specified Annealed	1788	20 20	29.1 28.8		(6);350 (40);803
Pt-Ir	80 Pt	80-20 20 Ir	High	Not Specified Annealed	1810	20 20	30.6 30.8		(6);350 (40);803
Pt-Ir	75 Pt 25 Ir	75-25	High	Not Specified Annealed	1821	20	31.8 31.4		(6);350 (40);803
Pt-Ir	70-Pt 30-Ir	70-30	High	Not Specified Annealed	1849	20	34.5 33.1		(40);803 (6);350

*Note: Oxidation Resistance of Pt-Ir
Pt-Rh
and Pt-Pd Alloys in Oxygen have been determined at 900°C and 1100°C/Ref. (14);25, 26, 2)

TABLE 2.3.2 (cont'd.)

- Alloys - Cont.

Pt-Ir	65-Pt 35-Ir	65-35	High	Not Specified Annealed	1899	20	34.5		(40);803
		Pt-Ru-Alloys							
Pt-Ru	95 Pt 5 Ru	95-5	High	Not Specified	1782	20	31.4		(40);803
Pt-Ru	90-Pt 10-Ru	90-10	High	Not Specified Annealed	1799 1840	20 20	43.2 42.4	8 X 10^{-4} (0-100°C)	(40);803 (10);1125 (19);23
Pt-Ru	89 Pt 11 Ru	89-11	High	Not Specified Annealed	1815	20	43.2		(40);803
Pt-Ru	86 Pt 14 Ru	86-14	High	Not Specified Annealed	1843	20	49.3		(40);803
		Pt-W Alloys							
Pt-W	96-Pt 4-W	96-4	High	Not Specified	1777 1800	20	34.5 36.9		(40);803 (10);1126
		Pd-Alloys							
Pd-	100-Pd	--	High	Not Specified	1554	20	1078		(40);803
		Pd-Ru Alloys							
Pd-Ru	99.5 Pd 4.5 Ru	99.5-4.5	High Free of oxide films	Not Specified Annealed	1593	20 20	24.5 24.2		(40);803 (32);79 (19);23
Pd-Ru	90-Pd 10-Ru	90-10	High Unstable oxide films formed at High Temp.	Not Specified Annealed	1649	20	26.6		(40);803 (32);79
		Pd-Ag-Alloys							
Pd-Ag	70-Pd 30-Ag	70-30	High	Not Specified	1377	20	40.2		(40);803
Pd-Ag	60-Pd 40-Ag	60-40	High Unstable oxide formed at high temperatures	Not Specified Annealed	1388 to -1330	20 20	43.2 43.9		(40);803 (32);39 (19);23

TABLE 2.3.2 (con t'd.)

- Alloys - Cont.

Pd-Ag	50-Pd 50-Ag	50-50	High	Not Specified Annealed	1288	20	31.4		(40);803
Pd-Ag-Ni	72-Pd 62-Ag 2-Ni	72-26-2Ni	High	Not Specified Annealed	1382	20	43.2		(40);803
		Pd-Cu-Alloys							
Pd-Cu	60-Pd 40-Cu	60-40	Low Stable oxide films formed	Not Specified	1199	20	34.3		(40);803 (32);79
		Pd-Complex - Alloys							
Pd-Ag-Au-Pt	40-Pd 30-Ag 20-Au 5-Pt	--	High	Not Specified	1371	20	38.4		(40);803
Pd-Ag-Cu Pt-Au-Zn	30 Pd 30 Ag 14 Cu 10 Pt 10 Au 1-Zn	--	Low	Not Specified	1085	20	34.5		(40);803
		Palladium Alloy No. 34							
Pd-Ag-Cu-Pt	35 Pd 30 Ag 15 Cu 10 Pt 10 Au		?	Heated Treated	1085	35.7			(19);23
		Gold-Alloys							
Au	100 Au	--	High	Not Specified	1063	20	2.30		(40);803
Au-Cu	90-Au 10-Cu	90-10	Medium	Not Specified	932	20	10.78		(40);803
Au-Ag	75 Au 25 Ag.	75-25	High	Not Specified	1030	20	10.78		(40);803

TABLE 2.3.2 (cont'd.)

- Alloys - Cont.

Au-Cu-Pt-Ag-Zn	72.5 Au 14. Cu 8.5 Pt 4 - Ag 1-Zn	--	Medium	Not Specified	954	20	17.24		(40);803
Au-Ag-Pt	69-Au 25-Ag 6 Pt	69-25-6 W.E. No. 1	High	Not Specified Annealed	1030	20 20	15.7 17.5		(40);803 (19);24
Au-Cu-Ni-Zn	41.7 Au 32.5 Cu 18.8 Ni 7 Zn	--	Low	Not Specified Annealed	1060	20	38.4		(40);803
Au-Ni-Zn-Cu	75-Au 18.5-Ni 5.25-Zn 1.25 Cu	18 K-white Gold	?	Annealed	1030	20	34.95		(19);24
Au-Ag	90 Au 10 Ag			Annealed		0°	6.3	0.0012 (0 to 100°C)	(39);674
Au-Ag	67-Au 33-Ag			Annealed		0°	10.8	0.00065 (0° to 100°C)	(39);674
Au-Mn	(See Metallic Compounds)								
Au-Cu-Ag	78.3 Cu 14.3 Ag Bal. Au					0°	3.6	0.0018 (0° to 100°C)	(39);674
Au-Cu-Ag	26.5 Cu 15.2 Ag Bal. Au					0°	13.6	0.00057 (0° to 100°C)	(39);674
Au-Cu-Ag	15.4 Cu 18.1 Ag Bal. Au					0°	14.6	0.00053	(39);674
Ag-CuZn	25 Cu 15 Zn Bal Ag					0°	8.3	--	(39);674

TABLE 2.3.2 (cont'd.)

- Alloys - Cont.

Ag-Cd- -Zn-Cu	18 Cd 16.5 Zn 15.5 Cu Bal. Ag					0°	7.0	--	(39);674
Cu-Be	Be-1 Cu-99	Beryllium Copper	Used for highly stressed Mechanical parts and as contacts	State (1); Soft Quenched Condition	950	20° (assumed)	6.8		(6);333 (24);282
" "	Be-1 Cu-99	"	" "	State (2); Precipitation Hardened from soft	"	"	6.1		(6);333 (24);282
"	Be-1 Cu-99	"	" "	State (3); Cold" worked	"	"	6.8		(6); 333 (24);282
"	Be-1 Cu-99	"	" "	State (4); Precipitation Hardened from cold-worked	"	"	5.7		(6);333 (24);282
"	Be-2 Cu-98	"	" "	State (1)	About 880	"	9.7	(6);33	(6);333 (24);282
"	Be-2 Cu-98	"	" "	State (2)	"	"	5.2		(6);333 (24);282
"	Be-2 Cu-98	"	" "	State (3)	"	"	10.3		(6);333 (24);282
"	Be-2 Cu-98	"	" "	State (4)	"	"	5.7		(6);333 (24);282
"	Be-3 Cu-97	"	" "	State (1)	866	"	10.0		(6);333 (24);282
"	Be-3 Cu-97	"	" "	State (2)	"	"	5.7		(6);333 (24);282
"	Be-3 Cu-97	"	" "	State (3)	"	"	10.6		(6);333 (24);282
Cu-Be	Be-3 Cu-97			State (4)	866	20° (assumed)	6.8		(6);333 (24);282

TABLE 2.3.2 (Continued)

- Alloys - Cont.

Cu-Cr	CR-0.5-1.0 Cu-Bal.	Cu-Cr	Stable to 450°	Precipitation hardening type of electrical material	Cast (4)		20°	About 2.0		(6);337
	Cr-0.5-1.0 Cu-Bal.	"	"	"	Wrought (heat treated)		20°	"		(6);337
Cu-Ni	Ni-10 Cu-90			Resistance of copper to oxidation is improved by additional nickel			20° assumed	14.7		(6);339
	Ni-15 Cu-85						"	21.4		(6);339
	Ni-20 Cu-80				Stable up to about 300°C.		"	28		(6);339
Cu-Ni *(See Note)	Ni-30 Cu-70						"	40.2		(6);339
"	Ni-40 Cu-60						"	47.7		(6);339
"	Ni-50 Cu-50						"	52.1		(6);339
"	Ni-60 Cu-40						20 assumed	51.7		(6);339
"	Ni-70 Cu-30						"	44.6		(6);339
"	Ni-80 Cu-20						"	31.2		(6);339
"	Ni-90 Cu-10						"	17.8		(6);339
	Ni-4 Cu-96				Sand Cast chill-cast			8.3 7.4		(6);340 (6);340

*Note—See also pure alloys and Industrial Alloys of copper per references (16);202 and (39)

TABLE 2.3.2 (cont'd.)

- Alloys - Cont.

Cu-Ni-Zn	Zn-26 Ni-10 Cu-64				1000	20	22		(6);341
"	Zn-21 Ni-15 Cu-64				1060		27		(6);341
"	Zn-18 Ni-20 Cu-62				1100		31		(6);341
"	Zn-16-17 Ni-30 Cu-53-54				1175		40		(6);341
Cu-Ag	Ag 0.034 Cu-Bal	Employed an Alloy to raise annoding temp. and not impair conductivity.		Conductivity 99.5% of copper	1083	20	1.73		(6);343
"	Cu 7 1/2 Ag 92.5	Alloys employed to increase the Hardness and Wear Resistance of Ag.	Improved oxidation resistance related to copper		804	20	1.9		(6);352
"	Cu-15 Ag-85	Alloys employed to increase the Hardness and Wear Resistance of Ag.	Improved oxidation Resistance related to copper.		850	20	--		(6);352
Pd-Cu	Cu-5 Pd-95	Pd-Cu Alloy 95-5			1500°	20	22.6		(6);348
"	Cu-10 Pd-90	90-10			1425	20	31.3		(6);348 (24);613
"	Cu-20 Pd-80	80-20			1330	20	42.5		(6);348 (24);613

TABLE 2.3.2 (Continued)

Pd-Cu	Cu-30 Pd-70	70-30			1240	20	46.5		(6);348 (24);613
..	Cu-40 Pd-60	60-40	ordered stable 300°C	Annealed Ordered	1200	20	35 3.5	3.2×10^{-4} 2.24×10^{-3}	(10);1128 (24);613
Pd Ag	Pd-10 Ag-90	Ag-Pd Alloy 90-10	Alloy Characteristics (1) hardness: 2) fairly high conductivity;		≈ 1000	20			(6);348, 349 (24);42
	Pd-20 Ag-80	80-20	3) high resistance to corrosion and oxidation when Pd content exceeds 40.		≈1070	20			(6);348, 349 (24);42
	Pd-30 Ag-70	70-30	4) Well suited for electrical contacts when Pd range is from 10-60%		≈ 1160	20	15.7		(6);348, 349 (24);42
	Pd-60 Ag-40	60-40			≈ 1330	20	35		(6);348, 349 (24);42
Pt-Ir-W	Not Specified				1880	20	22.2		(6);350
Pt-Ir-Ru	Not Specified				1890	20	39.0		(6);350
Pt-Ir-05	Not Specified				2000	20	--		(6);350
Pt-Ag	Ag-67 Pt-33				1200	20	32.4		(6);350
Pt-Au-Ag	Pt-7 Au-67 Ag-26				1120	20	16.8		(6);350
W-Cu	Cu-40-50 W. Bal.	(Interpreted as "Typical constitution)		Alloy; just a mixture (powder Metal)	Solidus ≈ M. P. of Cu=1083	20	5.1		(6);353, 354 (24);649
W-ag	Ag-40-50 W-Bal.	(Interpreted as "Typical constitution)		Alloy;just a mixture (Powder Met.)	Solidus ≈ M. P. of Ag. i. e. 961°	20	3.9		(6);353-355 (24);62
Ni-Ag	Ag-18 Ni Bal					R. T.	30-33	3×10^{-4}	(16);171

TABLE 2.3.2 (Continued)

- Alloys - Cont.

Ag-Ni	Ni-40 Ag-60	Ni-Ag "Alloy" 40-60	Improve Mech. Propt. of Ag and retain essentially high conductivity and free from oxidation	Alloy is essential a mixture (powder Met.)	Solidus ≈M. P. of Ag. i. e. 961°	20	2.14 (calc)		(6);355 (24);36
Ag-Mo	Not specified. Assume "Typical composition" Ag-50 Mo-50		Characteristic 1) high errosion and wear resistant 2) good conductivity	Alloy is essential a mixture (powder Met.)	"	20	3.3		(6);356 (24);34
Ag-Wc	Typical composition assumed WC-50 Ag-50		1) high conductivity 2) high arcing resistance 3) good oxidation resistance	Poweder Metallurgy Mixture	Solidus ≈M. P. of AG i. e. 961°	20	2.9		(6);356
Pt-Ni	Nt-1 Pt-99	Pt-Ni Alloy 1-99				20	12.7	3.3 x 10^{-3} (0° - 100°C)	(10);1125
	Ni-2 Pt-98	2-98				20	15.0	3. X 10^{-3} (0° - 100°C)	(10);1125
	Ni-5 Pt-95	5-95				20	23.3	2 x 10^{-3} (0° - 100°C)	(10);1125
Pt-Ir	Ir-10 Pt-90	Ir-Pt Alloy 10-90		T.C.C. Alloy		20	25	1.3 x 10^{-3} (0 - 100° C)	(5);12
	Ir-20 Pt-80	20-80		T.C.C. Alloy		0° 20	32.9 33.4	0.85 x 10-3 (0 - 100°C)	(5);12 (10);1124
Pt-Rh	Rh-10 Pt-90	Rh-Pt Alloy 10-90		T.C.C. Alloy		20	18.3 19.2	1.66 x 10^{-3}	(5); 12 (10);1124
	Rh-15 Pt-85	15-85		T.C.C. Alloy		20	20	1.50 x 10^{-3} (0 - 100° C) 1.7 x 10^{-3} (20 - 100°)	(5); 12 (10);1124

TABLE 2.3.2 (cont'd.)

Alloys - Cont.

Pt-Rh	Rh-20 Pt-80	20-80		T.C.C. Alloy		20	20.8 20.8	1.20 x 10^{-3} (0 - 1200°C) 1.4 x 10^{-3} (20 - 100°C)	(5);12 (10);1124
Pt-Rh-Cr	Gr-5 Rh-15 Pt-80	Cr-Rh-Pt 5-15-80				0	47.5	2.9 x 10^{-3} (0 - 360°)	(5);12
	Cr-10 Rh-15 Pt-75	Cr-Rh-Pt 10-15-75				0	48	1.6 x 10^{-3} (0 - 160°)	(5);12
Pt-Rh-Co	Co-5 Rh-15 Pt-80	CO-Rh-Pt 5-15-80				0	36		
Pt-Rh-Ru	Ru-5 Rh-15 Pt-80	Ru-Rh-Pt 5-15-80				0	24.7	0.87 x 10^{-3} (0 - 500°C)	(5);12

TABLE 2.3.3

Alloy	Nominal Composition (Wt. %)	Trade Name or Designation	Established Application	Conditions Annealed Quenched Etc.	Solidus Temperature (°C)	Temperature (°C)	(ρ) Resistivity, (Micro-ohm-am)	(α) Temperature coefficient of Resistivity	Reference number page
Cu-O	99.95% cu 0.04% 0	Electrolytic tough pitch copper (E.T.P) A.S.T.M. B224	Electrical Chemical etc.	Annealed	1065	20	1.71	0.00393	(40); 1007
Cu-O	99.95% 0.04%			Liquid		1100	21.52		(40); 1010
Cu-P	99.92% Cu 0.009%P	Deoxided copper, low residual phosphorus (D.L.P) Government number	Exposure to reducting atms. brazing. High ductility with cold work	Annealed	1083 (liquidus)	20.	may approach Or = 1.7241		(40); 1010 (40); 1010
Cu-P	0.48P; Bal. Cu					20	8.4	0.000843 (20°-100°C)	(39); 674
Cu-P	0.93P, Bal. Cu					20	15.2	0.000503 (20°-100°C)	(39); 674
Cu-P	99.95% Cu 0.02%P	Deoxidized copper, high residual phosphoros copper (D.H.P.)	Household Industrial Transportation	Annealed	1083 (liquidus)	20	2.03	0.003 (20°-200°C)	(40); 1010, 1011
Cu-X	99.95% cu "oxygen free"	"oxygen free copper (O.F) wire-soft-AMS 4701	Electrical conductors wave guides capped to glass seals	Annealed	1083 (liquidus)	20	1.707		(40); 1012

TABLE 2.3.3 (cont'd.)

Basic Data Alloys

Cu-Te	99.5% Cu 0.5% Te	Tellurium copper free machining copper A.S.T.M. B301, (Tellurium) copper red)	Electrical properties and requirements for free machining	Annealed	1050	20	2.82		(40); 1012
Cu-Pb	99% Cu 1% Pb	Free Machining copper-leaded copper	same as above	Annealed	953	20	1.76		(40; 1012
Cu-Sn	95% Cu 5% Zn	Gilding Metal, 95% U.S. Govt. No. JAN-G-439	Coinage; Munitions, Base for gold plate and/or vitreous enamel	Annealed	1050 liquid	20 1100 1300	3.1 24.4 26.6	0.00231 at 20°C	(40); 1013, 1014
Cu-Zn	90% Cu 10% Zn	Commercial Bronze Wave Guides MIL-W-85C Microwave-MIL-T-52 069	Architectural; Marine Hardware & Munitions	Annealed	1020	20 1100	3.9 27.2	0.00186 at 20°C	(40); 1014
Cu-Zn	87.5% Cu 12.5% Zn	Jewelry Bronze	Architectural; Hardware Novelties, and Base for Gold plate	Annealed	1005	20	4.4		(40); 1016

TABLE 2.3.3 (cont'd.)

Cu-Zn	85% Cu 15% Zn	Red Brass-85% other Designation after shape see Ref. (40); p1016	includes electrical conduit screw shells and sockets	Annealed	990	20 0 1100 1200	4.7 4.65 29.37 30.43	0.0016 at 20°C	(40); 1016 (19) 8 (39); 674
Cu-Zn	80% Cu 20% Zn	Low Brass-80% A.S.T.M. Flat Rolled products - No. B36-Alloy 4.		Annealed	965	20° 1000 2000	5.4 33.03 33.83	0.00154 at 20°C	(40); 1017
Cu-Zn	70% Cu 30% Zn	Cartridge Brass	Includes electrical application	Annealed	915	20 0 1000	6.2 6.85 39 extrop.	(0.00148) at 20°C 0.0016 (0° to 100°C)	(40); 1019 (39); 674
Cu-Zn	65% Cu 35% Zn	Yellow Brass; drawing Brass; high brass; hoop brass; ASTM-B36-Alloy 8	Includes electrical application	Annealed cold drawn	905 to 932	20 20	6.4 6.6		(40); 1020, 1021 (19); 9
Cu-Zn	60% 40%	Muntz Metal A.S.T.M. B135 Alloy 5	Hot Forging High Strength of Cu-Zn Subject to dezincification & stress corrosion	Annealed	900 to 904	20 0°	6.2 6.81	0.0017 (0° to 100°C)	(40); 1021 (39); 674 (19); 9
Cu-Zn-Pb	89% Cu 9.25% Zn 1.75% Pb	Leaded Commercial Bronze A.S.T.M. No: B140-Alloy B	includes electrical application	Annealed	1010	20	4.1		(40); 1022

TABLE 2.3.3 (cont'd.)

Cu-Zn-Pb	66% Cu 33.5% Zn 0.5% Pb	Low leaded Brass (tubes); high brass; yellow brass A.S.T.M. A.S.T.M. B135-Alloy 3		Annealed	905	20	6.6		(40); 1022
Cu-Zn Pb	65% Cu 34.0% Zn 1.0% Pb	Medium Leaded Brass but Brass matrix 11 Semi leaded Brass swaging A.S.T.M. B121, Alloy 3		Annealed	885	20	6.6		(40); 1022
Cu-Zn	66% Cu 32.4% Zn 1.6% Pb	High leaded brass free cutting tube brass A.S.T.M. B 135, Alloy 4		Annealed	900	20	6.6		(40); 1022 1023
Cu-Zn Sn	60% Cu- 39.25% Zn 0.75% Sn	Naval Brass A.S.T.M. B21 AMS 4611B; 4612C		Annealed	885	20	6.6		(40); 1026 (19); 9
Cu-Zn Sn-Fe-Mn	58.5 Cu 39.2 Zn 1 Sn 1 Fe 0.3 Mn	Manganese Bronze (ASTM B138)		Wrought cold drawn	896	20	7.5		(19); 9
Cu-Sn	95% Cu 5% Sn	Phosphor Bronze, 5% A. Grade Govt. QQ-P300, Comp. A.	Fuse clips included	cold drawn	950	20 0° 20	11. 9.5 11.5		(39); 674 (40); 1027 1028 (19); 9
Cu-Sn	92% Cu 8% Sn	Phosphor Bronze, 8% (C); Grade "C" ASTM-B103 Alloy C	same as above	Annealed	880	20	13.		(40); 1028

TABLE 2.3.3 (cont'd.)

Cu-Sn	90% Cu 10% Sn	Phosphor Bronze 10% - Grade "D" ASTM-B103, Alloy "D"		Annealed	845	20	16		(40); 1028
Cu-Sn	98.75% Cu 1.25% Sn	Phosphor Bronze, 1.25%, Grade "E". A.S.T.M. B105	Electric contacts trolley wire	Annealed	1035	20	3.6		(40); 1028 1029
Cu-Sn	88 Cu 12. Sn					20	18	0.0005 (0° to 100°C)	(39); 674
Cu-Pb.-Sn.-Zn.	88% Cu 4% Pb 4% Sn 4% Zn	Free cutting Phosphor Bronze; 444 Bronze Bearing Bronze A.S.T.M. B139, Alloy B2		Annealed	930	20	10.1		(40); 1029
Cu-Pb Sn-Zn	85-Cu 5-Pb 5 Sn 5 Zn	Red Brass (cast)		Cast "as-cast"	988 to 1004		10.5		(19); 8
Cu-Ni	70% Cu 30% Ni	Cupro-Nickel, 30% 70-30 cupro-nickel Sheet-A.S.T.M. B122	High resistance to stress corrosion application	Annealed (?) cold drawn	1170	20	37. 36.6	0.48×10^{-4} (20 to 200°C)	(40); 1029 (19); 8
Cu-Ni-Fe	88.7% Cu 10% Ni 1.3% Fe	Cupro-nickel, 10% A.S.T.M: B111, B171	condensers; distilling tubes salt water distillation etc.	Annealed cold drawn tube	1100	20 20	15. 18.8		(40); 1030 (19); 8

TABLE 2.3.3 (cont'd.)

Cu-Zn-Ni	65 Cu 25 Zn 10 - Ni	Nickel silver 10% (wrought) 65-10 A.S.T.M-B155 Alloy E		Wrought cold-rolled	1020	20	20.8		(19); 8
Cu-Ni-Zn	65% Cu 18% Ni 17% Zn	Nickel Silver, 65-18, 18% - Alloy A 2 A.S.T.M. B122, Alloy 2 B151, Alloy A B206, Alloy A	Corrosion resistance to organics, water, & atm	Annealed Cold rolled	1070	20	29. 28.8	0.000257 from (20° to 200°C;)	(40); 1030 (19); 8
Cu-Zn-Ni	55% Cu 27% Zn 18% Ni	Nickel Silver, 18%-Alloy B A.S.T.M. (B122 Alloy 4) (B151 Alloy B) (B206 Alloy B)	Same as above including electrical applications	Annealed (?)	1055 (liquidus)	20	31.		(40); 1031
Cu-Zn-Ni	65% Cu 23% Zn 12% Ni	German silver; A.S.T.M. B151, alloy D; B206; Alloy D.	same as above	annealed	1000	20	22	0.00045 (20° to 200°)	(40); 1031
Cu-Zn-Ni Pb-Sn	Bal. Cu 20Zn 12.5 Ni 10.5 Pb 2 Sn	Nickel Silver 13% (cast A.S.T.M. B149 No. 10A		cast		20	33.9		(19); 8

TABLE 2.3.3 (cont'd.)

Cu- Si	96% Cu 3% Si	High Silicon Bronze, (A). copper-silicon Alloys A.S.T.M. (B97 Alloy A) (B96 Alloy A) Etc.	Heat exchanged tubes, chemical equipment, (etc)	Annealed cold drawn	970 to 1018	20	24.9 26.6		(40); 1031 (19); 9
Cu- Si	97.7% Cu 1.5% Si	Low-Silicon Bronze, Type B A.S.T.M. for electrical conductor; B105, Alloy 8.5	Electrical Hydraulics; & Marine Hardware	Annealed	1030	20	14.3		(40); 1032
Cu- Al	97 Cu 3 Al					0°	8.26	0.00102 (0° to 100°C)	(39); 674
Cu- Al	95% Cu 5% Al	Aluminum Bronze, 5% Al. 5% Al. Bronze. ASTM: B169 alloy A & others	cold worked forms, sheets, etc.	Annealed hard	1050	20° 1100 20°	9.8 43.18 11.6	0.00160 from (20° to 200°C)	(40); 1033 (19); 9
Cu- Al	90-Cu 10 Al.					0°	12.6	0.0032 (0° to 100°C)	(39); 674
Cu- Al- Fe	91% Cu 7% Al 2% Fe	A.S.T.M. B150, Alloy 3; B169, Alloy D; B171, Alloy D.	Good strength & corrosion resistance Industrial Hardware Munitions, Etc.	Annealed	1045	20	12.		(40); 1034

TABLE 2.3.3 (cont'd.)

Cu-Al-Si	91% Cu 7% Al 2% Si	Aluminum Silicon Bronze-91-7-2 A.S.T.M. B124, Alloy 11a; B150, Alloy 1; B283, Al-Si bronze	Hot working characteristics strength & corrosion resistance	Annealed	985	20	18.56		(40); 1034
Cu-Al	91% Cu 9% Al	Aluminum Bronze, (1) 9% Aluminum Bronze A.S.T.M. B150 Alloy 1; B124 Alloy 11a	Corrosion resistance Marine hardware heat resistant & other applic.	Annealed	1030	20 1100	13.5 58.22	0.000829 at 20°C	(40); 1035
Cu-Al-Ni-Fe-Mn	81.5% Cu 9.5% Al 5.0 Ni 2.5 Fe 1.0 Mn	Aluminum Bronze (2) ASTM B171 Alloy E; B150, Alloy 2; B124, Alloy 11b	Adapted to hot rolled plates, rods, bars, forging & Marine shafting	Annealed (?)	1035	20	23.		(40); 1036
Cu-Be-Ni (or Co)	97.9% Cu 1.9% Be 0.2 W or Co.	Berrylium copper ASTM B194; ASTM B196; ASTM B197.	includes many electrical applications	Cold worked condition in precipitation hardened condition	864	20° 20°	9.6 to 11.5 5.7 to 7.8		(40); 1037 (40); 1037
Cu-Be	Bal. Cu 2.0 Be					20°	6.8-7.4	0.0013 (0° to 100°C)	(39); 674
Cu-Mn	Bal. Cu 3.0 Mn 1.32 Fe	See also Bronze's proceeding				0°	107.3	$4x10^{-5}$ (0° to 100°C)	(39); 674

TABLE 2.3.3 (cont'd.)

Cu-Mn	Bal. Cu 14.76 Mn 0.33 Fe	See also Bronze's proceeding				22.5	53.46		(39); 674
Cu-Mn	Bal. Cu 7.4 Mn	See also Bronze's proceeding				20°	19.7	$25x10^{-5}$ (20° to 100°C)	(39); 674
Cu-Mn	Bal. Cu 4.2 Mn	See also Bronze's proceeding				20°	17.9	$17x10^{-5}$ (20° - 100°C)	(39); 674
Cu-Mn	Bal. Cu 1.49 Mn	See also Bronze's proceeding				0°	6.66		(39); 674
Cu-Mn	Bal. Cu 0.98 Mn	See also Bronze's proceeding				0°	4.83		(39); 674
Cu-Mn Fe	Bal. Cu 23.2 Mn 6.2 Fe	See also proceeding similar alloys				0°	77	$22x10^{-6}$ (0° - 100°C)	(39); 674
Cu-Mn-Fe	Bal. Cu 7.1 Mn	See also proceeding similar alloys				0°	20	$12x10^{-5}$ (0° - 100°C)	(39); 674
Cu-Mn-Ni	Bal. Cu 24 Mn 3 Ni	See also proceeding alloys				0°	48	$-3x10^{-5}$ (0° - 100°C)	(39); 674
Cu-Mn-Ni	Bal. Cu 12 Mn 4 Ni	Manganin Minalpha telcuman tarnac	Electrical application			20°	44	0.00000 at 25°C	(39); 674
Cu-Mn-Ni	Bal. Cu 72 Mn 10 Ni	See also proceeding alloys				25°	175	0.0141 (25° - 100°)	(39); 674

TABLE 2.3.3 (cont'd.)

Cu-Ni	Ni 10 Cu Bal					20°	14.1	5.24×10^{-4} (20° - 100°C)	(30); 674
Cu-Ni	Ni 20 Cu Bal					20°	26.6	2.37×10^{-4} (20 - 100°)	(30); 674
Cu-Ni	Ni 30 Cu. Bal					20°	36.3	48×10^{-6} (20 - 100°C	(30); 674
Cu Ni	Ni 45 Cu. Bal.	Advance Constantan cupron Eureka Ferry Telconstan				20°	49	$\pm 18 \times 10^{-6}$	(30); 674, 658
						20°	48-49	1×10^{-5} to 2×10^{-5}	(10); 169 170

TABLE 2.3.4

Alloy	Nominal Composition (Wt. %)	Trade Name and/or Specification	Established Applications	Form and Condition: (1) Annealed, (2) Quenched, (3) Other	Solidus Temperature, (°C)	Temperature (°C)	Resistivity, (Micro-ohm-cm)	Temperature Coefficient of Resistivity	Reference
Ni-Co	99.55 (Ni+CO)	"A" Nickel A.S.T.M. No's: B160-58T; B161-58T; B162-58T; B163-58T.	Chemical Industry, Heat Resistant Applic. and others	Annealed	1435	20	9.5	0.00474 (20° to 100°C)	(40); 1118 (39), 16
				Hot Rolled			9.47		
				Annealed	1446	20	8.81		
Ni-Mn.	95. Ni. 4.5 Mn.	"D" Nickel ASTM-F290-5T (wire)	Spark Plug wires, and other Applic. requiring resistance to Sulfur Compds. in both oxidizing and reducing atmos.	Annealed	1427 (Approx.) (liquids)	20	14.		(40); 1118 (19); 16
				Annealed		20	18.3		
Ni-Al	94. Ni 4.5 Al	Duranickel "Z" Nickel (NOrd)-MIL-W-19487	High Strength and High Resistance to Corrosion - Applications	Annealed	1399 to 1435	20	46.5		(40); 1119 (19); 16
				Annealed-Age Hardened		20	43.3		
Ni-Si	97. Ni 1.5 Si	"Cast Nickel"	Similar to Wrought Nickel	Cast	1345 to 1425 (liquidus)	20	21		(40); 1119 (19); 16
Ni-Co	97.85 (Ni + Co)	"E-Nickel"		Annealed	1427	20	13.96		

TABLE 2.3.4 (cont'd.)

Ni-CO-X	98.65 Ni+Co 0.005 Si 0.10 Mr 0.10 Fe	0.02 Cu 0.10 Mn 0.45 Ti 0.6 Si 0.25 C	Permanickel	Annealed	1399 to 1438	20	15.7		(13); 16
Ni-Co-X	99.65 (Ni+Co)	"200" Nickel A.S.T.M B239 Grade 11		Annealed	1435 1 1446	0 20	8.81 9.47		(13); 17
Ni+Co-X	99.50 (Ni+Co)	"225" Nickel A.S.T.M. B239 Grade 3		Annealed	1435 1 1446	0 20	8.81 9.47		(13); 17 (13); 17
Ni-Cr-Fe	42.10 (Ni+Co) 0.40 Ti 29.70 Cr 0.25 Al 25.60 Fe 0.60 Si 0.85 Mn 0.06 C	Ni-Cr-Fe Alloy "804"		Annealed		20	108		(13); 17
(Ni+Co) Cr-Fe	77.40 (Ni+Co) 0.45 Si 20.50 Cr 0.007 S 0.50 Fe 0.06 Cu 0.45 Mn 0.15 Al 0.35 Ti	Nimonic "75"		Annealed	1388 to 1421	20 24.5	100 110		(13); 17
(Ni+Co) Cr-Fe	74.45 (Ni+Co) 20.45 Cr 0.55 Fe	Nimonic "80A"		Annealed	1388 to 1421	20 24.5	124 125		(13); 17
(Ni)+ Co-Cr- Al-Ti	57.00 1.65 Al (Ni(+Co) 20.55 Cr 2.60 Ti 16.90 Co	Nimonic "90"		Annealed	1354 to 1388	20	114.7 116.3		(13); 17

TABLE 2.3.4 (cont'd.)

Ni-Co-X	94.2 (Ni+Co)	"G" Nickel		AS-Cast	1315 to 1427	20	20.8		(13); 17
Ni-Co-X	91.5 (Ni+Co) 6.0 Si 0.80 C	"S" Nickel		AS-Cast	1315 to 1427	20	29.9		(13); 17
Fe-Ni-Cr	Bal. Fe 1.00 Si 29.00 Ni0.75 Mn 20.00 Cr 2.00 MD0.07 C	Carpenter Stainless No. 20		Annealed		20	74.8		(13); 17
(Ni+Co)-Cr Fe	72.85 +(X) (Ni+Co) 15.15 Cr 6.80 Fe	Inconel "X" AMS 5667; 5542 AMS 5668; 5698 5699		Annealed and Age Hardened		20	122		(13); 18
(Ni+Co)-Cr-Fe -Ti-Al	72.50 (Ni+Co) 2.30 Ti 15.15 Cr 1.15 Al 6.85 + (X)	Inconel "X", Type 550		Annealed and Age Hardened		20	123.5		(13); 18
(Ni-Co)-Cr-Fe-Ti-Mn-X	71.40 (Ni+Co) 3.05 Ti 16.40 Cr 2.20 Mn 6.70 Fe + X	Inconel "M"							(13); 18
(Ni-Co)-Cr-Fe-Ti-Mn-X	74.35 (Ni+Co) 2.40 Ti 15.30 Cr + X 6,50 Fe	Inconel "W" AMS-5541; plate, sheet, etc.		Annealed Annealed and Age Hardened	1393 1 1427	20 24.5	134.6 121		(13); 18
(Ni+Co)-Cr-Fe-(Cb+Ta)	73.55 +"X" (Ni+Co) (Cb+Ta) 16.00 Cr 7.55 Fe 2.30	Inconel "600"		Annealed		20	103.1		(13); 18

TABLE 2.3.4 (cont'd.)

(Ni+Co)- Cr-Fe (Cb+Ta)	73.55 (Ni+Co) 2.30 16.00 Cr +"X" 7.55 Fe	Inconel "700" (Cb+Ta)		Hot-Rolled	1393 1 1427	20	129.1		(13); 18
(Ni+Co) -X	99.55 + X (Ni+Co)	"330" Nickel		Annealed	1435 1 1446	0(°C) 20	8.81 9.47		(13); 18
(Ni+Co)- Cu-Fe-X	66.35 (Ni+Co) 0.90 Mn 31.00 Cu + X 1.35 Fe	"R" Monel AMS- 4674 ASTM-B164 (Cl. B).		Hot-Rolled	1299 1 1349	20	48.2		(13); 19
(Ni+Co)- Cu-Fe-X	58.10 (Ni+Co) 39.44 Cu + X 1.20 Fe	Monel "402"		Hot Rolled		20	50.7		(13); 19
(Ni+Co)- Cr-Fe- Si-Mn-X	71.5 (Ni+Co) 2.00 Si 16.0 Cr 1.00 Mn 8.0 Fe X	Inconel "Cast"		"AS-Cast"	1393 1 1427	20	116.3		(13); 20
(Ni+Co)- Cr-Fe-Si Mn-Cb-X	68.5 (Ni+Co) 1.60 Si 15.5 Cr 1.0 Mn + Cb 9.0 Fe 0.20 = C	Inconel Weldable Alloy		"AS-Cast"	1393 1 1427	20	116.3		(13); 20
(Ni+Co)- Cr-Fe-Si	68.0 5.5 Si (Ni+Co) + X 15.5 Cr 8.0 Fe 0.20 C	"S" Inconel		AS-Cast	1393 1 1427	20	126.3		(13); 20

TABLE 2.3.4 (cont'd.)

(Ni+Co)- Cu-Al	64.75 (Ni+Co) 1.00 Fe 29.85 Cu 0.45 Ti 2.85 Al 0.25 C	"KR" Monel MIL-N-2862 (Cl-B) MIL-W-4471 (Comp. B)		Hot Finished and Annealed	1315 1 1239	20	58.2		(13); 20
(Ni+Co)- Fe-Cr-X	36.85 (Ni+Co) .45 Mo 54.25 Fe 0.60 Si 7.10 0.55 Mn Cr 0.10 C	Iso-Elastic		Cold Worked		20	87.8		(13); 20
Fe-(Ni+ Co)-Cr-X	31.90 (Ni+Co) 46.05 FE + X 20.60 Cr	Incoloy		Annealed	1393 1 1427	20	99.7		(13); 21
Fe-Ni+ Co)-Cr-X	32.20 (Ni+ Co) 0.85 Mn 44.60 Fe 1.00 Ti 20.80 Cr X	Incoloy "T" AMS 5742							(13); 21
Fe-(Ni+ Co)-Cr Mo-Ti-X	42.65 Ni+Co 6.20 Mo 33.90 Fe 2.50 Ti 13.45 Cr X	Incoloy "901"		Annealed and Aged		20	110		(13); 21
Fe-Ni	Bal. Fe 36 Ni	Invar MIL-S-16598 A (Free Machining)		Annealed	1427	20	78.1 75	2×10^{-3}	(13); 23 (16); 185
Fe-Ni	Bal. Fe 31 Fe		Iron-Nickel Temperature Compensating Alloy	Annealed		20	79.8		(13); 23

TABLE 2.3.4 (cont'd.)

Fe-Ni	Bal. Fe 42 Ni.	42% Nickel Iron Alloy		Annealed	1427	20	67.3		(13); 23
Fe-Ni	Bal. Fe 47-50 Ni	49% Nickel Iron Alloy		Annealed	1427	20	44.9		(13); 23
Ni-Fe -Mo	Bal. Fe 79 Ni 4 Mo	Permalloy		Magnetic Annealed	1427		58.2		(13); 23
Ni-Cu	67 Ni 30 Cu	Monel ASTM-B127-58T; B-163-58T; B-164-58T and others	Includes Electrical and Marine	Annealed	1300 to 1350 (liquidus)	20	48.2	0.0011 (0° to 100°C)	(40); 1120
Ni-Cu-Al	66 Ni 29 Cu 3 Al	"K" Monel Govt. QQ-N-286A (Class A)	Applications for High Strength and Corrosion Resistance		1316	20	58.3	0.00018 (20° to 100°C)	(40); 1121, 1122 (19); 19
Ni-Cu Si	63 Ni 30 Cu 1.5 Si	Monel (Cast) Govt. QQ-N-288 (Comp. A)	Same as Above		1315 to 1345 (liquidus)	20	53.3		(40); 1122
Ni-Cu-Si	63 Ni 30 Cu 3 Si	"H" Monel (Cast) Govt. QQ-N-288 (Comp. B)		 As Cast	1285 to 1315 (liquidus)	20 20	58.3 101.5		(40); 1122 1123 (19); 19
Ni-Cu-Si	63 Ni 30 Cu 4 Si	"S" Monel Govt. QQ-N-288 (Comp. D)		Annealed and Aged	1260 to 1290 (liquidus)	20	63.3 63.2		(40); 1123 (19); 20

TABLE 2.3.4 (cont'd.)

Ni-Cr-Fe	76 Ni 16 Cr 8 Fe	Inconel - Govt. QQ-W-390	Where excellent resistance to high temperatures are required		1395		98.1	0.000125 (20° to 500°C)	(40); 1123
Ni-Cr-Fe-Si	72 Ni 16 Cr 8 Fe 2 Si	Inconel (Cast)			1370 to 1400 (liquidus)				(40); 1124
Ni-Fe-Cr	42 Ni 3Mo 30 Fe 2 Cu 22 Cr 1Ti	Ni-O-nel	Corrosion Resistance to Sulfuric and Phosphoric Acids			20	108.		(40); 1124
Ni-Mo-Fe	62 Ni 28 Mo 5 Fe	Hastelloy Alloy B	High Temperature oxidation resistance and strengths	Rolled and Annealed	1320 to 1349	25 20	135 135		(40); 1125 (19); 13
Ni-Mo-Cr-Fe-W	54 Ni 5Fe 17 Mo 4. 15 Cr	Hastelloy Alloy C*	Resistant to oxidizing and reducing atmospheres to 1093°C	Rolled and Annealed	1270 to 1304	25 20	130.0 * 138.6	"zero" * from (20° to 800°C)	(40); 1125 (19); 13
Ni-Si-Cu	85 Ni 10 Si 3 Cu	Hastelloy Alloy D	Sulfuric Acid Resistant. Not recommended for elevated temperatures under oxidizing conditions.	Sand Cast and Annealed	1110 to 1121	25	113.	"Virtually Zero" (20° to 800°C)	(40); 1126 (19); 13
Ni-Mo-Cr-Fe	47 Ni, 22Cr 7 Mo, 17Fe	Hastelloy Alloy F	Withstand alkaline and acid corrosion also oxidizing and reducing conditions	Hot Rolled, Annealed	1288 (liquidus)	24 20	139 112.4		(40); 1126 (19); 13
Ni-Mo-Cr-Fe	70 Ni 7 Cr 17 Mo 5 Fe	Hastelloy Alloy N	Good oxidation Resistance in Air to 982°C	Quenched (?)	1300	24	139		(40); 1126

TABLE 2.3.4 (cont'd.)

Ni-Mo-Cr-Fe	47 Ni 22 Cr 9 Mo 18 Fe	Hastelloy Alloy X	Exception strength and oxidation Resistance to 1200° C	Wrought Sheet	1288 (liquidus) (approx.)	22	118.3 118		(40); 1127 (19); 13
Ni-Cr-Fe Mo	Bal. Ni. x Al 15.5 Cr x Ti 10. Fe 5.5 Mo	Hastelloy Alloy R-235		Hot Rolled and Mill annealed	1288 to 1316	20	133		(19); 13
Ni-Cr-Mo-Cu	56 Ni 22.5 Cr 6.5 Mo. 6.5 Cu.	Illium G	Machineable high strength casting and for severe corrosion application	Quenched (?) Precipitation type alloy	1255	25 (Assumed)	123.5		(40); 1128
Ni-Cr-Mo-Cu	68 Ni 5 Mo 21 Cr 3 Cu	Illium R	Heat and corrosion resistant alloy in a machineable wrought alloy.		1324	Not Specified ≈ R.T.	119.6		(40); 1128

TABLE 2.3.5

Alloy	Nominal Composition (Weight %)	Trade Name or Designation	Established Application	Conditions Annealed Quenched Etc.	Solidus Temperature (°C)	Temperature (°C)	(ρ) Resistivity, (Microhm-cm)	α Temperature coefficient of resistivity	Reference Number Page
Co-Cr Mo- Ni-C	Bal. Co 28 Cr 5.5 2.5 Ni 0.25 C	AMS-5385 (cast Haynes Stellite Alloy C1 Vitallium type alloy		as investment cast	1352	20	87.6		(19); 14
Co-Cr Ni-W- C	Bal. Co 25.5 Cr 11.0 Ni 7.5W 0.50C	AMS 5382 (cast) Haynes Stellite No 31 (x-40 cast)		as investment cast	1371	20			(19); 14
Co-Cr W-Ni Mn- C	Bal. Co 20.0 Cr 15.0 W 10.0 Ni 1.50 Mn 0.15C	AMS 5537 (wrought) Haynes Stellite Alloy No. 25 (L605)		Wrought sheet	1410 1330	20	280		(19); 14
Co-Cr W-Ni Mn-C	Bal. Co 19.0 Cr 15.0 W 10.0 Ni 1.5 Mn 0.40 C	AMA-5376 (cast) AMS-5767, 5768, 5532b (wrought) Haynes Stellite Alloy No. 36 (N-155)		as investment cast	1390	20	280		(19); 14
Fe-Cr Ni-Co Mo-W C-N (cb+ta)	Bal. Fe 20-22.5Cr 19-21 Ni 18.5-21 Co 2.5-3.5 Mo 2.0-3.0 W 0.08-0.16 C 0.10-0.20 N 0.75-1.25 cb+ta	Multimet AMS-5376 (cast) AMS-5767 wrought 5768 5532(b) and N-155 Alloy)		mill annealed sheet	1282 to 1316	20°	83.1		(19); 14

TABLE 2.3.5 (cont'd.)

Ni Cr	80 Ni 20 Cr	ASTM-B344-59T Nichrome IV, V Bright ray C.S. Pyromic tophet A; Red Fox 80/20	employed as fine wires in electronics; highly resistant to oxidation up to 1200°C		1400 (liquids)	20° 0°	107.9 98-103	+0.000090 (-65-150°C) +0.00018	(40);1128 (39);675, 678
Ni Fe Cr	60 Ni 24 Fe 16 Cr	ASTM-B344	includes electrical; as heater elements and electronic application		1425 (approx. liquidus)	20	112	0.00015 (20° to 100°C)	(40);1129
Ni Fe Cr	35 Ni 45 Fe 20 Cr	ASTM-B344	includes electrical and usually serviceable to 815°C			20	100	0.00031 (20° to 500°C)	(40);1130
Ni Fe Cr	65 Ni 20 Fe 15 Cr	Calomic Bright ray B Nichrome Tophet C Red Fox -65/15	Max. safe temperature in air (950°)						(39);675, 678
Ni Cu	45 Ni 55 Cu	Constantan	Limits of use Annealed(electrical purposes) 500°C unprotected from oxidation		1220	not specified assured R. T.	50 48.2	±0.00002 (20° to 150°C)	(40);1130 (19);8
Cu Ni	98 Cu 2 Ni		Electrical Resistance Alloy	Annealed	1086	20	4.99	+0.001500 (0° to 100°C)	(40);798 (24);602
Cu Ni	94 Cu 6 Ni		same	Annealed	1094	20	9.98	+0.000800 (0° to 100°C)	(40);798 (24);602
Cu Ni	89 Cu 11 Ni		same	Annealed	1103	20	14.97	+0.000400 (0° to 100°C)	(40);798 (24);602
Cu Ni	78 Cu 22 Ni		same	Annealed	1130	20	29.94	+0.000300 (0° to 100°C)	(40);798 (24);602

TABLE 2.3.5 (cont'd.)

Cu Ni	55 Cu 45 Ni	Constantan	Electrical resistance alloy	Annealed	1220	20°	50	±0.000040 (20° to 100°C)	(40);798 (24);602
Cu Mn	87 Cu 13 Mn	Manganin	Electrical resistance alloys	Annealed	945	20°	48	±0.000015 (15° to 35°C)	(40);798 (24);597
Cu Mn Ni	83 Cu 13 Mn 4 Ni	Manganin	same	Annealed		20°	48	±0.000010 (20° to 35°C)	(40);798
Cu Mn Ni	85 Cu 10 Mn 4 Ni	Shunt Manganin	same	Annealed		20°	38	±0.000010 (20° to 45°C)	(40);798
Cu	70 Cu 20 Ni 10 Mn		same	Annealed		20°	48.9	±0.000020 (20° to 35°)	(40);798
Cu Ni Mn	67 Cu 5 Ni 27 Mn		same	Annealed		20°	99.84	±0.000020 (20° to 35°C)	(40);798
Ni+X	99.8 Ni Bal. impurities		Electrical Resistance Alloys	Annealed (assumed)	about 1455	20°	7.99	+0.006000 (20° to 35°C)	(40);798 (24);677
Ni+ Fe	71 Ni 29 Fe		same	same	1425°	20°	19.97	+0.004500 (20° to 100°C)	(40);798 (24);677
Ni + Cr	80 Ni 20 Cr		same	same	1400°	20°	112	+0.000085 (-55° to 100°C)	(40);798 (24);542
Ni Cr Al Cu	75 Ni 20 Cr 3 Al + Cu or Fe	Karma Evanohm Nikrothal	same	Annealed heat treated	1399	20°	120 133	±0.000020 (-55° to 100°C)	(40);798 (19);8
Ni Cr Si Mn	76 Ni 17 Cr 4 Si 3 Mn		same	same		20°	133	±0.000020 (-55° to 100°C)	(40);798

TABLE 2.3.5 (cont'd.)

Ni Cr Fe	60 Ni 16 Cr 24 Fe		same	same		20°	112	+0.000150 (20° to 100°C)	(40);798
Ni Cr Fe	35 Ni 20 Cr 45 Fe		same	same		20°	101.5	+0.000350 (20° to 100°C)	(40);798
Fe Cr Al Co	73 Fe 23 Cr 5 Al 0.5Co		Electrical resistance alloy	Annealed		20°	135.6	±0.000020 (-55° to 150)	(40);798
Co Cr W Mo -x-	55+ Co 20 Cr 4.5 W .5 Mo 1.10 C 2.00 Mn 2.00 Si 3.00 Ni		Wear resistant alloys & high hardness, & strength at elevated temperature	Metallurgical (Physical) structure of complex alloy is stable to 98°C to 1038°C		20	90.9		(40);669
Co Cr W Mn -X-	55 + Co 30.5 Cr 8.5 W 1.0 Mn 1.00 Si 3.00 Ni 1.35 C		same as above	same		20	98.3		(40);669
Co Cr W Mo Mn X	43 Cr 30 Cr 18.5 W 0.80 Mo 1.00 Mn 1.00 Si 3.50 Ni 2.00 C		same			20	113.5		(40);669
			Electrical Resistor Heating element Max. operating temperature in air (°C)						

TABLE 2.3.5 (cont'd.)

Ni Cr Si	78.5 Ni 20 Cr 1.5 Si	"80-20" Ni-Cr	1150°C			20	108		(40);621
Ni· Cr Si Al	73.5 Ni 20 Cr 5 Al 1.5 Si		1205°C			20	138		(40):621
Ni Cr Fe Si	8.5 Fe 2.0 Si 68 Ni 20 Cr		1150°C			20	116.3		(40);621
Ni Cr Fe Si	22.5 Fe 1.5 Si 50 Ni 16 Cr		1010°C			20	112.2		(40);621
Ni Cr Fe Si	43.5 Fe 1.5 Si 35 Ni 20 Cr		927°C			20	101.4		(40);621
Ni Cr Al	72 Fe 23 Cr 5 Al		1288°C			20	138.8		(40);621
Ni Cr Al	55 Fe 37.5 Cr 7.5 Al		1288°C			20	166.2		(40);621
Ni Be Cr C	96.5 Ni 2.7 Be 0.7 Cr 0.1 C	Nickel Beryllium Cr-1		Cast and heat treated 5 hours at 566°C Annealed soln annealed at 1065°C and heat treated 5 hrs at 510°C	1099 to 1266	20	57.4 28.6		(19);10 (19);10

TABLE 2.3.6

Alloy	Nominal Composition (Wt. %)	Trade Name and/or Designation	Established Applications & Oxidation Resistance	Form cast wrought Condition annealed quenched	Solidus Temperature (°C)	Temperature (°C)	Resistivity (ρ), (Microhm-cm)	Temp. Coeff. of Resistivity (α)	Reference Number Page
Fe-C	Bal. Fe 0.20C 0.45 Mn 0.25 Si	Carbon Steel AISI-SAE-1020		Annealed	1516	20	10.0		(19);25
Fe / Slag	Bal. Fe 2.5 Slag	Wrought Iron		Hot Rolled	1510	20	11.6		(19);24
Fe-X	99.9 Fe X	Ingot Fe		Hot Rolled	1535	20	9.5		(19);24
Fe-C-Si-X	Bal. Fe 0.5 Mn 3.4 C 1.8 Si	Cast Grey Iron (ASTM A48-48 Class No. 25)		As-Cast	1177	20	66.4		(19);24
Fe-C-Si-X	Bal. Fe 0.55 Mn 2.5 C 1.0 Si	Malleable Iron		Cast & Annealed	1232	20	29.9		(19);24
Fe-C-Ni-Si-X	Bal. Fe 1.8 Si 2.7 C 0.8 Mn 2.3 Ni 0.4 Mo 0.3 Cr	Ni-Tensy-Iron		As Cast	1177	20	----		(19);24

TABLE 2.3.6 (cont'd.)

Fe-Si-C-X	Bal. Fe 0.06 Mg. 4.3 Si 0.10 P 3.3 C 0.1 Ni	Ductile Iron (Mg. Containing) (Heat Resistant)		Annealed As-Cast	1149	20	59.8		(19);24
Fe-Ni-C-Si-Cr-Mn-X	Bal. Fe 2.0 Ni 1.0 Mn 2.8 C 0.2 P 2.5 Si 0.1 Mg	Ni-Resist-Ductile Iron (Mg. Contg.) AMS 5394		As Cast	1232	20	101.4		(19);24
Ni-Cr-Fe Cu-Mo-X	Bal. Ni 6.4 Mo 22.5 Cr Mn 6.5 Fe Si 6.5 Cu	Illium "G"		As Cast	1302		122.2		(19);24
Fe-Ni-Si-Cr-Mn-C-X	Bal. Fe 0.80 Mn 1.85 Ni 0.43 C 1.60 Si 0.38 Mo 0.85 Cr 0.08 V	300 - M		Hardened Coil-quenched, tempered at 600 (°F)	1504	20	11.6		(19);25
Fe-Ni-Cu-C-Cr-Si-Mn	Bal. Fe 2.8 C 15.5 Ni 2.5 Cr 6.5 Cr 2.0 Si 1.2 Mn	Ni-Resist Type L. (AMS 5392D)		As Cast	1232	20	140.		(19);25

TABLE 2.3.6 (cont'd.)

Fe-Si-C-Cr-Si-Mn	Bal. Fe 2.5 Cr 20.0 Ni 2.0 Si 2.8 C 1.0 Mn	Ni-Resist Type 2. (AMS 5393)		As Cast	1232	20	170.		(19);25
Fe-Ni-Si-Cr-C-Mn	Bal. Fe 2.6 C 30.0 Ni 0.6 Mn 5.5 Si 5.5 Cr	Ni-Resist Type 4		As Cast	1204	20	163.6		(19);26
Fe-Ni-C-Cr-Si-Mn-X	Bal. Fe 2.50 Si 20.0 Ni 1.0 Mn 2.90 C 0.2 P 2.50 Cr	Ni-Resist. Type D-2		As Cast	1232	20	102.0		(19);26
Fe-Si	Si 4 Fe Bal.					20	62	0.008 (0-100°C)	(39);675
Fe-Si	Si 25 Fe Bal.					20	45	---	(39);675
Fe-Ni	Ni-5 Fe Bal.	Ferritic Fe-Ni Alloy				20	26	$2.3\text{x}10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-10 Fe Bal.	Ferritic Fe-Ni Alloy				20	32.5	$2.1\text{x}10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-15 Fe Bal.	Ferritic Fe-Ni Alloy				20	35	$2.1\text{x}15^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-20 Fe Bal.	Ferritic Fe-Ni Alloy				20	36.5	$2.2\text{x}10^{-3}$ (0-100°C)	(39);676

TABLE 2.3.6 (cont'd.)

Fe-Ni	Ni-25 Fe-Bal.	Ferritic Fe-Ni Alloy				20	37.5	$2.25x10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-30 Fe-70	Austenitic Fe-Ni Alloy				20	83.	$1.2x10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-40 Fe-60	Austenitic Fe-Ni Alloy				20	69	$2.5x10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-50 Fe-50	Austenitic Fe-Ni Alloy				20	47	$3.35x10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-60 Fe-40	Austenitic Fe-Ni Alloy				20	33	$3.75x10^{-3}$ (0-100°C)	(39);676
Fe-Ni	Ni-70 Fe-30	Austenitic Fe-Ni Alloy				20	25	$3.8x10^{-3}$ (0-100°C)	(39);676
Fe-W	W-5 C-0.2 Fe Bal.					20	20	---	(39);676
Fe-W	W-20 C-0.2 Fe Bal.					20	24	---	(39);676
Fe-W	W-10 Fe-90								(16);203

TABLE 2.3.7

(Alloy Name) Mfg.	Other Trade Names	Composition (Wt. %)	Resistivity, ρ; (Microhm-cm) (20°C or R.T.)	Temperature Coefficient + Resistivity, , (°C^{-1})	Reference Number Page
Driver-Harris Alloys					Remarks: Ref. (37), has an error, in tabulator of α; corrected values are listed, but Units (corrected are = (°C^{-1}) and not "percent/°C" "α" values list in this table are corrected.
Karma		Ni - 73 Cr - 20 +Al+ Fe	133.	2. x 10^{-5}	(37); 14+
Nichrome		Ni - 60 Cr - 16 Fe - Bal	112	15x10^{-4}	(37); 14+
	Nichrome		110	4x10^{-4} to 3x10^{-5}	(16); 193
	Nichrome II	Cr-20-20; Ni-67-65; Fe 12-14; Mn 1.5-2	109-111	1.5 x 10^{-4}	(16); 193
	Nichrome III	Cr-15; Ni-85	90-97	5x10^{-5} to 1.9x10^{-4}	(16); 193
	Nichrome IV	Cr-20; Ni-80	98-103	1.8 x 10^{-4}	(16); 193
Nichrome V		Ni - 80 Cr - 20	108	1.1 x 10^{-4}	(37); 14+
Chromax		Ni - 35 Cr - 20 Fe - Bal	100	3.6 x 10^{-4}	(37); 14

TABLE 2.3.7 (cont'd.)

Nilver		Ni - 36 Fe - Bal.	83.2	1.35×10^{-4}	(37); 14+
Stainless Type 304		Cr - 18 Ni - 8 Fe - Bal.	72.8	9.4×10^{-4}	(37); 14+
142 Alloy		Ni - 41 Fe - Bal.	70.	2.5×10^{-3}	(37); 14+
Advance		Ni - 43 Cu - Bal.	48.9	-2×10^{-5}	(37); 14+
Therlo		Ni - 29 Co - 17 Fe - Bal.	48.9	3.3×10^{-3}	(37); 14+
	Therlo		46.5	0.01×10^{-3}	(16); 168
Manganin (Wire Only)		Mn - 12 Ni - 4 Cu - Bal.	48.2	$\pm 1.5 \times 10^{-5}$	(37); 14+
146 Alloy		Ni - 46 Fe - Bal.	45.8	3.2×10^{-3}	(37); 14+
	Platinitc	Ni - 46 Fe - Bal.	45.	3×10^{-3}	(16); 185 (10); 601
152 Alloy (52)		Ni - 51 Fe - Bal.	43.2	3.6×10^{-3}	(37); 14+
Dura Nickel		Ni - Additions	43.2	1×10^{-3}	(37); 14+
Midohm		Ni - 23 Cu - Bal.	30.	1.8×10^{-4}	(37); 14+
133 Alloy		Si - 3 Ni - Bal.	31.6	2.2×10^{-3}	(37); 14+

TABLE 2.3.7 (cont'd.)

R-63 Alloy		Mn - 4 Si - 1 Ni - Bal.	21.6	3×10^{-3}	(37); 14+
Hytemco		Ni - 72 Fe - Bal.	20.	4.5×10^{-3}	(37); 14+
Magno (Grade D Nickel)		Mn - 4.5 Ni - Bal.	17.5	3.6×10^{-3}	(37); 14+
Permanickel		Ni - ± Additions	16.62	3.6×10^{-3}	(37); 14+
95 Alloy		Ni - 11 Cu - Bal.	14.9	4.9×10^{-4}	(37); 14+
Grade "E" Nickel		Mn - 2 Ni - Bal.	14.1	4.5×10^{-3}	(37); 14+
Grade "A" Nickel		Ni - 99	10.	5×10^{-3}	(37); 14+
Lohm		Ni - 6 Cu - Bal.	10.	8×10^{-4}	(37); 14+
High Brass		(cu-Zn); (not specified)	8.3	1.6×10^{-3}	(37); 14+
99 Alloy		Ni - 99.8	8.0	6×10^{-3}	(37); 14+
Low Brass		Cu - Zn (Not Specified)	6.6	1.7×10^{-3}	(37); 14+
30 Alloy		Ni - 2.25 Cu - Bal.	4.97	1.5×10^{-3}	(37); 14+
111 Alloy		Cu - Ni (Not Specified)	2.91	2.5×10^{-3}	(37); 14+

TABLE 2.3.7 (cont'd.)

Jelleff Alloys					
Alloy 815		Cr - 22.5 Al - 4.5 Fe - 73	135.	1 x 10^{-4}	(37); 14+
Alloy 800		Ni - 61 Cu - 20 (Bal Not Specified)	133.	2 x 10^{-5}	(37); 14+
Alloy C		Cr - 16 Fe - 24 Ni - 60	112	1.3 x 10^{-4}	(37); 14+
Alloy A		Cr - 20 Ni - 80	108	1.2 x 10^{-4}	(37); 14+
Alloy 45		Ni - 45 Cu - 55	48.9	2 x 10^{-5}	(37); 14+
Alloy 180		Ni - 22 Cu - Bal.	29.9	1.8 x 10^{-4}	(37); 14+
Alloy 90		Ni - 12 Cu - Bal.	14.9	4.4 x 10^{-4}	(37); 14+
Alloy 60		Ni - 6 Cu - Bal.	10.	6. x 10^{-4}	(37); 14+
Wilbur B. Driver Alloys					
Evanohm		Al - 2.5 Cu - 2.5 Cr - 2.0 Ni - 75	134.	-2 x 10^{-5}	(37); 14+

TABLE 2.3.7 (cont'd.)

Tophet C		Cr - 15 Ni - 61 Fe - Bal.	112.	1.3×10^{-4}	(37); 14+
Tophet A		Cr - 20 Ni - 80	108	1×10^{-4}	(37); 14+
	Tophet		107		(16); 194
Cobenium		Mo - 7 Ni - 15 Cr - 20 Co - 40	99.6		(37); 14+
Nilstain		Ni - 8 Cr - 18 Fe - Bal.	73.		(37); 14+
Cupron		Ni - 45 Cu - 55	48.4	-4×10^{-5}	(37); 14+
Manganin		Mn - 13 Cu - Bal.	48.2	-1.5×10^{-5}	(37); 14+
	Manganin		34 - 100	-3×10^{-5} -2×10^{-5}	(37); 14+
Monel		Cu - 30 Ni - Bal.	48.2	1×10^{-4}	(37); 14+
	Monel		42 - 50	2×10^{-5} to 2×10^{-3}	(16); 170
No. 180 Alloy		Ni - 22 Cu - Bal.	30.	1.8×10^{-4}	(37); 14+
Sylvaloy		Si - 3 Ni - 97	26.4	2.32×10^{-3}	(37); 14+

TABLE 2.3.7 (cont'd.)

Modified Hilo		Co - 20 Ni - 80	25.	2.25×10^{-3}	(37); 14+
Balco		Fe - 30 Ni - 70	20.0	4.5×10^{-3}	(37); 14+
Mangrid		Mn - 4.5 - 50 Ni - Bal.	20.	3.6×10^{-3}	(37); 14+
No. 90 Alloy		Ni - 12 Cu.- Bal.	15.	4×10^{-4}	(37); 14+
No. 60 Alloy		Ni - 6 Cu - Bal.	10.	5×10^{-4}	(37); 14+
No. 30 Alloy		Ni - 2 Cu - Bal.	5.0	1.3×10^{-3}	(37); 14+

TABLE 2.3.8

Alloy	Nominal Composition; (Wt. %)								Trade Name &/or Designation	Established Applications	Form and Condition - Cast Wrought; - Annealed Quenched Etc.	Solidus Temperature, (°C)	Temperature (°C)	Resistivity, (ρ) (Micro-ohm-cm)	Temperature Coefficient of Resistivity (α)	Reference No. & Page
	Fe	Cr	Ni	Mn	Si	C	Mo		AISI (1959) Types.	Wrought Stainless Steel & Heat-Resistant Steels (Max. Temp., (°C) for Normal Atmos. & uses.	W = Wrought C = Cast	Approx. (M. M.) Melting Temp.				
Fe-Cr-Ni-X	Bal.	16-18	6-8	2.00	1.00	0.15			Austenitic Type 301	—	W; Annealed	1400	R.T. 20°C	72 72.3		(40);422 (19);21
Fe-Cr-Ni-X	Bal.	17-19	8-10	2.00	1.00	0.15			302	900°C	W; Annealed	1400	R.T. 20.	72 72.3		(40);422 (19);21
Fe-Cr-Ni-X	Bal.	17-19	8-10	2.00	3.00	0.15			302 B	—	W; Annealed	1372	R.T.	72		(40);
Fe-Cr-Ni-X	Bal.	17-19	8-10	2.00	1.00	0.15		0.15 Min. Sulfur	303	900°C	W; Annealed	1400	R.T.	72		(40);
Fe-Cr-Ni-X	Bal.	18-20	8-12	2.00	1.00	0.08			304	900°C	W; Annealed	1400	R.T. 20.	72.3		(40); (19);21
Fe-Cr-Ni-X	Bal.	17-19	10-13	2.00	1.00	0.12			305	—	W; Annealed	1400	R.T.	72		(40);

TABLE 2.3.8 (cont'd.)

Fe-Cr-Ni-X	Bal. 19-21 10-12 2.00 1.00 0.08	Austenitic Type	308	—	W; Annealed	1400	R.T.	72		(40);423
Fe-Cr-Ni-X	Bal. 22-24 12-15 2.00 1.00 0.20		309	1095°C	W; Annealed	1400	R.T.	78 78.4		(40);423 409 (19);21
Fe-Cr-Ni-X	Bal. 24-26 19-22 2.00 1.50 0.25		310	1095°C	W; Annealed	1400	R.T. 20.	78 78.4		(40);423 (19);21
Fe-Cr-Ni-X	Bal. 23-26 19-22 2.00 1.5 to 3.00 0.25		314	—	W; Annealed	—	R.T.	77		(40);
Fe-Cr-Ni-X	Bal. 16-18 10-14 2.00 1.00 0.08 2-3% Mo.		316	900°C	W; Annealed	1372	R.T. 20	74 74.		(40); (19);21
Fe-Cr-Ni-X	Bal. 18-20 11-15 2.00 1.00 0.08 3 to 4% Mo.		317	—	W; Annealed	1372	R.T.	74		(40);
Fe-Cr-Ni-X	Bal. 17-19 9-13 2.00 1.00 0.08 10XC = Min. of Cb-Ta.		321	900°C	W; Annealed	1400	R.T.	72		(40);
Fe-Cr-Ni-X	Bal. 17-19 9.00-13.00 2.00 1.00 0.08 10XC = Min. Cb-Ta; 0.10 Max Ta.		347	900°C	W; Cold Rolled	1400	R.T. 20.	73 72.3		(40); (19);21
	Fe Cr Ni Mn Si C Mo									
Fe-Cr-X	Bal. 4.00-6.00 1.00 1.00 0.10 Min 0.40 to 0.65	Martensitic Type	501	—	W; Annealed	1482	R.T.	40		(40);422 409

TABLE 2.3.8 (cont'd.)

Fe-Cr-Ni-X	Bal. 4.00 to 6.00 1.00 1.00 0.10 Max 0.40 to 0.65	Martensitic Type	502	620°C	W; Annealed	1482	R.T.	40		(40);409 422
Fe-Cr-X	Bal. 11.50 to 13.00 1.00 0.50 0.15		403	—	W; Annealed	1482	R.T.	57		(40);409 422
Fe-Cr-X			405	—	W; Annealed	1482	R.T.	60		(40);
Fe-Cr-X	Bal. 11.50- 13.50 1.00 1.00 0.15		410	675°C	W; Annealed	1482	R.T. 20	57 56.5		(40); (19);22
Fe-Cr-X	Bal. 12.00- 14.00 1.25 1.00 0.15		416	—	W; Annealed	1482	R.T.	57		(40);
Fe-Cr-X	Bal. 12.00- 14.00 1.00 1.00 0.15		420	650°C	W; Annealed	1454	R.T. 20	57 54.8		(40); (19);22
Fe-Cr-X	Bal. 14-18 1.00 1.00 0.12	Ferritic Type	430	843°C	W; Annealed	1482	R.T. 20	60 59.8		(40);409, 423 (19);22
Fe-Cr-X	Bal. 14-18 1.25 1.00 0.12 0.15% Min. S.		430 F	—	W; Annealed	1427	R.T.	60		(40);409, 423
Fe-Cr-X		Martensitic Type	431	—	W; Annealed	—	R.T. 20	72 71.5		(40);409, 423 (19);22
Fe-Gr-X	Bal. 16-18 1.00 1.00 0.65- 0.75 0.75 Max Mo.		440 A	—	W; Annealed	1370	R.T.	60		"

TABLE 2.3.8 (cont'd.)

Fe-Cr-X	Bal. 16-18 1.00 1.00 0.75- 0.95 0.75 Max. Mo.	Martensitic Type 440 B	—	W; Annealed	1370	R. T.	60		(40);409, 423 (19);22
Fe-Cr-X	Bal. 16-18 1.00 0.95- 1.20 0.75 Max. Mo.	Martensitic Type 440 C	—	W; Annealed	1370	R. T.	60		"
Fe-Cr-X	Bal. 23-27 1.50 1.00 .20 0.25 Max N.	Ferritic Type 446	1090°C	W; Annealed	1482	R. T. 20°	67 67.3		"
Fe-Cr-Al	72 Fe Possibly 23 Cr Indicates 5 Al also Co.	Kanthal Dr; 200 Alloy; Alchrome.		Wrought and Annealed	1510	20	135		(19);8
Fe-Cr-X	Bal. Fe 11.5-14 Cr 1.00 Ni 1.50 Si 1.00 Mn 0.15 C	Cast 12 Cr. Alloy (CA-15) (see also the cast-Alloys below).	Corrosion Resistant Casting	Air-cooled	1510	20	77.8		(19);10
Fe-Ni-Co	54 Fe 29 N 17 Co	Thero; Rodar		Wrought and Annealed	1454	20	48.9		(19);8
Fe-Cr-Ni-Mo-X	52.75 Fe 16.0 Cr 25.0 Ni 6.0 Mo 0.15 N 0.10 C (max)	16-25-6 Alloy AMS 5725 Bars AMS 5727-8 (Forgings)		Annealed Cold or Warm Worked	1288 to 1399	20	74.8 (estm).		(19);10

TABLE 2.3.8 (cont'd.)

Fe-Ni-Cr-Mo-W-Cb-Ti	68.55 Fe 1.25 W 9 Ni 0.40 Cb 19.25 Cr 0.30 Ti 1.25 Mo	Uniloy 19-9DL AMS 5720-1 (Bars)		Hot Worked and Stress Relieved	1427	20	78.		(19);10
Ti-Cr-Fe-Mo-X	94 Ti 0.08 C 2.0 Fe 0.05 N_2 2.0 Cr 0.015 H_2 2.0 Mo	Ti-Cr-Fe-Mo Alloy (Ti-140A)		Heat Treated	1649	20	130		(19);10
Ti-Al-Fe-Cr-Mo-X	Ti 1.2 Mo 5.0 Al 0.015 H_2 1.4 Fe 0.08 C 1.4 Cr 0.05 N_2	Ti-Al-Fe-Cr-Mo-Alloy (Ti-155A)		Annealed Heat Treated	1649	20	164.5		(19);10
Ti-Al-V	90. Ti 0.25 (max) Fe 6.0 Al 0.08 " C 4.0 V 0.0125 " H_2 0.05 " N_2	Ti-Al-V; Alloys (Ti-6Al-4V)		Annealed Heat Treated	1649	20	169.5		(19);10
Mo-Ti	99.5 Mo 0.5 Ti	"Molybdenum 0.50 Titanium"		AS Rolled	2610	20	5.202		(19);23
Fe-Cr-Si-Ni-Mn	Bal. Fe 1.00 Mn 11.5-14 Cr 0.2-04 C 1.5 Si 1.00 Ni	Cast 12 Cr Alloy (CA-40)	"C" of CA, CB, etc., designates corrosion resistant castings	Cast Air Cooled	1496	20	75.8		(19);11

TABLE 2.3.8 (cont' d.)

Fe-Cr-Ni-Si-Mn	Bal. Fe 1.00 Si 18-22 Cr 1.00 Mn 2.00 Ni 0.30 C	Cast 20 Cr Alloy (CB-30)		Cast Annealed	1496	20	75.8		(19);11
Fe-Cr-Ni-Si-Mn	Bal. Fe 1.00 Si 26-30 Cr 1.00 Mn 4.00 Ni 0.50 C	Cast 28-4 Alloy (CC-50)		Cast Annealed(?)	1496	20	76.8		(19);11
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 26-30 Cr 1.50 Mn 8-11 Ni 0.08 C	Cast 29-9 Alloy (CE-30)		AS Cast	1454	20	84.8		(19);11
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 18-21 Cr 1.50 Mn 8-11 Ni 0.08 C	Cast 20-10 Alloy (CF-8)		Water Quenched from 1950(°F) to 2050(°F)	1427	20	76.0		(19);11
Fe-Cr-Ni-Mo-Si-Mn	Bal. Fe 2.00 Si 18-21 Cr 1.50 Mn 8-11 Ni 0.20 C	Cast 20-10 Alloy (CF-20)		Water Quenched from above 2000(°F)	1413	20	77.7		(19);11
Fe-Cr-Ni-Mo-Si-Mn	Bal. Fe 1.50 Si 18-21 Cr 1.50 Mn 9-12 Ni 0.08 C 2.50 Mo	Cast 20-10-2.5 Alloy (CF-8M)		Water Quenched from 1950 to 2100(°F)	1399	20	81.8		(19);11
Fe-Ni-Cr-Si-Mn	Bal. Fe 2.50 Si 37-41 Ni 2.00 Mn 17-21 Cr to (0.35) (0.75) C	Cast 18-38 Alloy (HU)	Symbol "H" designates "heat resistant Castings	Cast Treatment not specified	1343	20	100		(19);11
Ni-Fe-Cr-Si-Mn	Bal. Fe 2.50 Si 58-62 Ni 2.00 Mn 10-14 Cr to (0.35) (0.75) C	Cast 12-60 Alloy (HW)		Cast Not Specified	1288	20	112		(19);11

TABLE 2.3.8 (cont'd.)

Ni-Fe-Cr-Si-Mn	2.50 Si Bal. Fe 2.00 Mn 64-68 Ni 15-19 Cr to (0.35) (0.75) C	Cast 15-65 Alloy (HX)		Cast Not Specified	1288	20			(19);11
Fe-Cr-Si-Mn	Bal Fe to (0.35) (0.65) Mn 8-10 Cr 1.00 Si 0.20 C	Cast 9 Cr Alloy (HA)		Cast Not Specified	1510	20	69.8		(19);11
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 26-30 Cr 1.00 Mn 4.00 Ni 0.50 C	Cast 28-4 Alloy (HC)		Cast Not Specified	1496	20	76.8		(19);11
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 26-30 Cr 1.50 Mn 4-7 Ni 0.50 C	Cast 28-7 Alloy (HD)		As cast	1482	20	80.8		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 26-30 Cr 2.00 Mn 8-11 Ni (0.20-0.50) C	Cast 29-9 Alloy (HE)		Cast Not Specified	1454	20	84.8		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 19-23 Cr 2.00 Mn 9-12 Ni (0.20-0.40) C	Cast 21-10 Alloy (HF)		Cast Not Specified	1399	20	79.8		(19);12

TABLE 2.3.8 (cont'd.)

Fe-Cr-Ni-Si-Mn	Bal. Fe 24-28 Cr 11-14 Ni 2.00 Si 2.00 Mn (0.20-0.50) C	Cast 25-12 Alloy (HH)		Cast Not Specified	1371	20	84.8		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 26-30 Cr 14-18 Ni 2.00 Si 2.00 Mn (0.20-0.50) C	Cast 28-15 Alloy (HI)		Cast Not Specified	1399	20	—		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 24-28 Cr 18-22 Ni 2.00 Si 2.00 Mn (0.20-0.60) C	Cast 25-20 Alloy (HK)		Cast Not Specified	1399	20	89.8		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 28-32 Cr. 18-22 Ni 2.00 Si 2.00 Mn (0.20-0.60) C	Cast 30-20 Alloy (HL)		AS cast	1427	20	95.4		(19);12
Fe-Ni-Cr-Si-Mn	Bal. Fe 23-27 Ni 19-23 Cr 2.00 Si 2.00 Mn (0.20-0.50) C	Cast 20-25 Alloy (HN)		AS cast	1399	20	—		(19);12
Fe-Ni-Cr-Si-Mn	Bal. Fe 33-37 Ni 13-17 Cr 2.50 Si 2.00 Mn (0.35-0.75) C	Cast 15-35 Alloy (HT)		Cast Not Specified	1330	20	99.7		(19);12

TABLE 2.3.8 (cont'd.)

Fe-Cr-Ni-Mo-Si-Mn	Bal. Fe 1.50 Si 18-21 Cr 1.50 Mn 9-12 Ni 2.5 Mo 0.12 C	Cast 20-10-2.5 Alloy (CF-12M)		Cast Water Quenched from above 2000(°F)	1399	20	81.8		(19);12
Fe-Cr-Ni-Cb-Si-Mn	Bal. Fe 2.00 Si 18-21 Cr 1.50 Mn 9-12 Ni "X" Cb(cb-Ta) 0.08 C	Cast 20-19 Cb Alloy (CF-8C)		Cast Water Quenched from 1950-2050(°F)	1427	20	70.8		(19);12
Fe-Cr-Ni-Mo-Si-Mn	Bal. Fe 2.00 Si 18-21 Cr 1.50 Mn 9-12 Ni 1.5 Mo 0.16 C	Cast 20-10 Alloy (CF-16F)		Cast Water Quenched from above 2000(°F)	1399	20	71.9		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 22-26 Cr 1.50 Mn 12-15 Ni 0.20 C	Cast 25-12 Alloy (CH-20)		Cast Water Quenched from above 2000(°F)	1427	20	83.8		(19);12
Fe-Cr-Ni-Si-Mn	Bal. Fe 2.00 Si 23-27 Cr 1.50 Mn 19-22 Ni 0.20 C	Cast 25-20 Alloy (CK-20)		Cast Water Quenched from 2100(°F)	1427	20	89.8		(19);12
Fe-Ni-Cr-Si-Mn	Bal. Fe 1.00 Si 21-31 Ni 1.50 Mn 18-22 Cr 0.07 C	Cast 25-20 Alloy (Cn-7M)		AS cast	1454	20	89.4		(19);12

TABLE 2.4

BASIC DATA - ALLOYS II (RESISTIVITY AT 20°C AND T_m°C, THE MAXIMUM TEMPERATURE AT WHICH DATA IS AVAILABLE)

Alloy	Composition Range (Wt. %)	Temperature Range		Resistivity, ρ, (microhm-cm)				Remarks - (1)	Remarks - (2)	Reference
				ρ 20°C (or other)		ρT°C; at (T = Max.)				
		°R	°C	Minimum	Maximum	Minimum	Maximum			
Fe-Si	0.20 to 1.0% Silicon	132 to 1266	-200°C to +430°C	12.	23.	44. at 430°C	52. at 430°C	Magnetic transformation does not allow data to be linearly extrapolated to elevated temperatures		(1); 115, 116
Fe-V	0. to 10% V	537 to 672	25°C to 100°C	20.	78.	52. at 100°C	82 at 100°C		Limited Data, & Magnetic Transformation prohibits linear extrapolation of Data to 1200°C	(1); 137, 138
Porous-Fe + Graphite +X; Antifriction Alloys	6 Alloys - (Powder Metallurgical type)	657 to 1432	92 to 522	20.	---	---	92	Elevated Temperatures would change composition due to reactions		(1); 139, 140
Fe + Cr + X	10.2 to 12.06 % Cr + X = Al; X = W, + C + M_n, etc.	492 to 1932	0° to 800°C	62	71	109	112			(1); 249, 250
Fe + Ni	46.2% Ni	537 to 672	25°C to 100°C	43	---	---	57	Magnetic transformation & influence to Curie Pt. prevents limited data to be extrapolated		(1); 261, 262
Fe + Co	29 to 40.6% Cobalt	537 to 672	25° to 100°C	8.	11.6	10.5	14.5			(1); 313, 314
Porous Iron & Copper + Graphite	10.54 to 40.69% Cu	537 to 1163	25 to 373 °C	12.	22.	---	49.	Elevated temperature & further sintering could alter the valid of extrapolation of given data		(1); 317, 318
Fe + V	10 to 50% V	537 to 672	25 to 100°C	71	141	72	143		Too limited data for valid extrapolations	(1); 321, 322
Porous Copper + Tin Compacts	89 Cu + 11% Sn of Various Porosities	528 to 852	20 to 200°C	33	81	33	81		Limited cryogenic data is not valid for extended extrapolations to 1200°C	(1); 365, 366
Titanium Hydride	6 Alloys given	1140 to 2125	300 to 907	103 at 300°C	140 at 300°C	140	149			(1); 349, 350
Cu + Ni + X	0.02 to 5.28% Ni	2° to 564	-272. to +40.	1.9	8.1	2.1	8.1			(1); 381, 382
Cu + Mn + Ni + X	6 Alloys	492 to 564	0° to +40	38.6	51.1	38.6	51.1		Limited data & temperature range prevents (via authority of constitutional diagram) linear extrapolation to elevated temperatures	(1); 411, 412
Cu + Co + Pd	7 Alloys	537 to 672	25 to 100°C	10.	17.6	11.	19.8		Same as above	(1); 447, 448
Cu + Fe	2 Alloys (Dilute Alloys)	519 to 564	15°C to 40°C	2.4	3.2	2.5	3.3		Alloys, essentially not applicable for high-temperature considerations	(1); 449, 450
Cu + Pd + Co	10% Pd + 5% Co to 30% Pd + 30% Co (9 Alloys)	537 to 672	25 to 100°C	11.	37.5	11.5	39.		Low-temperature data is insufficient for validity of extrapolations to eleveted temperature	(1); 451, 452

TABLE 2.4 (Continued)

Alloy	Composition Range (Wt. %)	Temperature Range		Resistivity, ρ, (microhm-cm)				Remarks - (1)	Remarks - (2); (Cont)	Reference
				$\rho_{20°C}$ (or other)		$\rho_{T(Max)}$; °C				
		°R	°C	Minimum	Maximum	Minimum	Maximum			
Cu + Pt	13 Alloys 19.40 to 47.43 Pt	537 to 672	25 to 100°C	19. at 20°C	73 at 20°C	20 at 100°C	73.5 at 100°C	Experimental Data demonstrates diff. between - Annealed & Quenched Alloys	Not valid for linear extrapolation to elevated temperatures	(1); 457, 458
Ni + Cr	3 Alloys; 20, 30, and 40% Cu	115 to 558	-210 to +37°C	28. at 20°C	47. at 20°C	-- at 37°C	46.5* at 57°C *(for 30% Cu Alloy only)		Cryogenic data insufficient beyond Curie Pt. for valid extrapolations to elevated temperatures	(1); 475, 476
Co-Pd-Cu	8-Alloys- From (10-Pd; 5 Cu) to (30 Pd; 30 Cu)	537 to 672	25 to 100°C	10. at 20°C	24.4 at 20°C	12.2 at 100°C	28. at 100°C	Fully annealed at 100°C. Cooled in 10 hours	Limited data is unlikely valid for high temperature extrapolations	(1); 621, 622
Co-Pd-Au	10-Alloys-Range (Pd-; Au-) 10 to 30%; -2 to 30%	537 to 672	25 to 100°C	8 at 25°C	35 at 25°C	10.7 at 100°C	42.5 at 100°C	Fully annealed samples - Slowly cooled	Too limited data for valid extrapolations	(1); 623, 624
Co-Cu-Pd	7-Alloys-; Au (20 to 30%) Pd; (10 to 30%)	537 to 672	25 to 100°C	9.6 at 25°C	18.4 at 25°C	12. at 100°C	21.6 at 100°C	Fully annealed samples - Slowly cooled.	Same as above	(1); 629, 630
Co-Au-Pd	7-Alloys-Au; (20 to 40%) Pd, (10 to 30%)	537 to 672	25 to 100°C	10.2 at 25°C	18.8 at 25°C	12.6	22.6	Same as above	Same as above	(1); 631, 632
Co-Au	7-Alloys-Au, (2 to 40%)	537 to 672	25 to 100°C	5.6 at 25°C	9.8 at 25°C	8.6	12.4	---	Same as above plus influence of magnetic transformation for the ferromagnetic alloys prohibits valid extrapolations of data to elevated temps.	(1), 633, 634
Ni-Fe	16-Alloys; Ni from (51.24 to 91.39%)	537 to 672	25 to 100°C	9.0 at 25°C	33 at 25°C	15.	45.	---	Same as above	(1); 531, 532
Ni-Mn	5 Alloys; Nickel from 51.90 to 75.89%	537 to 672	25 to 100°C	36 at 25°C	64 at 25°C	---	67	---	Same as above	(1); 577, 578
V-Al	4 Alloys; Al from 0.60 to 15.0%	547	30°C	30 at 30°C	240 at 30°C	---	---	---	Same as above	(1); 687, 688
Cr + Te	69.79 Te 30.21 Cr	492 to 654	0°C to 90°C	(4.8)* at 0°C *Change of Units; (See Note)	(6.4)* at 90°C	---	--	Data is grouped about the Curie Point (range) *NOTE-Ref.(1); 675, 676 gives values x 10^{-8} ohm-cm) which, perhaps should be 4.8 x 10^{-4} ohm-cm;	Good data, but limited for elevated temp extrapolations. (see ref (4); 219	(1); 675, 676
V + X	10-Alloys-2 points of Data/Alloy	8 to 547	-269° and 30°C	0.5 at -269	8. at -269	23. at 30°C	35. at 30°C		Data too limited for valid extensive extrapolations	(1); 689, 690
Zr + Sn	10-Alloys, Sn; (0.5 to 25%)	132 to 2292	-200. to 1000.°C	46 at 20°C	164 at 20°C	---	40 at 1000°C for 5% Sn.	Available data in Desired temp. range indicated alloys have too high values		(1); 703, 704
Zr + U	3-Alloys-U; from 3.6 to 14%	537 to 960	25 to 260°C	59 at 25°C	85 at 25°C	93. at 260°C	116. at 260°C		Too high ρ values & too little data	(1); 715, 716
Zr + Hf + X	3-Dilute Alloys	595 to 1747	57 to 697° C	53 at 57°C	62 at 57°C	---	130 at 697°C	---	These alloys have too high resistivities	(1); 733, 734

TABLE 2.4 (Continued)

Alloy	Composition Range (Wt. %)	Temperature Range		Resistivity, ρ, (microhm-cm)				Remarks (1)	Remarks - (2); (Cont)	Reference
		°R	°C	ρ 20°C (or other)		ρ T°C at (T = Max.)				
				Minimum	Maximum	Minimum	Maximum			
Zr-Nb-Hf-X	1-Alloy; Dilute Type-1.52 Nb; 0.14 Hf, 0.08C	615 to 1620	68 to 627(°C)	60 at 68°C	---	---	124 at 627°C	Annealed at 600°C for 48 hr. in vac. & Water Quench	Resistivity values too high to be of interest	(1); 735; 736
Th + U	1-Alloy-3pts. of Data. 2 to 10% U	1932 to 2292	800 to 1000(°C)	5.7 at 800°C	---	---	9.3 at 1000°C	Are melted - 5-7 times in the atm.; cast; cold swaged; annealed; water quenched	Doubtful oxidation resistant; & alloy is exceedingly dense	(1); 751, 752
Al + Cu + Mg + X	4-Alloys; Cu; (4.10 to 2.31%)	528 to 1032	20 to 356°C	3.8 at 20°C	4.7 at 20°C	---	8.1 at 356°C	For alloys. (a) Partially stabilized (b) Stabilized	Alloys are limited to relative low temps.	(1); 775, 776
Al + Cu + Ni + X	Al Alloy "Y" (Brit. design) at 3.78% Cu; 1.85% Ni, 1.33% Mg	528 to 1032	20 to 356°C	3.5 at 20°C	5. at 20°C	7. at 356°C	7.2 at 356°C	Wrought Alloy (1) As received (2) Aged	Same as above	(1); 776, 778
Al + Cu + Xi + X	5 Complex Alloys-Relatively Dilute	528 to 1932	20°C to 800°C	4.3 at 20°C	4.9 at 20°C	9.5 at 800°C	10.6 at 800°C	Cast Al. Alloys	Same as above	(1); 779, 780
Al + Si + Cu + X	11 Alloys-; 2-8% Si, 1-3% Cu	528 to 1392	20 to 500 (°C)	3.9 at 20°C	5.3 at 20°C	9.8 at 500°C	11.2 at 500°C		Same as above	(1), 793, 794
Al + Si + Cu + X	10- Alloys; 11-12% Si; 1-5% Cu	528 to 1032	20 to 356°C	4.2 at 20°C	7. at 20°C	8.2 at 356°C	10.6 at 356°C	---	Same as above	(1); 795, 796
Al + Si + Mg + X	12.0% Si, 0.35 Mg, 0.29 Mn, 0.28% Fe	528 to 1032	20 to 356°C	3.8 at 20°C	4.4 at 20°C	8.1 at 356°C	---	Alloy (1) as received (2) Cast, held 4 hrs. at 515°C, Water Quenched + held 16 hrs. at 150 to 165°C	Same as above	(1), 801, 802
Al + Mg + X	5-Alloys. (1.4 to 12% Mg)	528 to 1168	20 to 375°C	5.6 at 20°C	7. at 20°C	9.6 at 375°C	11. at 375°C	---	Same as above	(1); 815, 816
Al + Zn + X	5-Alloys; Zn (4.5 to 48.9)	528 to 1212	20 to 400°C	4.2 at 20°C	6. at 20°C	---	12.1 at 400°C	In "As Received" & Heat Treated conditions	Same as above	(1), 827, 828
Al + Ag	5-Alloys; Ag; (0% to 38%)	492 to 1293	0° to 445°C	2.6 at 20°C	5.2 at 20°C	5.9 at 298°C	9.7 at 298°C		Too low temperature restriction for intended applications	(1); 837, 838
Al + Ni + X	17-Alloys-Ni- (3 to 5%)	528 to 1032	20 to 356°C	4.6 at 20°C	9.6 at 20°C	8.4 at 356°C	13.2 at 356°C	Dilute Alloys of Nickel in Al. - Wrought & Cast Alloys	Same as above	(1); 847, 848, 849
Mg + Al + Zn + X	12 Alloys S &/or (Alloy States)	528 to 926	20 to 241°C	9. at 20°C	16.8 at 20°C	12.6 at 241°C	---	---	Same as above	(1); 861, 862
Mg + Al + X	5 Alloys-but only one with data in excess of one pt. i.e. Mg + 7% Al + 1% Si	528 to 1158	20 to 370°C	(6.8); at 20°C	17.2 at 20°C	11.6 at 370°C	---	---	Same as above	(1); 869, 870
Mg + Rare Earth + Zn + X	3-Alloys-	528 to 989	20 to 276°C	5.9 at 2.°C	7. at 20°C	10.4 at 276°C	11.4 at 276°C	Cast; Aged; and Cast, temper T5 and aged	Same as above	(1); 875, 876

TABLE 2.4 (Continued)

Alloy	Composition Range (Wt. %)	Temperature Range		Resistivity, ρ, (microhm-cm)				Remarks - (1)	Remarks - (2); (Cont)	Reference
				ρ 20°C (or other)		ρ T°C; (T = Max.)				
		°R	°C	Minimum	Maximum	Minimum	Maximum			
Mg + Rare Earths + X	(Alloy EZ-33A) 4 Alloy-States with 3+% Rare Earths	528 to 988	20° to 276°C	5.7 at 20°C	6.3 at 20°C	10.2 at 276°C	10.9 at 276°C	Cast; soln. treated; and soln. treated & aged	Too low a solidus for these alloys to be considered for high temps.	(1); 877, 878
Mg + Rare Earths + X	Alloy EK-41A-. 4% Rare Earths	528 to 960	20° to 260°C	6.8 at 20°C	7.2 at 20°C	11.2 at 260°C	11.8 at 260°C	Aged; and soln. treated + aged	Same as above	(1); 879, 880
Mg + Th + X	Alloy HM-21 X A-2. + % Th	528 to 960	20° to 260°C	5. at 20°C	6.3 at 20°C	9.2 at 260°C	9.6 at 260°C	As rolled; and rolled, temper T8	Same as above	(1); 881, 882
Mg + Th + X	Alloy-HZ-32 X A at Th≈3.%	528 to 960	20° to 260°C	6.6 at 20°C	7.1 at 20°C	10.7 at 260°C	11.2 at 260°C	As cast; and cast + aged	Same as above	(1), 883, 884
Ti + Al	9-Alloys-Al-(0 to 10%)	150 to 2220	-190° to 960°C	77. at 20°C	183. at 20°C	184. at 782°C	200. at 782°C	---	Alloys have too high resistivity for interest as good conductors	(1); 913, 914
Ti + Mn + X	3-Proprietary Alloys- 4 to 8% Mn; X = 4% Al	36 to 1460	-253° to +538°C	92. at 20°C	182. at 20°C	250 at 538°C	185 at 538°C	---	Alloys have too high resistivities for consideration as good conductors	(1); 927, 928
Ti + Fe + Cr + X	2.2 Fe; 2.1 Cr; 2.0 Mo	560 to 1460	38° to 538°C	(75) at 20°C	---	142 at 538°C	---	---	Same as above	(1); 947, 948
Ti + Oxygen + X	7 Alloys: Oxygen 0.028 to 2.68%	492 to 3223	0° to 1517°C	48 at 20°C	128 at 20°C	144. at 976°C	210 at 976°C	---	Same as above	(1); 951, 952
Ti + Hydrogen	6 Alloys; Hydrogen from 0 to 2.1%	1212 to 2119	400 to 904°C	100. at 482°C	142. at 482°C	124 at 754°C	148 at 754°C	Ti in equilibrium with Hydrogen Atmos.	Same as above	(1); 965, 966
Au + Co + Pd	8 Alloys.Cobalt-10 + 40% Pd-9.9 to 20%	537 to 672	25 to 100°C	14.3 at 25°C	33 at 25°C	16.7 at 100°C	35.1 at 100°C	Fully annealed samples cooled slowly to R.T.	Limited Data prevents valid extrapolation to solidus temps.	(1); 983, 984
Au + Co	9-Alloys-or compositions Co. from 0 to 48.8%	537 to 672	25° to 100°C	2.1 at 25°C	12.2 at 25°C	---	13.5 at 100°C	Samples cast into porcelain tube via siphon principle	Same as above	(1); 985, 986
Au + Cd.	2-Alloys Cd. (34.03 to 35.39%)	541 to 636	27° to 80°C	7.8 at 27°C	10.2 at 27°C	8.8 at 80°C	10.4 at 80°C	Effect of Thermal cycling on single crystals	Same as above	(1); 979, 980
Au + Pd + Co	13-Alloys-Pd (10 + 40%); Co (4.7 to 29.7%)	537 to 672	25° to 100°C	18. at 25°C	88. at 25°C	21. at 100°C	111. at 100°C	Samples fully annealed & slowly cooled to R.T. Alloy - 85Au 10 Pd. 5Co may be of further interest	Same as above	(1); 989, 990
Au + Ni	4-Dilute Alloys Ni-(0.06 to 0.36)	2.3 to 492	-272° to 0°C	0.1 at -272°C	0.8 at -272°C	2.15 at 0°C	3.95 at 0°C	---	Same as above	(1); 997 to 998
Au + Cu + Zn	4-Alloys-; Cu (15.3 to 32.8) Zn (8.62 to 18.4)	528 to 1482	20° to 550°C	14. at 20°C	23.7 at 20°C	24. at 504°C	30. at 504°C	Erratic electric characteristics due to order-disorder transformation	---	(1); 1023, 1024
Au + Cu	Copper-9.70%	4 to 513	-271° to +12°C	8.4 at -271°C (ordered)	8.9 at -271°C (disordered)	11.3 at +12°C (disordered)	12. at +12°C (ordered)	Investigation of order-disorder Reaction for Cu Au_3	Same as above	(1); 1025, 1026
Ag + Al	15 Alloys Al (0 to 49.81%)	492 to 672	0° to 100°C	1.5 at 0°C	39. at 0°C	2. at 100°C	44.5 at 100°C	---	Same as above + too low a solidus temp. for serious consideration	(1); 1035, 1036
Ag + Cd	10-Alloys and/or states. Cd. (1.96 to 29.97%)	0 to 528	-273° to 20°C	0.7 at -273°C	3.7 at -273°C	2.2 at 20°C	6.3 at 20°C	Wires annealed/Rod annealed for 5 different alloys	Same as above	(1); 1043, 1044

TABLE 2.4 (Continued)

Alloy	Composition Range (Wt. %)	Temperature Range		Resistivity, ρ, (microhm-cm)				Remarks - (1)	Remarks - (2); (Cont)	Reference
				$\rho_{20°C}$ (or other)		$\rho_{T°C}$; at (T = Max.)				
		°R	°C	Minimum	Maximum	Minimum	Maximum			
Pt + Cu	15-Alloys- &/or States-Cu- (0 to 29%)	537 to 672	25° to 100°C	14. at 25°C	74. at 25°C	15 at 100°C	75 at 100°C	Investigation essentially involves difference in annealed & quenched states for these alloys. Quenched from 900°C. In the solid state, there are 2 & possibly 4 Superlattice states or compounds i.e. Pt Cu$_3$, PtCu, Pt$_3$Cu, & Pt$_7$Cu Or-Order disorder Influences	Limited low temperature data is insufficient for extrapolation to 900°C	(1); 1077, 1078 Ref. (24); 817
Pt + Cu	8-Alloys Cu. (25 to 30%)	537 to 672	25° to 100°C	18 at 25°C	71 at 25°C	19+ at 25°C	74+ at 100°C	Same as above	Same as above	(1); 1079, 1080
Pd + Au + Co	13-Alloys.; Au (5 to 40%); Co (4.7 to 30%)	537 to 672	25° to 100°C	18 at 25°C	88 at 25°C	*23 at 100°C	110 at 100°C	Samples fully annealed & cooled slowly to R.T.	Limited data is not valid for extrapolation to solidus	(1); 1085, 1086
Pd + Co + Cu	7-Alloys.; Co (3.6 to 40%) Cu (5.4 to 30.%)	537 to 672	25 to 100°C	24.5 at 25°C	47. at 25°C	28 at 100°C	58.5 at 100°C	Similar to above	Same	(1); 1081, 1082
Pd + Co + Au	8-Alloys; Co (19.6 to 40%); Au (10.3 to 30%)	537 to 672	25 to 100°C	18 at 25°C	80. at 25°C	21. at 100°C	102 at 100°C	Similar to above	Same	(1); 1083, 1084
PD + Cu + Co	7-Alloys; Cu (15 to 41.3%) Co (5 to 30%)	537 to 672	25 to 100°C	31. at 25°C	79. at 25°C	36. at 100°C	80. at 100°C	Similar to above	Same	(1); 1087, 1088
Mn + Ni	14-Alloys Ni (0 to 47.00%)	537 to 672	25 to 100°C	97. at 25°C	103. at 25°C	106. at 100°C	106. at 100°C	Similar to above	Same as above & resistivity values are too high for interest in these alloys as good conductors	(1); 1135, 1136
Si + B	7-Alloys; B (0.0005 to 1%)	190 to 1800	-100°C to +727°C	---	---	---	---	Alloys, in certain temp ranges have metallic characteristics i.e. ρ increases with temp	Alloys have too high resistivities for consideration as good conductors	(1); 1223, 1224
Si + P	4-Alloys; P (0.001 to 1%)	180 to 1800	-180 to +727°C	---	---	---	---	Similar to above	Similar to above	(1); 1225, 1226
Ge + Si	2-Alloys Si (34 to 38%)	142 to 569	-194 to +43	4. at 30°C	15. at 30°C	5. at 43°C	18. at 43°C	Similar to above	Too low solidus for serious considerations at elevated temps & ltd data prevents extrapolation to solidus	(1); 1265, 1266
Sn + Mg	2 Alloys Mg (31.5 to 37.0%)	528 1167	0° to 375°C	3.3 at 50°C	5.4 at 50°C	3.8 at 365°C	5.8 at 365°C	at ≧365°C; These alloys appear to exhibit improved electrical conduction	Same as above	(1); 1267, 1268

TABLE 2.5

RESISTIVITY OF ALLOYS SYSTEMS AS A FUNCTION OF TEMPERATURE FROM 0°C TO 1200°C

Alloy	Composition (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
(Ag-Mn)	1-Mn	1.2×10^{-3} (0° to 500°C)	4.6	4.8	5.3	5.8	6.4	6.9	7.4									(1); 1071	
(Ag-Mn)	2-Mn	7.2×10^{-4} (0° - 500°C)	7.2	7.3	7.8	8.2	8.8	9.3	9.8									(1); 1071	
(Ag-Mn)	4-Mn	3.3×10^{-4} (-200° to 0°C)	11.2	11.4													10.5 at -200°C	(1); 1071	
(Ag-Mn)	6-Mn	1.47×10^{-4} (0° - 500°C)	19.		19.3	19.6	19.85	20.2	20.4									(1); 1071	
(Ag-Mn)	10-Mn	2.2×10^{-4} (-172°C to 0°C)	30.2														29.1 at -172°C	(1); 1071	
Ref (Ag)	100-Ag	3.82×10^{-3} (20° - 500°C)		1.66		2.5		4.0	4.7	5.3			7.5 at 927°C			Ag. (liq) 19.4		Table L8	2nd Section; p. 40.
		3.87×10^{-3} (0° - 500°C)	1.6	1.8	2.2	2.8	3.5	4.0	4.7									Table L8	
																		(1); 1071	

Re: (Ag-Mn.) Alloys.

(1) Alloys from 1% to 6% Mn have progressive decreases of ($\frac{d\rho}{dt}$) with increases of Mn and relative to pure Ag.

(2) α vs. % Mn (0° - 500°C) confirms note (1) above and up to 6% Mn additions to Ag.

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
(Ag-Pd)	1-Pd	3.5×10^{-3} (0° to 100°C)	2.0	2.1	2.7	3.2	3.7	4.27	4.8									(1); 1051	Solidus Temperature Range ≈ 961°C - 1000°C
(Ag-Pd)	2-Pd	2.3×10^{-3} (0° to 100°C)	2.57	2.73	3.2	3.75	4.27	4.77	5.2									(1); 1051	
(Ag-Pd)	3-Pd	2.1×10^{-3} (0° to 100°C)	2.93	3.05	3.55	4.15	4.63	5.15	5.6									(1); 1051	
(Ag-Pd)	4-Pd	1.8×10^{-3} (0° to 100°C)	3.4	3.55	4.02	4.6	5.13	5.7	6.2									(1); 1051	
(Ag-Pd)	5-Pd	2.07×10^{-3} (-200° to 0°C)	3.75	3.9	-	-	-										2.65 at -200°C	(1); 1051	
(Ag-Pd)	10-Pd	1.26×10^{-3} (-200° to 0°C)	5.93	6.05	-	-	-										4.83 at -200°C	(1); 1051	
(Ag-Pd)	50-Pd	5.1×10^{-4} (-245° to 0°C)	40.5														36. at -245°C	(1); 1107	Solidus ≈ 1290°C
(Ag-Pd)	70-Pd	3.54×10^{-4} (-245° to 0°C)	31.5														29. at -245°C	(1); 1107	Solidus ≈ 1370°C
(Ag-Pd)	95-Pd	5.1×10^{-3} (-245° to 0°C)	16.2														7.2 at -245°C	(1); 1107	Solidus ≈ 1500°C
Ref (Ag)	100-Ag	3.82×10^{-3} (20° to 500°C)		1.66		2.5		4.0	4.7	5.3			7.5 at 927°C			Ag. (liq.) 19.4		Table 1.8	
Ref (Pd)	100-Pd	3.03×10^{-3} (20° to 200°C)		11.65		18.0		24.4	27.2	30.	33.5 at 727°C		38.4 at 927°C			44.0		Table 1.8	

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ag-Pt	1-Pt	2.45×10^{-3} (20°-200°C)	2.1	2.2	2.64	3.17	3.8	4.45	5.2									(1); 1073	
Ag-Pt	2-Pt	1.04×10^{-3} (20°-200°C)	2.95	3.05	3.50	4.07	4.65	--	--									(1); 1073	
Ag-Pt	3-Pt	1.70×10^{-3} (20°-200°C)	3.6	3.7	4.2	4.83	5.46	6.15	6.8									(1); 1073	
Ag-Pt	4-Pt	1.29×10^{-3} (20°-200°C)	4.65	4.75	5.25	5.85	6.42	6.97	7.5									(1); 1073	
Ref Ag	100-Ag	3.82×10^{-3} (20°-500°C)		1.66		2.5		4.0	4.7	5.3						Ag.(liq.) 19.4		Table 1.8	
Ref Pt	100-Pt	3.78×10^{-3} (20°-200°C)		11.0		18.5		25.2	28.5	31.5						48.		Table 1.8	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α), °C^{-1}	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
		3.83×10^{-3} (20° - 227°C)																	
Au-Mn	Mn-21.78 Au-78.22	1.34×10^{-3} (227° - 800°C)		41.7	55.	71.	76.	77.3	78.3	79.3	80.4						at 227°C ρ = 74.8	(4); 220	AuMn-Disorder ≧ 615°C
Au-Mn	Mn-8.68 Au-91.32	1.78×10^{-3} (20° - 400°C)		49.2	50	51	51.4	52.4	54.	56.4	64.4	64.8						(4); 220	Au_3Mn - Disorder ≧ 645°C
Au-Mn	Mn-12.22% Au-87.78	6.52×10^{-3} (0° - 100°C)	23.	25.5	38.	54.	70.											(1); 1001	Au_2Mn
Au-Mn	Mn-6% Au-94	6.1×10^{-3} (0° - 100°C)	41.	41.7	43.5	39.5	40.	44.3										(1); 1003	
Au-Mn	Mn-4 Au-96	2.58×10^{-4} (0° - 100°C)	31.5	31.7	32.3	32.5	33.	33.										(1); 1003	
Au-Mn	Mn-2 Au-98	4.7×10^{-4} (0° - 100°C)	17.	17.3	17.8	18.5	19.2	20.3										(1); 1003	
Au-Mn	Mn-1 Au-99	1.2×10^{-3} (0° - 100°C)	10.	10.5	11.2	12.	12.7	14.										(1); 1003	
Au-(Ref)	Au-100	4.0×10^{-3} (0° - 100°C)	2.	2.3	2.8	3.7	4.7	6.4										(1); 1003	

NOTES: (1) Order-disorder Temperature for AuMn and Au_3Mn, are per. (Ref.): Hansen's - Constitution of Binary Alloys, 1958 edition.

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity (α)	Resistivity, (ρ), Microhm-cm, at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Au-Pd	2.2 - Pd	2.01×10^{-3} (20° to 200°C)	3.6	3.67	4.3	5.3	5.8	6.8	7.65									(1); 991	ρ values at 500°C obtn. by extropolation from about 465°C
Au-Pd	1.7 - Pd	2.41×10^{-3} (20° to 200°C)	3.2	3.35	4.0	4.8	5.6	6.5	7.4									(1); 991	Same
Au-Pd	1.0 - Pd	2.59×10^{-3} (20° to 200°C)	2.8	3.0	3.67	4.4	5.2	6.2	7.2									(1); 991	Same
Au-Pd	0.44 - Pd	3.33×10^{-3} (20° to 200°C)	2.4	2.5	3.2	4.0	4.95	5.8	6.7									(1); 991	Same
Ref-Au	100 - Au	4.08×10^{-3} (20° to 200°C)	2.0	2.2	2.9	3.8	4.65	5.6	6.6									(1); 991	Same
Ref-Au	100 - Au	4.02×10^{-3} (20° to 200°C)		2.32		4.0		5.7	6.7							Au(liq). 33.		Table L8	
Ref-Pd	100 - Pd	3.03×10^{-3} (20° to 200°C)		11.65		18.0		24.4	27.2	30						44.0		Table L8	

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks:
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Au-Pt	1-Pt	2.22×10^{-3} (20°-200°C)	3.2	3.43	4.1	4.8	5.5	6.4	7.55									(1); 1027	ρ values at 500°C are extrapolated from about 465°C
Au-Pt	2-Pt	1.72×10^{-3} (20°-200°C)	4.0	4.2	4.8	5.5	6.3	7.1	8.1									(1); 1027	Same
Au-Pt	3-Pt	1.76×10^{-3} (20°-200°C)	4.75	4.9	5.6	6.45	7.4	8.2	8.9									(1); 1027	Same
Au-Pt	4-Pt	1.19×10^{-3} (20°-200°C)	5.75	5.93	6.5	7.2	8.0	8.9	9.9									(1); 1027	Same
Au-Pt	0-Pt	4.02×10^{-3} (20°-200°C)	2.0	2.2	2.87	3.8	4.7	5.7	6.6									(1); 1027	Same
Ref-Au	100-Au	4.02×10^{-3} (20°-200°C)		2.32		4.0		5.7	6.7							Au(liq) 33.		Table 1.8	
Ref-Pt	100-Pt	3.79×10^{-3} (20°-200°C)		11.0		18.5		25.2	28.5							48.		Table 1.8	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; At Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Co - Fe	40 - Fe	4.17×10^{-3} (20° to 200°C)	3.	4.	5.5	7.0	11.	17.	23.	32.	42.5	55.	71.	100.	-	-		(1); 615	Alloy Prep. Electrolytically. (Ordered Structure.)
Ref - Co	100 - Co	6.15×10^{-3} (20° to 200°C)	-	6.5	-	13.7	-	24.	31.3	36.7	53.5 at 727°C	-	72.5 at 927°C	-	-	95.		Table 1.8	
Ref - Fe	100 - Fe	8.06×10^{-3} (20° to 200°C)	-	9.86	-	24.2	-	47.5	60.7	75.2	94 at 727°C	-	111. at 927°C	-	-	122.		Table 1.8	
Ref-(Pt-Rh)	40 - Rh	1.327×10^{-3} (20° to 200°C)	(16.99)	17.45	(19.3)	(21.62)	(23.94)	(26.25)	(28.20)	(30.89)	33.21	(35.52)	(37.84)	39.9	(42.48)	44.8		Table 2.2	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %). Nominal	Temperature Coefficient of Resistivity (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Cu-Cr	0.16 - Cr	1.50×10^{-3} (20° to 200°C)	4.1	4.25	4.80	5.40	5.96	6.36	6.10	6.80								(1); 423	+0.2%Zr; 0.1 to 0.2% Ti; and 0.2% Ni
Cu-Cr	0.37 - Cr	1.21×10^{-3} (20° to 200°C)	4.6	4.75	5.25	5.78	6.10	5.66	5.90	-								(1); 423	+0.25% to 0.28% Zr.
Cu-Cr	0.5 - Cr	4.26×10^{-3} (20° to 200°C)	2.0	2.15	2.90	3.80	4.55	5.03	5.86	6.95								(1); 423	
Cu-Cr	0.9 - Cr	2.56×10^{-3} (20° to 200°C)	3.0	3.15	3.85	4.60	5.20	5.30	-	-								(1); 423	+0.25 to 0.28% Zr
Ref-Cr	100 - Cr	2.22×10^{-3} (20° to 200°C)	-	14.3		20.		27.7	32	41.2	42.7 at 727°C		52.7 at 927°C			67.5		Table 1.8	
Cu-Mn	1-Mn	1.45×10^{-3} (20° to 200°C)	4.4	4.6	5.1	5.8	6.4	7.0	7.75									(1); 413	
Cu-Mn	2-Mn	9.44×10^{-4} (20° to 200°C)	7.8	7.95	8.6	9.3	10.0	10.7	11.4									(1); 413	
Cu-Mn	4-Mn	6.67×10^{-4} (20° to 200°C)	12.2	12.5	13.8	14.0	14.5	15.0	15.5									(1); 413	
Cu-Mn	6-Mn	3.97×10^{-4} (20° to 200°C)	17.8	18.2	19.1	19.5	19.8	20.0	20.2									(1); 413	
Cu-Mn	8-Mn	3.49×10^{-4} (20° to 200°C)	21.8	22.3	23.5	23.7	24.0	24.3	25.5									(1); 413	
Ref-Mn	100-Mn	4.90×10^{-4} (0 - 200°C)	255			280		300		310		150		130		70		(3); 311	
Cu-Si	1.32-Si	7.80×10^{-4} (20° to 200°C)	11.25	11.40	12.1	13.0	13.85	14.75	15.60	16.47	17.32	18.27	(19.07)					(1); 403	( ) electroplated value
Cu-Si	2.03-Si	5.76×10^{-4} (20° to 200°C)	16.20	16.40	17.1	18.1	19.1	20.1	21.0	22.0	22.9	23.9	(24.9)					(1); 403	( ) electroplated value
Ref-Cu	100-Cu	3.92×10^{-3} (20° to 200°C)	1.6	1.7	2.2	2.9	3.6	4.2	4.8									(1); 413	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity - Microhm-cm at Temperature, °C															Reference	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Cu-Ni	10.79 (Ni)	4.76×10^{-4} (20° - 400°C)		14.9	15.5	16.17	16.88	17.6										(4); 218	
Cu-Ni	21.40 (Ni)	2.04×10^{-4} (20° - 400°C)		27.10	27.54	28.09	28.65	29.20										(4); 218	
Cu-Ni	30.19 (Ni)	1.40×10^{-4} (20° - 400°C)		37.6	38.0	38.6	39.1	39.6										(4); 218	
Cu-Ni *	39.71 (Ni)	3.37×10^{-5} (avg) (20° - 400°C)		46.8	46.7	46.7	46.9	47.4										(4); 218	
Cu-Ni *	49.74 (Ni)	3.52×10^{-5} (avg) (20° - 400°C)		52.2	52.3	52.4	52.4	52.9										(4); 218	
Cu-Ni *	58.28 (Ni)	6.17×10^{-5} (20° - 400°C)		51.2	52.1	52.4	52.5	53.4										(4); 218	
Cu-Ni	70.27 (Ni)	1.44×10^{-3} (20- 100°C) 2.56 x 10-4 (200 - 400°C)		42.5	47.4	49.2	50.5	51.8										(4); 218	
Cu-Ni	79.18 (Ni)	3.02×10^{-3} (20° - 100°C) 4.17 x 10-4 (200° - 400°C)		30.5	37.9	44.3	46.7	48.										(4); 218	
Cu-(Ref)	100. (Cu)	4.18×10^{-3} (20° - 400°C)		1.70	2.28	2.98	3.69	4.40										(4); 218	
Ni-(Ref)	100. (Ni)	5.17×10^{-3} (20° - 100°C)		8.14	11.5	16.3	23.0	30.8										(4); 218	

NOTES: (1) Values of ρ have been scaled, from figures presented by reference (4), 218 of ρ vs. Temperature, and converted from ohm-meters to microhm-cm.
(2) Atomic % of Ni in these alloys have been converted to Weight % Ni in the Cu-Ni Alloys cited.
* (3) (Cu-Ni) Alloys from 10.79 Wt. % Ni through 58.28 Wt. % Ni, and note especially the near constantcy of ρ vs. Temp. for the range from 20°C to 400°C.

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm, at Temperature (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Cu-Pd	1.7 - Pd	2.56×10^{-3} (20° to 200°C)	2.5	2.63	3.17	3.84	4.47	5.07	5.65									(1); 453	
Cu-Pd	3.3 - Pd	1.78×10^{-3} (20° to 200°C)	3.3	3.43	3.94	4.53	5.12	5.70	6.25									(1); 453	
Cu-Pd	5. - Pd	1.30×10^{-3} (20° to 200°C)	4.3	4.4	4.9	5.43	6.0	6.54	7.1									(1); 453	
Cu-Pd	6.7 - Pd	1.14×10^{-3} (20° to 200°C)	5.2	5.35	5.87	6.45	7.0	7.55	8.1									(1); 453	
Ref-Cu	100.-Cu	4.0×10^{-3} (20° to 200°C)	1.53	1.65	2.2	2.84	3.47	4.14	4.8									(1); 453	
Cu-Pt	1. - Pt	2.51×10^{-3} (20° to 200°C)	2.15	2.3	2.8	3.34	3.85	4.36	4.8									(1); 455	
Cu-Pt	2. - Pt	2.38×10^{-3} (20° to 200°C)	2.7	2.8	3.35	4.0	4.6	5.1	5.5									(1); 455	
Cu-Pt	3. - Pt	1.80×10^{-3} (20° to 200°C)	3.2	3.3	3.78	4.37	4.9	5.5	6.1									(1); 455	
Cu-Pt	4. - Pt	1.44×10^{-3} (20° to 200°C)	4.05	4.15	4.64	5.23	5.8	6.4	6.93									(1); 455	
Ref-Cu	100. - Cu	4.16×10^{-3} (20° to 200°C)	1.40	1.6	2.15	2.8	3.54	4.2	(4.9)									(1); 455	( ) extrapolated value.

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C).														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Cu-Sn	20-Sn	5.09x10^{-4} (20° to 200°C)	(22.7)	(22.9)	24.	25.	27.	28.3	29.3	29.	30.	---					30.-27. at 522°C	(1);363	
Cu-Sn	25-Sn	3.94x10^{-4} (20° to 200°C)	23.5	24.	24.5	25.7	27.2	28.8	36.5	36.	39.	---					40. at 522°C	(1);363	
Cu-Sn	30-Sn	4.39x10^{-4} (20° to 200°C)	41.4	41.7	43.	45.	47.	49.	51.5	40.	42.	---					52. at 522°C	(1);363	
Cu-Zn	48-Zn	2.91x10^{-3} (20° to 200°C)	4.0	4.2	5.2	6.4	7.9	9.8	12.0	14.4	16.9	18.6					19.4 at 870°C	(1);341	
Cu-Zn	53-Zn	3.25x10^{-3} (20° to 200°C)	5.2	7.7	14.7	12.2	15.0	18.1	22.0	26.0	27.5	29.6					32.5 at 857°C	(1);1269	
Cu-Zn	56.5-Zn	1.69x10^{-3} (20° to 200°C)	11.	11.5	12.8	15.0	17.7	21.0	25.5	29.0	31.0	29.6					29. at 828°C & 30 at 857°C	(1);1269	
Cu-Zn	62-Zn	1.63x10^{-3} (20° to 200°C)	13.	13.15	14.5	17.0	20.5	24.2	28.6	33.2	38.0	42.5						(1);1269	
Cu-Zn	65-Zn	2.23x10^{-3} (20° to 200°C)	11.	11.7	13.5	16.4	20.0	23.7	28.6	33.2	38.0	42.5						(1);1269	
Cu-Ni-Be-Zr	Ni Be Zr 0.55 0.107 0.25	2.22x10^{-3} (20° to 200°C)	(3.36)	(3.55)	(4.15)	4.97	5.67	6.14	6.35	-							6.7 at 562°C	(1);379	Normalized
Cu-Ni-Be	0.62 0.14 --	2.34x10^{-3} (20° to 200°C)	(3.06)	(3.2)	3.8	4.55	5.30	5.90	6.2	-							(6.8) at 562°C	(1);379	Normalized
Cu-Ni-Be	0.90 0.18 --	2.05x10^{-3} (20° to 200°C)	3.7	(3.93)	4.58	5.38	6.07	6.3	6.4	-							6.9 at 562°C	(1);379	Normalized
Cu-Ni-Be	0.98 0.21 --	1.92x10^{-3} (20° to 200°C)	(4.03)	4.2	4.87	5.65	6.34	6.6	6.53	-							6.7 at 562°C	(1);379	Normalized
Ref - Cu	100 - Cu	3.92x10^{-3} (20° to 200°C)	1.6	1.7	2.2	2.9	3.6	4.2	4.8									(1);413	

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Cu-Zr	0.5 - Zr	4.12×10^{-3} (20° to 200°C)	(1.93)	(2.10)	2.80	3.66	4.45	5.2	5.95	6.70	(7.40)							(1); 429	Normalized
Cu-Zr-Al	0.27 - Zr 0.3 - Al	1.915×10^{-3} (20° to 200°C)	(3.33)	(3.45)	4.0	4.64	5.25	5.85	6.45	(7.0)	(7.57)							(1); 429	Normalized
Cu-Zr-Al	0.27 - Zr 0.3 - Al	1.904×10^{-3} (20° to 200°C)	(3.2)	(3.5)	4.0	4.7	5.0	5.7	6.4	(7.0)	(7.5)							(1); 397	Normalized
Cu-Al	13.9 - Al	2.12×10^{-3} (20° to 200°C)	(10.6)	11.3	13.0	15.6	18.0	19.0	23.	25.4	28.0	29.7	31.0	34.3				(1); 397	Solid State phase reactions involved
Cu-Al	14.5 - Al	1.92×10^{-3} (20° to 200°C)	(10.6)	11.0	12.3	14.8	16.8	16.4	21.0	24.3	26.6	28.7	28.	31.7				(1); 397	Same as above
Cu-Al	14.9 - Al	1.86×10^{-3} (20° to 200°C)	(11.6)	12.3	14.0	16.4	19.0	20.	24.	28.4	32.0	34.7	32.	36.				(1); 397	Same as above
Cu-Al	15.15 - Al	2.55×10^{-3} (20° to 200°C)	13.	13.5	16.4	19.7	23.0	25.0	30.7	31.3	34.7	38.6	38.	33.				(1); 397	Same as above
Cu-Al	16.4 - Al	2.02×10^{-3} (20° to 200°C)	15.	15.7	18.5	21.4	25.0	29.	32.6	37.	41.3	47.4	53.	50.				(1); 397	Same as above
Cu-Al	16.41 - Al	1.60×10^{-3} (20° to 200°C)	15.	15.3	17.	19.7	23.3	26.8	30.3	34.7	39.7	45.0						(1); 395	γ_2 Phase
Cu-Al	17.05 - Al	2.44×10^{-3} (20° to 200°C)	13.	13.7	16.3	19.7	23.3	27.3	31.7	37.3	43.7	51.7						(1); 395	Same as above
Cu-Al	17.40 - Al	2.15×10^{-3} (20° to 200°C)	13.5	-	-	19.3	23.3	26.8	30.3	34.7	39.7	45.0						(1); 395	Same as above
Cu-Al	18.30 - Al	3.06×10^{-3} (20° to 200°C)	19.3	20.	24.4	31.	39.5	49.	54.5	60.5	67.	75.0						(1); 395	Same as above
Cu-Al	19.30 - Al	2.04×10^{-3} (20° to 200°C)	-	15.	17.2	20.5	24.7	29.7	35.7	43.	52.	63.5						(1); 395	Same as above
Ref-Cu	100 - Cu	3.92×10^{-3} (20° to 200°C)	1.6	1.7	2.2	2.9	3.6	4.2	4.8									(1); 413	--

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %) Nominal	Temperature Coefficient of Resistivity (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Fe-Al	17.6-Al	5.76×10^{-4} (20° to 200°C)	(81.5)	82	86.	90.5	96.	102.7	111.	122.	132.	138.	140.					(1); 283	Approx. Comp. of (Fe_3 Al).
Fe-Al	21.5-Al	1.135×10^{-3} (20° to 200°C)	90.	93.	103.	112.	118.	121.4	123.4	133.	142.	144.	(146)					(1); 283	
Fe-Al	23.7-Al	1.94×10^{-3} (20° to 200°C)	82.5	86.	99.	116.	130.	143.5	150.	152.	157.	159.	159.5					(1); 283	
Fe-Al	24.5-Al	2.235×10^{-3} (20° to 200°C)	82.5	87	104	122.	137.5	153.	162.7	162.	162.	(163.5)	(163.5)					(1); 283	
Fe-Al	26.9-Al	1.415×10^{-3} (20° to 200°C)	102.	106	118.	133.	147.	160.	166.	164.	163.5	163.5	(163.5)					(1); 283	Approx. Comp. of (Fe Al).
Ref-Al	100-Al	4.32×10^{-3} (20° to 200°C)	--	2.69	3.64	4.78	5.99	7.30											Smithells; Vol. 2: Metals Ref. Book.
Ref-Fe	100-Fe	8.08×10^{-3} (20° to 200°C)	--	9.86	--	24.2	--	47.5	60.7	75.2						122		Table 1.8	
Ref-Ni	100-Ni	6.40×10^{-3} (20° to 200°C)	--	7.2	--	15.5	--	33	36.5	39.3	43. At 727°C	--	49. At 927°C	--	--	53.		Table 1.8	
Ni-Al	13.8 Al	1.59×10^{-3} (20° to 200°C)	(48.5)	50.	56.5	64.3	72.	(80)	(88)									(1); 581	Approx. Comp. of Ni_3Al. Heat treated 72 hrs. at 1100°C, furnace cooled.

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity (α)	Resistivity (ρ) Microhm-cm; at Temperature, (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Fe-C	0.08 - C	5.44×10^{-3} (20° to 200°C)	(12.7)	13.0	18.5	25.5	34.	45.5	58.	74.	91.	110.	-	-	-	-		(1); 43, 44	Annealed at 600°C
Fe-C	0.10 - C	5.44×10^{-3} (20° to 200°C)	12.7	13.0	18.5	25.5	34.	45.5	58.	74.	91.	110.	(122.)	-	-	-		(1); 43, 44	S.A.E. 1010
Fe-C	0.10-C	6.25×10^{-3} (20° to 200°C)	(13.4)	16.0	23.5	34.	48.	62.	83.	105.	125.	143.	-	-	-	-		(1); 43, 44	S.A.E. 1010
Fe-C	0.13-C	3.55×10^{-3} (20° to 200°C)	16.5	18.	22.5	29.5	38.	48.5	60.	74.7	92.	111.	118.	120.	(122.5)	(123.)		(1); 43, 44	
Fe-C	0.46-C	4.01×10^{-3} (20° to 200°C)	(16.5)	18.	24.	31.	39.5	48.5	59.	72.	89.	110.5	114.	121.	(126.5)	(132)		(1); 49, 50.	C as Fe_3C
Fe-C	0.86-C	4.01×10^{-3} (20° to 200°C)	(16.5)	18.	24.	31.	41.	52.	65.	78.5	97.5	117.5	123.	128.	(132)	(136)		(1); 49, 50.	C as Fe_3C
Fe-C	1.22-C	3.57×10^{-3} (20° to 200°C)	19.5	20.7	26.6	34.	42.5	53.5	65.	79.	94.	116.5	119.5	122.	124.5	127.		(1); 61, 62.	Annealed at 800° - 930°C
Fe-C	1.35-C	3.63×10^{-3} (20° to 200°C)	(21)	23.	29.	38.	48.	58.5	71.	86.	106.	121.5	128	133.	(137)	(141)		(1); 49, 50.	C as Fe_3C
Ref-Fe	100-Fe	8.08×10^{-3} (20° to 200°C)	-	9.86	-	24.2	-	47.5	60.7	75.2	94. at 727°C	-	111. at 927°C	-	-	122.		Table 1.8	

NOTE: All (Fe-C) Alloys contain significant number of additional but minor alloying elements. See original Reference for complete chemical identification.

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %), Nominal		Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm, at Temperature, (°C)															Reference -Number -Page	Remarks
	Cr	C		0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Fe-Cr-C	1.15	0.42	2.66×10^{-3} (20° to 200°C)	(21.5)	(23)	28.	34.	43.	52.	65.									(1); 99, 100	Quenched-Annealed-Reheated to 650°C for 120 hr. cooled slowly
Fe-Cr-C	1.5	1.05	3.24×10^{-3} (20° to 200°C)	(22)	24.	30.	38.	45.5	57.	67.	82.	99.	113.	118.5	122.5	124.	(126)		(1); 99, 100	Quenched from 830°C, Tempered 2 hr. at 750°C
Fe-Cr-C	2.02	1.41	1.304×10^{-3} (20° to 200°C)	(31.)	32.	35.	39.5	45.	53.	66.	82.	98.5	113.	126	130.	133.	(135)		(1); 99, 100	C as $(Fe, Cr)_3C$
Fe-Cr-C	2.09	0.56	3.05×10^{-3} (20° to 200°C)	(19.)	20.	24.	31.	40.	50.7	60.	72.	90.	107.	113.	116.	117.	118		(1); 99, 100	C as $(Fe, Cr)_3C$
Fe-Cr-C	2.21	1.05	3.20×10^{-3} (20° to 200°C)	(24.)	26.	33.	41.	50.	59.	70.	82.5	98.5	125.5	131.5	(133)	(135)	(136)		(1); 99, 100	C as $(Fe, Cr)_3C$
Fe-Cr-C	5.85	0.62	2.33×10^{-3} (20° to 200°C)	(29.5)	31.	37.	44.	54.	64.	76.	89.5	105.5	121.5	125.5	128	(129.5)	(132.)		(1); 99, 100	C as $(Cr, Fe)_7C$
Fe-Cr-C	11.05	0.43	1.83×10^{-3} (20° to 200°C)	(42)	44.	50.	58.5	68.0	72.	79.5	88.5	98.	104.	102.5	106.	(112)	(118)		(1); 155, 156	C as $(Cr, Fe)_{23}C_6$
Fe-Cr-C	11.08	1.01	1.85×10^{-3} (20° to 200°C)	(48)	49.5	57.	66.	75.	90.	100.	109.	118.	129.	127.	128.	(131)	(138)		(1); 155, 156	C as $(Cr, Fe)_7C_3$
Fe-Cr-C	13.2	0.17	9.91×10^{-4} (20° to 200°C)	(63.4)	64.5	69.	76.	83.	89.3	96.	102.5	108.	112.	116.	(118)	(120)	(122)		(1); 155, 156	Tempered
Fe-Cr-C	13.23	2.11	2.025×10^{-3} (20° to 200°C)	(36)	37.	42.5	50.5	59.	69.5	81.	93.5	106.	120.	124.	126.5	130.	(138)		(1); 155, 156	Slowly Heated and cooled at 100°C/hr.
Fe-Cr-C	13.23	2.11	1.54×10^{-3} (20° to 200°C)	(70)	72.	80.	92.	103.	115.	128	143.	156.	174.	189.	207.	(224)	-		(1); 155, 156	20 min at 1130°C; Air Cooled to 500°C, Furnace cooled to R.T.
Fe-Cr-C	26.0	0.13	2.04×10^{-3} (20° to 200°C)	57.	58.5	68.5	80.	89.	98.	106.	113.5	119.	122.	124.	(126)	(129.5)	(136)		(1); 155, 156	----
Ref-Fe	100-Fe		8.08×10^{-3} (20° to 200°C)	-	9.86	-	24.2	-	47.5	60.7	75.2	94 at 727°C	-	111 at 927°C	-	-	122.		Table 1.8	

NOTE: (All (Fe-Cr-C) alloys, above, may contain significant number of additional but minor alloying elements.
See original reference for complete chemical identification.

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %), Nominal						Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm - cm; at Temperature, (°C)														Reference -Number -Page	Remarks
								0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Fe- -Co- -Cr- -Ni-	Bal. 20 20 20						6.06×10^{-4} (20° to 200°C)	(87.7)	(89.0)	93.3	98.7	103.2	106.6	108.7	110.7	112.2	(113.5)	(114.8)	(115.7)	(116.7)	(117.7)		(1); 183, 184 271, 272 315, 316	( ); values are extrapolated. Forged; Quenched in oil from 1200°C; aged 70 hrs, at 760°C
	Cr.	C.	Mn.	Mo.	Ni.	Si.																		
Fe-Cr-C -Mn-Mo- -Si-	.52	.15	.54	.50	-	.28	2.20×10^{-3} (20° to 200°C)	(23.)	24.	28.	33.5	41.	49.5	60.	72.	84.	95.	104.	(116.)	(126.)	(135)		(1); 105, 106	
Fe-Cr-C- -Ni- (S.S. 310)	25.54	0.10	1.83	-	20.68	0.84	5.48×10^{-4} (20° to 200°C)	(95.)	(96.5)	101.5	106.	111.	115.	119.	122.5	125.5	127.	129.5	(131.)	(134.)	(136.)		(1); 171, 172.	
Fe-Cr-C -Ni- (S.S. 303)	18.42	0.17	0.61	-	8.97	0.51	1.05×10^{-3} (20° to 200°C)	72.	74.	80.	88.	96.	101.5	107.	111.	114.	118.	121.	(124).	(126.)	(129.)		(1); 171, 172.	
Fe-Cr-Ni-W; & (W) at 2.76%	15.3	0.10	0.43	0.72	12.3	0.59	1.05×10^{-3} (20° to 200°C)	(72)	(74)	81.	87.	93	98.5	104.	108.	112.	116.	116.5	(123)	(126)	(130.5)		(1) 231, 232	Stabilized 10 hr. at 800°C
Fe-Cr-Ni-Mn (S.S. 347)	18.0	0.07	1.80	-	11.2	.70	5.08×10^{-4} (20° to 200°C)	(81)	(82)	85.5	89.5	93.	96.	99.	101.	103.	105.5	107.	(109.)	(110)	(112)		(1); 231, 232	
Fe-Cr-C-Ni- (S.S. 303)	18.42	0.17	0.61		8.97	0.51	8.05×10^{-4} (20° to 200°C)	72	76.	80.	87.	94.5	100.5	106.5	111.	113.5	118.	120.	(123)	(125.5)	(128.)		(1); 231, 232	
Fe-Cr-Ni-W- & (W) at 2.76%	15.3	0.10	0.43	0.72	12.3	0.59	8.81×10^{-4} (20° to 200°C)	(81)	(82)	88	95.	101.	106.	111.	115.	118.	120.	123.	(125.4)	(127.)	(129)		(1) 231, 232	Austenitic condition
Fe-Cr-Mn-C	12.05 to 14.66	0.05 to .26	20. to 20.9	-	-	.66 to .83	1.04×10^{-3} (20° to 200°C)	69.5	71.2	77.2	84.5	91.	97.	103.	108.	112.7	117.3	121.5	(126)	(130.7)	(135.)		(1); 297, 298	Stabilized at 800°C for 10 hours.
Fe-C-Mn (Brit. Type EN 8.)	-	0.39	1.05	-	0.12	0.14	2.90×10^{-3} (20° to 200°C)	(20.6)	(22.)	26.	33.5	42.	52.	64.	77.3	91.5	101.3	(119.)	(133)	(147)	-		(1); 79, 80	Normalized
Ref-Fe	100-Fe						6.08×10^{-3} (20° to 200°C)	-	9.86	-	24.2	-	47.5	60.7	75.2	94 at 727°C	-	111 at 927°C	-	-	122.		Table L8	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %) Nominal				Trade Designation	Max. Safe Temperature of Operation, without Protection, (°C)	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)															Reference -Number -Page	Remarks
	Fe	Ni	Cr	X				0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Fe-Ni-Cr	Bal.	30	2	Mn- 1.0	Alloy-193. (Driver-Harris)	-	6.69×10^{-4} (20° to 200°C)	-	91.4	97.3	102.4	105.9	110.7	114.4	119.4	121.25	125.5	131.4						
Fe-Ni-Cr	Bal.	30	2	Mn- 1.0	Same	-	1.103×10^{-3} (20° to 200°C)	-	95.5	104.35	114.45	123.75	130.35	136.10	140.50	143.5	146.9	151.4						Same as above.
Fe-Ni-Cr	43	37	18	Si- 2.0	Brightray "F"	1000	2.61×10^{-4}	-	108.	110.26	113.07	115.66	118.47	120.96	123.12	125.06	127.22	129.37	130.78					
Ni-Fe-Cr	20	65	15	-	Brightray-B-Calomic-Nichrome-	950	1.28×10^{-4} (20° to 200°C)		108.5	109.58	111.0	112.63	114.36	115.77	115.0	114.90	115.23	115.98	117.18	119.02				
Ni-Fe-Cr	4.8 to 27	54. to 80	10 to 22	Mn to 2.0	Nichrome I		2.86×10^{-4} (20° to 200°C)	-	109.75	112.25	115.4	118.1	119.9	121.4	122.2	121.4	123.7	125.	126.9					
Ni-Fe-Cr	12 to 14.	65 to 67	20 to 22	Mn 1.5 to -2.0	Nichrome II		1.32×10^{-4} (20° to 300°C)		110.7	-	-	114.9	116.2	117.6	117.2	117.1	117.4	118.2	119.0					Same as above
Ni-Cr	-	85	15	-	Nichrome III		1.45×10^{-4} (20° to 200°C)	-	89.75	90.75	92.1	93.4	94.75	95.75	95.75	96.	97.1	98.1	99.75					Same as above
Ni-Cr	-	85	15	-	Nichrome III		1.53×10^{-4} (20° to 300°C)	-	97.15	-	-	101.3	102.5	103.5	103.4	103.75	104.4	105.7	107.2					Same
Ni-Cr	-	80	20	-	Nichrome IV		1.18×10^{-4} (Mean) (20° to 300°C)	-	98-103	104.9	106.	100.75 to 106.9	101.75 to 108.	102.6 to 108.9	101.85 to 108.5	101.65 to 108.	101.85 to 108.9	102.35 to 109.4	103.5 to 110.6					Same
Ni-Cr	-	80	20	-	Nichrome IV & V	1200	6.13×10^{-5} (20° to 200°C)		107.	107.53	108.18	108.82	109.47	110.12	109.14	108.29	108.39	109.0	109.57	110.54				Ref. (39), p. 678
Fe-Cr-Al	Bal.	-	20. to 30.	Al- 5.0	Kanthal-	1150-1350	2.82×10^{-5} (20° to 200°C)	-	140.0	140.28	140.71	140.98	141.56	142.38	142.96	143.23	143.93	145.33	146.32	146.87				Ref. (39), p. 678

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %). Nominal	Temperature Coefficient of Resistivity (α)	Resistivity, (ρ), Microhm-cm, at Temperature, (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Fe-Si	15-Si	6.12×10^{-3} (20° to 200°C)	36	40	62	88	115	140	158	167	173.	177	179	180	181	182		(1); 319	Approximates the comp. of Fe_3Si
Fe-Si	17-Si	2.94×10^{-3} (20° to 200°C)	80	85	106	130	155	178	203	227	233.	228	222	211	200	--		(1); 319	Heating
Fe-Si	17-Si	3.40×10^{-3} (20° to 200°C)	(80)	(85)	108	137	164	190	214	227	226.	220	201	198	198	--		(1); 319	Cooling
Ref-Fe	100-Fe	8.08×10^{-3} (20° to 200°C)	-	9.86	-	24.2	-	47.5	60.7	75.2	94 at 727°C	-	111. at 927°C	--	--	122			1st Quarter Rpt. 2nd Sect. p. 40
Ni-Si	0.04-Si	7.20×10^{-3} (20° to 200°C)	6.5	7.4	11.3	17.0	24.3	31.4	34.8	(38.3)								(1); 585	Curie Point ≈ 350°C
Ni-Si	0.20-Si	4.01×10^{-3} (20° to 200°C)	8.4	9.0	11.7	15.5	25.	32.5	36.	(39.8)								(1); 585	Curie Point ≈ 354°C
Ni-Si	1.0-Si	4.53×10^{-3} (20° to 200°C)	12.7	13.5	17.8	24.5	32.	35.7	39.	(42.5)								(1); 585	Curie Point ≈ 295°C
Ni-Si	2.0-Si	3.05×10^{-3} (20° to 200°C)	17.5	18.4	22.6	28.5	34.	37.5	41.	(45.)								(1); 585	Curie Point ≈ 262°C
Ni-Si	3.0-Si	2.95×10^{-3} (20° to 200°C)	22.7	23.5	28.	36.0	39.	42.3	45.4	(48.5)								(1); 585	Curie Point ≈ 200°C
Ref-Ni	100-Ni	6.40×10^{-3} (20° to 200°C)	-	7.2	-	15.5	-	33.	36.5	39.3	43.at 727°C		49. at 927°C			53.		Table 1.8	Curie Point at 350°C

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)															Reference Number Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Mn-Cu	6-Cu	3.25×10^{-3} (100° to 200°C)	(33)	(34.5)	43.	57.	78.	100.	128.									(1); 1123	( ) values are extrapolated
Mn-Cu	11-Cu	2.24×10^{-3} (100° to 200°C)	(63.)	(64)	76	93.	113.	136.	152.									(1); 1123	Same
Mn-Cu	17-Cu	1.30×10^{-3} (100° to 200°C)	(96.)	(97.5)	108.	122.	140.	157.	(165.)									(1); 1123	Same
Mn-Cu	22-Cu	7.04×10^{-4} (100° to 200°C)	(133)	(134.5)	142.	152.	161.	173.	(177)									(1); 1123	Same
Mn-Cu	28-Cu	3.54×10^{-4} (100° to 200°C)	(192)	(193)	198.	205	214.	218.	220.									(1); 1123	Same
Mn-Cu	34-Cu	1.065×10^{-4} (100° to 200°C)	(185)	(187)	188.	190.	191.	191.	190.									(1); 1123	Same
Ref-Cu	100-Cu	3.2×10^{-3} (100° to 200°C)	1.6	1.7	2.2	2.9	3.6	4.2	4.8									(1); 413	

TABLE 2.5 (Continued)

Alloy	Composition (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ni-Cr	5-Cr	1.11×10^{-3} (20° to 200°C)	39.	40.	43.5	48.	52.3	56.5	60.	63.	66.	69.	70.5	72.5	(75)	(77)		(1); 569	( ); values are extrapolated.
Ni-Cr	9-Cr	4.34×10^{-4} (20° to 200°C)	63.	64.	66.	69.	72.5	75.5	78.5	80.5	82.5	84.	86.	87.5	(89)	(90)		(1); 569	
Ni-Cr	14-Cr	2.11×10^{-4} (20° to 200°C)	86.	86.7	88.	90.	91.5	93.	94.2	95.5	96.8	97.5	98.7	99.5	(100.)	(100.5)		(1); 569	
Ni-Cr	18-Cr	9.46×10^{-5} (20° to 200°C)	100.	100.3	101.	102	103.	104	104.3	105.	105.5	105.8	105.8	106.	(106)	(106)		(1); 569	
Ni-Cr	24-Cr	1.09×10^{-4} (20° to 200°C)	112.	112.3	113.	114.5	115.3	116.	116.	116.5	116.5	116.	115.5	115.	(114.2)	(113)		(1); 569	
Ni-Cr	29-Cr	2.34×10^{-5} (0° to 200°C)	119.5	120.	120.	120.	120.	120.	120.5	120.7	121.	121.3	121.5	121.8	(122.2)	(122.7)		(1); 569	
Ref-Cr	100-Cr	2.22×10^{-3} (20° to 200°C)	--	14.3	--	20.	--	27.7	32.	41.2	42.7 at 727°C	--	52.7 at 927°C	--	--	67.5		Table L8	
Ref-Ni	100-Ni	6.40×10^{-3} (29° to 200°C)	--	7.2	--	15.5	--	33.	36.5	39.7	43. at 727°C		49. at 927°C			53.			
Ni-Cr-X	20-Cr; 2.5-Al; 2.5 Cu	Zero (0° to 100°C)	133.	133.	133.												133. at -51°C	(1); 567	
Ni-Cr-Fe-X	(14-16; Cr) (5-9; Fe) (2.2-2.7 Ti) (1. Nb, + Si)	1.37×10^{-4} (20° to 200°C)	(121.2)	(121.4)	122.8	124.4	126.	127.7	129.2	131.	130.	128.4	126.					(1); 553	Inconel-X Precipitation at >600°C
Ni-Co-Cr-X	24.9-Co 18.7-Cr 7.0-Fe 2.2-Ti	2.72×10^{-4} (20° to 200°C)	(109.4)	110.4	113.4	115.8	118.	120.4	122.6	124.6	124.	123.4	123.4	(124.)	(125.2)			(1); 509	Cooling rate at 2.5°C/Minute
Ni-Co-Cr-X	24.9-Co 18.7-Cr 7.0-Fe 2.2-Ti	-- --						(116.3)	120.	122.	121.8	122.2	(123.4)					(1); 509	Cooling rate at 75°C/Minute

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; At Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ni - Mn	24.4 - Mn.	2.03×10^{-3} (20° to 200°C) And: 2.767×10^{-4} (452° to 600°C)	35.1	36.6	42.0	50.	60.	71.7	78.	80						(93.3)	76.85 at 452°C	(2); 435, 436	Approx. Ni_3 Mn; Comp.
Ref - Ni	100 - Ni	6.40×10^{-3} (20° to 200°C)		7.2	-	15.5	-	33.	36.5	39.3	43 at 727°C	-	49 at 927°C			53.		Table 1.8	
Ref - Mn.	100 - Mn.	4.90×10^{-4} (0° - 200°C)	255	-	-	280		300		310		150		130		70.		(3); 311	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Pd-Ni	6-Ni	1.91×10^{-3} (20° to 200°C)	17.0	18.	20.8	24.2	28.	31.0	32.2	(33.5)				(35.5)				(1); 1105	ρ values extrapolated at 600°C+
Pd-Ni	11-Ni	1.68×10^{-3} (20° to 200°C)	20.4	21.5	24.5	28.0	31.7	35.1	37.7	(40.)				(42.)				(1); 1105	Same
Pd-Ni	21-Ni	2.41×10^{-3} (20° to 200°C)	21.3	23.	28.5	33.	36.6	40.5	42.8	(45.)				(50.)				(1); 1105	Same
Pd-Ni	31-Ni	4.24×10^{-3} (20° to 200°C)	-	19.	26.0	33.5	37.4	41.4	44.2	(46.5)				(54.)				(1); 1105	Same
Pd-Ni	41-Ni	4.05×10^{-3} (20° to 200°C)	-	18.5	24.2	32.	37.0	41.0	43.7	(46.)				(53.)				(1); 1105	Same
Pd-Ni	50-Ni	4.39×10^{-3} (0° to 55°C)	14.5	15.7	-	-	-	-	-	-	-	-	-				18. at 55°C	(1); 1105	--
Ref-Pd	100-Pd	3.03×10^{-3} (20° to 200°C)		11.65		18.0		24.4	27.2	30	33 at 727°C		38.4 at 927°C			44.		Table 1.8	
Ref-Ni	100-Ni	6.40×10^{-3} (20° to 200°C)		7.2		15.5		33.0	36.5	39.3	43 at 727°C		49. at 927°C			53.		Table 1.8	
Ni-Pd	17-Pd	2.07×10^{-3} (20° to 200°C)	9.5	10.2	14.	20.	27.5	34.	(37.5)									(1); 583	( ); value extrapolated
Ni-Pd	49-Pd	3.87×10^{-3} (20° to 200°C)	15.7	16.5	21.	28.	35.7	40.	(42.7)									(1); 583	( ); value extrapolated

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
(Pt-Fe)	8-Fe	9.5×10^{-4} (0-100°C)	42.	43.	46.	50.	54.	58.	61	64	66	68.						(1); 1081	Approximates ($FePt_3$) *
(Pt-Fe)	23-FE	5.8×10^{-3} (0-100°C)	24.	26.	38.	60 (approx.)	83.	100	113	120	124	126						(1); 1081	Approximates (FePt)
(Pt-Fe)	30-Fe	5.0×10^{-3} (0 - 100°C)	30.	33.	45.	60. (approx.)	73.	83	89	91	92	93						(1); 1081	
(Pt-Fe)	35-Fe	3.48×10^{-3} (0° - 100°C)	66.	72.	89.	106	120.	131.	137.	140	141.5	142.						(1); 1081	
(Pt-Fe)	39-Fe	4.25×10^{-3} (0° - 100°C)	80.	90.	114.	135.	152.	158	163.	167	171.	175.						(1); 1081	
(Pt-Fe)	43-Fe	5.5×10^{-3} (0° - 100°C)	80.	-	124.	135	142.	148	152.	156	160	163						(1); 1081	Approximates (Fe_3Pt)
Ref-(Fe)	100-Fe	8.08×10^{-3} (20° - 200°C)		9.86		24.2		47.5	60.7	75.2						122.		Table 1.8	
Ref-(Pt)	100-Pt	3.78×10^{-3} (20° - 200°C)		11.0		18.5		25.2	28.5	31.5									Mean values of ρ Vs T
																48		Table 1.8	

* Desirable ρ values

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)													Other	Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200			
Pt-Rh-Cr	15-Rh 5-Cr	2.496×10^{-3} (20° to 200°C)	(47.24)	(50.0)	61.72	72.45	76.30	80.0	83.6	87.27	90.90	94.5					69.7 at 158.5°C (pt of inflec)		Ref. (5); p. 16.
Pt-Rh-Cr	15-Rh 10-Cr	$(1.545 \times 10^{-3}$ (20° to 200°C)	(51.52)	52.92	59.50	67.65	75.70	82.93	85.86	89.35	92.35	94.0	95.23				82.0 at 383°C		Ref. (5); p. 15.
		$(1.520 \times 10^{-3}$ (20° to 200°C)	(48.0)	49.53	55.62	63.09	70.63	76.23	79.07								74.37 at 350°C		
Pt-Rh-Co	15-Rh 5-Co	--							≈ 26.	32.5	38.1	47.65	58.9						Ref. (5); p. 14. Alloy-not at equilibrium. 4th Run-Data-Cooling
Pt-Rh-Ru	15-Rh 5-Ru	8.58×10^{-4} (20° to 200°C)	24.71	25.12	26.85	29.0	31.16	33.34	(35.42)										Ref. (5); p. 17.
Ref-Pt-Rh	10-Rh	1.438×10^{-4} (20° to 1200°C)	--	19.1	(21.3)	(24.04)	(26.79)	(29.53)	32.4	(35.03)	(37.77)	(40.53)	(43.25)	(46.00)	(48.75)	51.5		Table 2.2	
Ref-Pt-Rh	20-Rh	1.130×10^{-3} (20° to 1200°C)	--	20.7	(22.57)	(24.91)	(27.25)	(29.58)	31.5	(34.26)	(36.61)	(38.94)	(41.27)	(43.62)	(45.97)	48.3		Table 2.2	
Ref-Pt-Rh	40-Rh	1.328×10^{-3} (20° to 1200°C)	--	17.45	(19.30)	(21.62)	(23.94)	(26.25)	28.5	(30.88)	(33.20)	(35.53)	(37.82)	(40.13)	(42.45)	44.8		Table 2.2	
Ref-Pt	100-Pt	3.79×10^{-3} (20° to 200°C)	--	11.0	--	18.5	--	25.2	28.5	31.5	35.2 at 727°C	--	41. at 927°C	--	--	48.		Table 1,8	
Ref-Rh	100-Rh	4.29×10^{-3} (20° to 200°C)	--	4.8	--	8.5	--	12.5	14.5							(29.)		Table 1,8	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ti-Al	12-Al	1.88×10^{-4} (20° to 200°C)	265.	266.	272.	275.	275.1	274.	272.	270	270.	270.	270.	(270.)				(1); 915	
Ti-Al	20-Al	-3.03×10^{-5} (0° to 300°C)	220.	220.	220.	220.	218.	216.	212.5	209.	204.	201.5	200.	200.	(200)			(1); 915	
Ti-Al	22-Al	-1.11×10^{-5} (0° to 400°C)	225.	225.	225.	225.	225.	224	222.	220.	217.	213.	208	205.				(1); 915	
Ref-Ti	100-Ti	2.46×10^{-3} (20° to 200°C)	--	61.	--	88.	--	116.7	130.5	144.2	159. at 727°C	--	161.5 at 927°C	--	--	154		Table L8	
Ref-Al	100-Al	4.32×10^{-3} (20° to 200°C)	--	2.69	3.64	4.78	5.99	7.30											Smithells-Vol. II, Metal Reference Book, p. 637; 1955.
Ti-Cu	1.-Cu	2.61×10^{-3} (20° to 200°C)	62.	66.	80.	97.	112.	124.	136.	146.	154.	(162)						(1); 961	
Ref-Cu	100-Cu	3.92×10^{-3} (20° to 200°C)	1.6	1.7	2.2	2.9	3.6	4.2	4.8									(1); 413	
Ti-Nb	50-Nb	2.76×10^{-4} (20° to 200°C)	83.5	84.5	86.5	88.7	--	--	--	97.	100.5	104.	107.	(110.5)				(1); 655	
Ti-Nb	66-Nb	3.04×10^{-4} (20° to 200°C)	63.	64.	65.5	67.5	68	69.3	71.	74.	79.	83.	87.	(91.5)				(1); 655	
Ti-Nb	84.7-Nb	6.32×10^{-4} (20° to 200°C)	43.	44.	46.5	49.	50.7	52.7	55.3	59.	63.5	67.	71.3	(72.7)				(1); 655	
Ti-Nb	91.7-Nb	1.21×10^{-3} (20° to 200°C)	26.	27.5	29.5	33.5	37.	40.3	44.	47.5	51.3	54.7	58.7	(62.)				(1); 655	
Ref-Nb	100-Nb	2.51×10^{-3} (20° to 200°C)	14.5	15.5	18.5	22.5	26.3	30	34.	38.	42.	46	50.	(54.)				(1); 655	
Ref-Nb	100-Nb	2.73×10^{-3} (20° to 200°C)	--	18.3	--	27.3	--	37.	41.7	46.2	51.7 at 727°C	--	(61.) at 927°C					Table L8	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm, at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ti-Al-X	4-Al 4-Mn	4.78×10^{-4} (20° to 200°C)	(158)	(159.3)	166.	173.	178.5	182.3	184.7								185.2 at 535°C	(1); 917 918	C-310 AM; (Trade Designation)
Ti-Al-X	5-Al 2.5 Sn	7.22×10^{-4} (20° to 200°C)	(143)	(146).	155.	165.	173.	179.	183.6								185.2 at 535°C	(1); 917 918	A-110 AT, (Trade Designation)
Ti-Al-X	5-Al 1.4-Cr 1.5 Fe 1.2-Mo	3.42×10^{-4} (20° to 200°C)	(161)	(162.3)	167.	172.3	176.3	179.5	181.5								182. at 535°C	(1); 917 918	Ti-155A (Trade Designation)
Ti-Al-X	6-Al 4-V	3.18×10^{-4} (20° to 200°C)	(168.7)	(169.7)	174.5	179.4	183.6	186.5	188.								188.3 at 535°C	(1); 917 918	Ti-6Al-4V (Trade Designation)
Ti-Nb	1-Nb	3.15×10^{-4} (20° to 200°C)	50.	53.	67.	83.	99.	116.	130.	142.	150.5	(158).						(1); 967 968	Alpha Phase
Ti-Nb	32.7-Nb	-2.42×10^{-4} (20° to 200°C)	116.	115.	113.	(110)	Alpha-phase Precipitates				120.	124.	126.5	(130.)				(1); 967 968	Quenched to retain Beta phase
Ti-Nb	39.3-Nb	Zero- (20° to 200°C)	100.	100	100	100	α -phase Precipitates			111.	114.	117.	120.	(124.)				(1); 967 968	Same
Ti-Nb	50-Nb	2.98×10^{-4} (20° to 200°C)	83.	84.	86.	88.5	α -Phase Precipitates			97.5	101.	104.	106.	(110.)				(1); 967 968	Same

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %) Nominal	Temperature Coefficient of Resistivity (α)	Resistivity, (ρ), Microhm-cm, at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ti-Ge	1.0 - Ge	2.78×10^{-3} (20° to 200°C)	59.	63.	78.	94.5	110.	122.	132.	141.	148.7	155.	155.	147.				(1); 963 964	Heating Rate of 50°C/Min.
Ti-Ge	1.5 - Ge	2.80×10^{-3} (20° to 200°C)	64.	68.5	85.	103.	119.	131.	140.5	148.	155.	161.	160.	148.				(1); 963 964	Same
Ti-Sn	2. - Sn	1.945×10^{-3} (20° to 200°C)	78.	81.5	94.	110.	125.5	140.	151.	159.	166.	171.5						(1); 969 970	Alpha-Phase
Ti-Sn	3. - Sn	1.39×10^{-3} (20° to 200°C)	101.	104.	116.	130.	144.	155.	164.	172.	178.	180.						(1); 969 970	Same
Ti-Sn	5. - Sn	1.00×10^{-3} (20° to 200°C)	122.	125.	136.	147.5	157.	166.	172.	178.	181.5	184.						(1); 969 970	Same
Ti-Sn	6. - Sn	8.31×10^{-4} (20° to 200°C)	133.5	137.	147.	157.5	167.	174.	179.	184.	186.5	189.						(1); 969 970	Same
Ti-Sn	8. - Sn	5.30×10^{-4} (20° to 200°C)	154.	157.	164.	172.	178.5	184.	188.	191.	193.5	194.5						(1); 969 970	Same
Ti-Zr	10. - Zr	3.50×10^{-3} (20° to 200°C)	52.7	58.	76.	94.5	110.	123.5	135.	145.5								(1); 971 972	Alpha-Phase Initial Sample.
Ti-Zr	30. - Zr	1.74×10^{-3} (20° to 200°C)	84.	88.	101.5	115.3	126.	136.	143.	147.3								(1); 971 972	Same
Ti-Zr	50. - Zr	1.40×10^{-3} (20° to 200°C)	91.3	95.	106.6	119.	129.	138.5	144	147.3								(1); 971 972	Same
Ref-Ti	100. - Ti	2.46×10^{-3} (20° to 200°C)	-	61.	-	88.	-	116.7	130.5	144.2	159. at 727°C	-	161. at 927°C	-	-	154.		Table 1.8	

TABLE 2.5 (Continued)

Alloy	Composition, (Wt. %) Nominal		Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), microhm-cm, at Temperature, (°C)															Reference -Number -Page	Remarks
				0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
	Cr.	C.																		
U-Cr-C	0.1	<0.01	2.25×10^{-3} (20° to 200°C)	(27.8)	29.4	35.	41.3	46.5	50.5	54.	(56.7)								(1); 1147 1148	Repeated Quenches to obtn. Beta-U
U-Cr-C	0.43	<0.01	2.38×10^{-3} (20° to 200°C)	(30.)	31.7	38.7	45.3	50.7	55.5	59.	(62.)								(1); 1147 1148	Same
U-Cr-C	0.47	0.08	2.29×10^{-3} (20° to 200°C)	(29.3)	30.8	37.	43.5	48.8	53.3	56.8	(59.5)								(1); 1147 1148	Same
U-Cr-C	0.36	0.11	2.29×10^{-3} (20° to 200°C)	(29.7)	31.5	38.	44.5	49.7	54.6	58.3	(61.)								(1); 1147 1148	Same
U-Mo	9- Mo.		-8.78×10^{-5} (20° to 200°C)	69.7	69.6	69.1	68.5	68.4	68.2	68.1	68.3	69.	69.8	70.7					(1); 1167 1168	γ-quenched
U-Mo	9- Mo.		1.236×10^{-3} (0° to 100°C)	51.	52.3	57.3													(1); 1167 1168	γ-quenched, than α transformed by 13 days at 525°C
	Zr.	C.																		
U-Zr-C	1.13	<0.01	2.10×10^{-3} (20° to 200°C)	(31.2)	32.3	38.	44.5	49.5	54.	57.3	(60.2)								(1); 1185 1186	Quenched to retain Beta-U
U-Zr-C	2.22	<0.01	1.99×10^{-3} 20° to 200°C)	(32.3)	33.5	39.5	45.5	51.	55.5	59.3	(62.)								(1); 1185 1186	Heated-1 hr at 800°C in Vac., 1 hr at 500°C, Air-Cooled
U-Zr-C	1.22	0.31	2.10×10^{-3} (20° to 200°C)	(31.2)	32.3	38.	44.5	49.5	54.7	58.0	(61.2)								(1); 1185 1186	Quenched to retain Beta-U
U-Zr-C	2.25	0.40	1.99×10^{-3} (20° to 200°C)	(32.3)	33.5	39.5	45.5	51.	55.5	59.3	(62.)								(1); 1185 1186	Heated - 1 hr at 800°C in Vac., 1 hr at 500°C, Air-Cooled
Ref--U	100- U		2.84×10^{-3} (20° to 200°C)	-	43.	-	45.2	-	49.7	53.2	58.3	57.8 at 727°C	-	58. at 927°C	-	-	(70); U-(liquid)		Table 1.8	

TABLE 2.5 (Continued)

Alloy and/or Compound	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Zr - O_2-X	0.33 - O_2 0.051 - Fe 0.03 - Hf	2.37 x 10^{-3} (20° to 200°C)	57.	61.	73.	87.	101.	111.5	121.3	129.5	135.	139.	137.5	121.5				(1); 737 738	$\alpha \rightarrow \alpha + \beta$ at $\geqq$ 862°C
Zr-Ta-X	0.98-Ta- 0.97-Hf. 0.03-C	2.97 x 10^{-3} (20° to 200°C)	(49.)	(51.5)	64.	79.	92.	105.	115.	123.5	130.	(135.5)						(1); 739 740	Annealed 48 hrs at 600°C in Vac; and Water quenched.
Ref-Zr	100-Zr	3.50 x 10^{-3} (20° to 200°C)	-	43.3	-	70.6	-	102.	111.5	124.7	130 at 727°C	-	114 at 927°C			122	133 at 836°C (Phase change)	Table 1.8	

TABLE 2.6

PROPERTIES OF ALLOYS SELECTED FOR POSSIBLE USE AS ELECTRICAL CONDUCTORS AT ELEVATED TEMPERATURES HAVING RESISTIVITY DATA AT 20°C

ALLOY and Composition (Wt. %)	Solidus Temperature (°C); (Approximate)	ρ_{20}, Resistivity (Microhm-cm) at 20°C	Temperature Coefficient of Resistivity, (α) °C^{-1}	Oxidation Resistance Characteristics (Approximation)	Crystal Structure And/or Types of Phases	Remarks	Reference
Ag - Pd 60 - 40	≈1230	21.5	3.84×10^{-4}	Improved relative to Ag.	Continuous with series of Solid Solution F.C.C.		(24); 41, 42 (16); 202, 204
Ag - Pd 70 - 30	≈1227	14.4		Similar to above	Same as above		(40); 803
Au - Pd 80 - 20	1340	11.5	7.3×10^{-4}	Excellent	Solid Solution F.C.C. Lattice		(16); 202, 204 (40); 803
Au - Pt 75-25	1215	13.8		Excellent	>980°C; Solid Solution (F.C.C.) disordered Lattice <980°C; Possible ordered F.C.C.	Ordered compound is Pt Au_3	(16); 202, 204
Au - Ag 60 - 40	1015	10.	6.93×10^{-4}	Good	Solid Solution F.C.C. Lattice	Near composition for equivalence to (Au Ag)	(16); 202, 204 (24); 6
Cu - Au 80 - 20	1050	6.54	1.22×10^{-3}	Fair to good	Solid Solution F.C.C. Lattice		(24); 41, 42 (16); 202
Cu - Ni 94 - 6	1090	10.	8×10^{-4}	Slight improvement relative to copper	Solid Solution F.C.C. Lattice	"Lohm" Trade designation	(37); 14
Cu - Zn 95 - 5	1050	3.1	2.31×10^{-3} at 20°C	Improved relative to copper	Solid Solution F.C.C. Lattice	"Gilding Metal" adaptable for vitreous enamel	(40); 1013

TABLE 2.6 (Cont'd)

Alloy and Composition (Wt.%)	Solidus Temperature (°C), (Approximate)	ρ 20°, Resistivity, (microhm-cm) at 20°C	Temperature Coefficient of Resistivity, (α), °C^{-1}	Oxidation Resistance Characteristics. (Approximation)	Crystal Structure And/Or Types of Phases	Remarks	Reference
Fe - Au 90 - 10	1200 to 1430	19.3		Improved relative to iron	>1125°C; single phase Solid Solution (F.C.C.) <1125°C; 2 phase field, B.C.C. + F.C.C.	Uncertainty of solidus at given composition is due to extrapolated nature of phase diagram in region of interest	(16); 202, 204 (24); 204
Ni - Co 80 - 20	1460	6.92		Fair to good	Solid Solution F.C.C. Lattice - (disorder) Possible super lattice (ordered) structure for Co Ni$_3$ has not been determined; i.e., temperature (order↔disorder)	Composition is near the equivalent to CoNi$_3$. Very close solidus to liquidus throughout the Binary system. This Alloy has a Curie Pt. near 600°C	(16); 202 (24); 485, 486, 487.
Ni - Co 80 - 20	1460	25.	2.25 x 10^{-3}	Same as above	Same as above	Same as above "Modified Hilo" Trade designation	(37); 14
Ni - Fe 80 - 20	1455	21.7	3.4 x 10^{-3}	Fair to good	Solid Solution F.C.C. Lattice	Composition is in the range favoring the formation of the super lattice structure ordered F.C.C Lattice, i.e., Fe$_3$Ni.	(16); 203, 204 (10); 1212
Pd - Pt 80 - 20	1600 (Assumed) Not been determined	19.3	1.54 x 10^{-3}	Good to excellent	Solid Solution F.C.C. Lattice		(16); 204, 205
Pd - Pt 90 - 10	1580 (Assumed) Not been determined	15.0	2.15 x 10^{-3}	Good to Excellent	Solid Solution F.C.C. Lattice		(16); 204, 205

TABLE 2.6 (Cont'd)

Alloy and Composition (Wt.%)	Solidus Temperature (°C), - (Approximate)	ρ_{20}, Resistivity (microhm-cm) at 20°C	Temperature Coefficient of Resistivity, (α) °C-1	Oxidation Resistance Characteristics (Approximate)	Crystal Structure And/or Types of Phases	Remarks	Reference
Pt - Ir 95 - 5	1770	18.5 to 19.2	1.92×10^{-3}	Excellent	Solid Solution F.C.C. Lattice	There is a suggestion for a super lattice structure below 700°C Ref. (24); 872	(16); 204, 205 (43); Table I-C (40); 803
Pt - Pd 90 - 10	1760 (Assumed) Not been determined	19.3	1.42×10^{-3}	Excellent	Solid Solution F.C.C. Lattice		(16); 204, 205
Pt - Rh 90 - 10 (Reference)	1845	19.45	1.3×10^{-3}	Excellent	Solid Solution F.C.C. Lattice		(19); 23
Pt - Rh 95 - 5	1810	16.9	--	Excellent	Solid Solution F.C.C. Lattice		(16); 204, 205

TABLE 2.7

PROPERTIES OF ALLOYS SELECTED FOR POSSIBLE USE AS ELECTRICAL CONDUCTORS HAVING RESISTIVITY DATA AT 20°C AND T_m°C, (THE MAXIMUM TEMPERATURE AT WHICH DATA IS AVAILABLE)

ALLOY and Composition (Wt. %)	Solidus Temperature or Melting Point, (°C) (Approximate)	ρ, Resistivity (Microhm-cm) at Temperature		Temperature Coefficient of Resistivity, (α) ($^\circ C^{-1}$)		Crystal Structure And/or Types of Phases	Remarks	References
		20°C or (other)	Tm(°C) *					
Selected Reference Standard Alloys								
Pt - Rh 90 - 10	≈ 1840	19.1	51.5 at 1200°C	1.438×10^{-3} (20° to 1200°C)	Excellent	Binary system - continuous series of Solid Solution F.C.C. Lattice		Table 2.2; Ref. (24)
80 - 20	≈ 1885	20.7	48.3 at 1200°C	1.130×10^{-3} (20° to 1200°C)	Excellent	Same as above		Same as above
60 - 40	≈ 1935	17.45	44.8 at 1200°C	1.328×10^{-3} (20° to 1200°C)	Excellent	Same as above		Same as above
Ag - Mn 99 - 1	≈ 961	4.8	7.4 at 500°C	1.2×10^{-3} (0° to 500°C)	Probably fair to poor	After Ref. (24), 54 above 300°C - this series of Ag-Mn alloys are Solid Solution type of Alloys; with F.C.C. Lattices	Mn probably hardens the Ag	(1); 1071; (24)
98 - 2	≈ 961	7.3	9.8 at 500°C	7.2×10^{-4} (0° to 500°C)	Same as above		Same	Same
96 - 4	≈ 961	11.2 at 0°C	11.4 at 20°C	3.3×10^{-4} (-200° to 0°C)	Same as above		Same	Same
94 - 6	≈ 961	19. at 0°C	20.4 at 500°C	1.47×10^{-4} (0° to 500°C)	Same as above		Same	Same
Ag - Pd 99 - 1	≈ 961	2.1	4.8 at 500°C	3.5×10^{-3} (0° to 100°C)	Probably fair to poor	Solid Solution F.C.C. Lattice		(1); 1051; (24)
98 - 2	≈ 963	2.73	5.2 at 500°C	2.3×10^{-3} (0° to 100°C)	Same	Same		Same
97 - 3	≈ 965	3.05	5.8 at 500°C	2.1×10^{-3} (0° to 100°C)	Same	Same		Same
96 - 4	≈ 967	3.55	6.3 at 500°C	1.8×10^{-3} (0° to 100°C)	Same	Same		Same
95 - 5	≈ 970	3.9		2.07×10^{-3} (-200° to 0°C)	Same	Same		Same
90 - 10	≈ 1000.	6.05		1.26×10^{-3} (-200° to 0°C)	Same	Same		Same
5-95	≈ 1520	16.2 at 0°C		5.1×10^{-3} (-245° to 0°C)	Good to Excellent	Same		Same
Ag - Pt 99 - 1	≈ 961	2.2	5.2 at 500°C	2.45×10^{-3} (20° to 200°C)	Probably fair to poor	Solid Solution F.C.C. Lattice		(1); 1073; (24)
98 - 2	≈ 961+	3.05	4.65 at 200°C	1.04×10^{-3} (20° to 200°C)	Same	Same		Same
97 - 3	≈ 963	3.7	6.8 at 500°C	1.70×10^{-3} (20° to 200°C)	Same	Same		Same
96 - 4	≈ 963	4.75	7.5 at 500°C	1.39 x 10 (20° to 200°C)	Same	Same		Same

Note: * Where Tm Max. temperature for available data, and/or desirable maximum temperature

TABLE 2.7 (Cont'd)

Alloy and Composition (Wt.%)	Solidus Temperature or Melting Point, (°C) (Approximate)	ρ, Resistivity (Microhm-cm) At Temperature		Temperature Coefficient of Resistivity, (α)	Oxidation Resistance Characteristics (Approximate)	Crystal Structure And/or Types of Phases	Remarks	Reference
		20°C or (other)	Tm(°C)					
Au - Mn 99 - 1	≈1045	10.5	14. at 400°C	1.2×10^{-3} (0° to 100°C)	Good to Excellent	Solid Solution F.C.C. Lattice		(1); 1003; Ref. (24)
98 - 2	≈1030	17.3	20.3 at 400°C	4.7×10^{-4} (0° to 100°C)	Same	Same		Same
Au - Pd 99.56 - 0.44	≈1064	2.5	6.7 at 500°C	3.33×10^{-3} (20° to 200°C)	Excellent	Solid Solution F.C.C. Lattice		(1); 991; Ref. (24)
99. - 1.0	≈1080	3.0	7.2 at 500°C	2.59×10^{-3} (20° to 200°C)	Same	Same		Same
98.3 - 1.7	≈1090	3.35	7.4 at 500°C	2.41×10^{-3} (20° to 200°C)	Same	Same		Same
97.8 - 2.2	≈1100	3.67	7.65 at 500°C	2.01×10^{-3} (20° to 200°C)	Same	Same		Same
Au - Pt 99 - 1	≈1069	3.43	7.55 at 500°C	2.22×10^{-3} (20° to 200°C)	Excellent	Solid Solution F.C.C. Lattice		(1); 1027; Ref. (24)
98-2	≈1075	4.2	8.1 at 500°C	1.72×10^{-3} (20° to 200°C)	Same	Same		Same
97 - 3	≈1083	4.9	8.9 at 500°C	1.76×10^{-3} (20° to 200°C)	Same	Same		Same
96 - 4	≈1089	5.93	9.9 at 500°C	1.19×10^{-3} (20° to 200°C)	Same	Same		Same
Co - Fe 60 - 40	≈1480	4.	42.5 at 700°C (100. at 1000°C)	4.17×10^{-3} (20° to 200°C)	Probably fair	Ordered structure - B.C.C. Lattice ≨ 700°C	Composition given-range of superlattice-ordered FeCo ≲ 700°C. B.C.C. Lattice Above 700°C-Disorder and B.C.C. Lattice Above 950°C; Austenite or F.C.C. Lattice	(1); 615; Ref. (24)
Cu - Cr - 0.16	≈1083 Same	4.25	6.80 at 600°C	1.50×10^{-3} (20° to 200°C)	The equivalent of copper	Solid Solution F.C.C. Lattice - with evidence of precipitation type of hardening for copper	Dilute Alloy contains also: 0.2% Zr 0.2% Ti 0.2% Ni	(1); 423; Ref. (24)
- 0.37	Same	4.75	5.90 at 500°C	1.21×10^{-3} (20° to 200°C)	Same	Same	Dilute Alloy also contains 0.25% to 0.28% Zr	Same
- 0.5	Same	2.15	6.95 at 600°C	4.26×10^{-3} (20° to 200°C)	Same	Same		Same
- 0.9	Same	3.15	5.30 [illegible]00°C	2.56×10^{-3} (20° to 200°C)	Same	Same	Dilute Alloy [illegible] ntains 0.25 to 0.28[illegible] r	Same

TABLE 2.7 (Cont'd)

Alloy and Composition (Wt. %)	Solidus Temperature or Melting Point, (°C) (Approximate)	ρ_{20}, Resistivity (Microhm-cm) At Temperature		Temperature Coefficient of Resistivity, (α) $-{}^\circ C^{-1}$	Oxidation Resistance Characteristics (Approximate)	Crystal Structure And/or Types of Phases	Remarks	References
		20°C or (other)	Tm(°C)					
Cu - Mn - 1	≈1070	4.6	7.75 at 500°C	1.45×10^{-3} (20° to 200°C)	Equal to or less than copper	Solid Solution F.C.C. Lattice	Note the modest $\rho_{500°C}$ value	(1); 413; Ref. (24)
- 2	≈1057	7.95	11.4 at 500°C	9.44×10^{-4} (20° to 200°C)	Same	Same	Same	Same
- 4	≈1031	12.5	15.5 at 500°C	6.67×10^{-4} (20° to 200°C)	Same	Same	Same	Same
- 6	≈1005	18.2	20.2 at 500°C	3.97×10^{-4} (20° to 200°C)	Same	Same	Same	Same
- 8	≈ 980	22.3	25.5 at 500°C	3.40×10^{-4} (20° to 200°C)	Same	Same	Same	Same
Cu - Si - 1.32	≈1033	11.40	16.27 at 800°C	7.8×10^{-4} (20° to 200°C)	Improved - with inhibition effect of oxidation of Si $\longrightarrow$ Si O_2	Solid Solution F.C.C. Lattice	Note the modest $\rho_{800°C}$ value	(1); 403; Ref. (24)
- 2.03	≈1006	16.40	23.9 at 800°C	5.76×10^{-4} (20° to 200°C)	Same	Same	Same	Same
Cu - Ni -10.79	≈1100°C	14.9	17.6 at 400°C	4.76×10^{-4} (20° to 400°C)	Nickel improves oxidation resistance of Cu but still restricts the unprotected metal to relatively low temperatures	Solid Solution F.C.C. Lattice	Nickel alloyed with Cu: 1) raises Solidus 2) improves oxidation resistance 3) reduces (R_T/Ro) Vs Temp. relative to copper 4) reduces (R_T/Ro) Vs Temp. relative to (Pt-Rh) Ref Standards Selected	(4); 218; Ref. (24)
- 21.40	≈1135	27.10	29.20 at 400°C	2.04×10^{-4} (20° to 400°C)	Same	Same	Same	Same
- 30.19	≈1165	37.6	39.6 at 400°C	1.40×10^{-4} (20° to 400°C)	Same	Same	Same	Same
- 39.71	≈1210	46.8	47.4 at 400°C	3.37×10^{-5} (20° to 400°C)	Same	Same	Same	Same
- 49.74	≈1240	52.2	52.9 at 400°C	3.52×10^{-5} (20° to 400°C)	Same	Same	Same	Same
- 58.28	≈1280	51.2	53.4 at 400°C	6.17×10^{-5} (20° to 400°C)	Same	Same	Same	Same
Reference Standards Pt - Rh 90 - 10	≈1840	19.1	29.53 at 400°C	1.438×10^{-3} (20° to 1200°C)	Excellent	Solid Solution F.C.C. Lattice		Table 2.2; Ref. (24)
80 - 20	≈1865	20.7	29.58 at 400°C	1.130×10^{-3} (20° to 1200°C)	Same	Same		Same
60 - 40	≈1935	17.45	26.25 at 400°C	1.328×10^{-3} (20° to 1200°C)	Same	Same		Same

TABLE 2.7 (Cont'd)

Alloy and Composition (Wt.%)	Solidus Temperature or Melting Point, (°C) (Approximate)	ρ, Resistivity (Microhm-cm) At Temperature		Temperature Coefficient of Resistivity, (a) °C-1	Oxidation Resistance Characteristics (Approximate)	Crystal Structure And/or Types of Phases	Remarks	Reference
		20°C or (other)	Tm(°C)					
Cu - Pd. - 1.7	≈1083	2.63	5.65 at 500°C	2.56×10^{-3} (20° to 200°C)	Doubtful of significant improvement relative to copper	Solid Solution F.C.C. Lattice	No apparent superlattice structure or ordered compound for the range of Pd. indicated. Pd additions increase solidus temperature, but slowly.	(1); 453; (24)
- 3.3	≈1083	3.43	6.25 at 500°C	1.76×10^{-3} (20° to 200°C)	Same	Same		Same
- 5.	≈1083	4.4	7.1 at 500°C	1.30×10^{-3} (20° to 200°C)	Same	Same		Same
- 6.7	≈1083	5.35	8.1 at 500°C	1.14×10^{-3} (20° to 200°C)	Same	Same		Same
Cu - Pt - 1	≈1085	2.3	4.8 at 500°C	2.51×10^{-3} (20° to 200°C)	Probably slight improvement relative to copper	Solid Solution with F.C.C. Lattice -, with perhaps faint traces of ordered F.C.C. Lattice	Pt. alloy additions increased the solidus temperature of copper alloys, relative to the same Wt.% additions of Pd. to copper (See above) alloy	(1); 455; (24)
- 2	≈1087	2.8	5.5 at 500°C	2.38×10^{-3} (20° to 200°C)	Same			Same
- 3	≈1089	3.3	6.1 at 500°C	1.80×10^{-3} (20° to 200°C)	Same			Same
-4	≈1091	4.15	6.93 at 500°C	1.44×10^{-3} (20° to 200°C)	Same			Same
Cu - Zn - 48	≈870	4.2	18.6 at 800°C	2.91×10^{-3} (20° to 200°C)	Maximum temperature for stability, in air, is typlified for 70 (Cu)-30(Zn), at 700°C per Ref. (10); 226	Solid Solution - B.C.C. Ordered (B.C.C.) < 468°C	Low Solidus limits maximum temp. usage	(1); 341; (24)
- 53	≈860	7.7	29.6 at 800°C	3.25×10^{-3} (20° to 200°C)	See above	2 phase field below ≈ 660°C B.C.C. & Cubic (low symmetry). > 660°C, one/phase = B.C.C.	Same	(1); 1269; (24)
- 56.5	≈834	11.5	29.6 at 800°C	1.69×10^{-3} (20° to 200°C)	See above	Same as above, except one phase field = > 750°C and is B.C.C. Lattice	Same	Same
- 62.	≈834	13.15	42.5 at 800°C	1.63×10^{-3} (20° to 200°C)	See above	One phase field, Cubic - but low symmetry Lattice	Same	Same
- 65	≈800	11.7	42.5 at 800°C	2.23×10^{-3} (20° to 200°C)	See above	Same as above for 62% Zn	Same	Same
Cu-Ni-Be-Zr 0.55 - 0.107 - 0.25	≈1083 (estm.)	(3.55)	6.35 at 500°C	2.22×10^{-3} (20° to 200°C)	Probably equivalent to copper	Solid Solution, (F.C.C. Lattice) at elevated temp., i.e. > 400°C	Dilute alloys of interest for precipitation hardening of copper	(1); 379; (24)
0.62 - 0.14 -	≈1083 (estm.)	(3.2)	6.2 at 500°C	2.34×10^{-3} (20° to 200°C)	Same	Same	Same	Same
0.90 - 0.18 -	≈1083 (estm.)	(3.93)	6.4 at 500°C	2.05×10^{-3} (20° to 200°C)	Same	Same	Same	Same
0.98 - 0.21 -	≈1083 (estm.)	4.2	6.53 at 500°C	1.92×10^{-3} (20° to 200°C)	Same	Same	Same	Same

TABLE 2.7 (Cont'd)

Alloy and Composition (Wt.%)	Solidus Temperature or Melting Point, (°C) (Approximate)	ρ, Resistivity (Microhm-cm) At Temperature		Temperature Coefficient of Resistivity, (α) °C-1	Oxidation Resistance Characteristics (Approximate)	Crystal Structure And/or Types of Phases	Remarks	Reference
		20°C on (other)	Tm(°C)					
Cu-Zr-Al - 0.5 -	≈1083	2.10	7.40 at 700°C	4.12×10^{-3} (20° to 200°C)	Equivalent to copper	F.C.C. Lattice - Solid Solution with perhaps 2nd phase	Possible interest in precipitation hardening of copper by Zr. Diagram is incomplete.	(1); 429; (24)
0.27-0.3	≈1083	3.45	7.57 at 700°C	1.915×10^{-3} (20° to 200°C)	Selective oxidation of Al is expected--otherwise about ≈ copper	Same	Same	Same
-0.27-0.3	≈1083	3.5	7.5 at 700°C	1.904×10^{-3} (20° to 200°C)	Same	Same	Same	(1); 397; (24)
Cu - Al - 13.9	≈1044	11.3	28.0 at 700°C	2.12×10^{-3} (20° to 200°C)	Fair to good - due to inhibition of further oxidation when Al → Al_2O_3	3-Two phase fields to 850°C a) F.C.C. + Cubic (to) 565°C b) B.C.C. + $Cubic_{(2)}$ to 785°C c) B.C.C. + $Cubic_{(1)}$ to 850 d) B.C.C. to Solidus at 1044°C	Solidus state transformation - involve complex the time - temperature cycling of these alloys for constancy of reproduction of electrical properties for these alloys for cycling duty.	(1); 397; (24)
- 14.5	≈1040	11.0	26.6 at 700°C	1.62×10^{-3} (20° to 200°C)	Same	Same as above except change in (c) & (d), i.e., c) B.C.C. + $Cubic_{(1)}$ to 940°C d) B.C.C. + Solidus at 1040°C	↓	Same
- 14.9	≈1038	12.3	32.0 at 700°C	1.86×10^{-3} (20° to 200°C)	Same	Similar to above		Same
- 15.15	≈1036	13.5	34.7 at 700°C	2.55×10^{-3} (20° to 200°C)	Same	Same as above except c) B.C.C. + $Cubic_{(1)}$ to 963°C d) B.C.C. + (X) to solidus at 1063		Same
- 16.4	≈1030	15.7	41.3 at 700°C	2.02×10^{-3} (20° to 200°C)	Same	Phases (4) Solid state phase transformation to Solidus		(1); 395; (24)
- 16.41	≈1030	15.3	39.7 at 700°C	1.60×10^{-3} (20° to 200°C)	Same	Similar to above		Same
- 17.09	≈1022	13.7	43.7 at 700°C	2.44×10^{-3} (20° to 200°C)	Same	2 Solid state phase transformation to solidus		Same
- 17.40	≈1022	13.5 at 0°C	39.7 at 700°C	2.15×10^{-3} (20° to 200°C)	Same	Similar to above		Same
- 18.30	≈1000	30.	67. at 700°C	3.06×10^{-3} (20° to 200°C)	Same	3 Solid state phase transformation to solidus		Same
- 19.30	≈982	15.	52. at 700°C	2.04×10^{-3} (20° to 200°C)	Same	Similar to above (3) transformations and reactions - to solidus		Same
Pd - Ni -6	≈1452	10.	32.3 at 500°C	1.91×10^{-3} (20° to 200°C)	By reason of selective oxidation, the low nickel alloys may be considered equivalent to nickel	These alloys form a continuous series of single phase solid solutions, of F.C.C. Lattice throughout the binary system. No known superlattice structures. Influence of Ferro-magnet characteristics on Resistivity Vs T varies with the Curie point.	Non-magnetic except at cryogenic temperatures	(1); 1105; (24)
-11	≈1372	21.5	37.7 at 500°C	1.68×10^{-3} (20° to 200°C)	Same		Curie Pt. less than 0°C	Same
-21	≈1273	23.	42.8 at 500°C	2.41×10^{-3} (20° to 200°C)	Same	↓	Curie Pt. at 97°C	Same
-31	≈1238	18.	44.3 at 500°C	4.34×10^{-3} (20° to 200°C)	Same		Curie Pt. at 170°C	Same
-41	≃1236	18.5	43.7 at 500°C	4.05×10^{-3} (20° to 200°C)	Same		Curie Pt. at 220°C	Same
-50	≃1237	15.7		4.30×10^{-3} (0° to 55°C)	Same		Curie Pt. at 256°C	Same
-51	≃1238	18.5	(42.7) at 500°C	3.87×10^{-3} (20° to 200°C)	Same		Curie Pt. at 283°C	Same
-63	≈1344	10.2	(37.5) at 500°C	2.07×10^{-3} (20° to 200°C)	Same		Curie Pt. at 341°C	Same

TABLE 2.8

COMPARATIVE OXIDATION CHARACTERISTICS OF CERTAIN REFRACTORY METALS AND ALLOYS

Refractory Metal, Element	Temperature (°C)	Period, (Hours)	Oxidation Rate, (Micrograms/cm2 hour.) Approx.	Atmosphere	Reference Number Page
Cr.	300				(13);13
	500				(13);13
	700	0 - 3	15. 3.5	1.0 atm(Air) 0.1 atm(O_2)	(13);13 (13);13
	900	0 - 3	165. 17	1.0 atm(Air) 0.1 atm(O_2)	(13);13 (13);13
	1100	0 - 3	1,100 265	1.0 atm(Air) 01. atm(O_2)	(13);13 (13);13
Cb(Nb)	300	1 - 2	5	0.1 atm(O_2)	(13);13
	500	0.3 - 2.0	700	0.1 atm(O_2)	(13);13
	700	0 - 16	1,150	1.0 atm(Air)	(13);13
	900	3.6 - 16 0 - 16	20,000 29,000	1.0 atm(Air) 1.0 atm(Air)	(13);13 (13);13
	1100	3.6 - 16 0 - 16	22,000 31,000	1.0 atm(Air) 1.0 atm(Air)	(13);13 (13);13
Mo	400	1 - 2	5	0.1 atm(O_2)	(13);13
	450	1 - 2	35	0.1 atm(O_2)	(13);13
				0.1 atm(O_2)	(13);13
	700	-	-	-	-
	900	-	-	-	-
	1100	-	-	-	-

TABLE 2.8 (Cont'd)

Ta	300	1 - 2	2.8	0.1 atm(O_2)	(13);13
	400	1 - 2	10.8	0.1 atm(O_2)	(13);13
	700	0 - 16	1,650	1.0 atm, (Air)	(13);13
	900	0 - 16	15,500	1.0 atm, (Air)	(13);13
	1100	0 - 16	≈31,000	1.0 atm, (Air	(13);13
V	400	1.6 - 2.0	10.8	0.1 atm, (O_2)	(13);13
	500	1.6 - 2.0	25.	0.1 atm(O_2)	(13);13
	600	1.6 - 2.0	100.	0.1 atm(O_2)	(13);13
	900	-	-	-	-
	1100	-	-	-	-
W	400	1 - 1.3	10.1	0.1 atm (Air)	(13);13
	500	1 - 1.3	86	0.1 atm (Air)	(13);13
	700	0 - 0.3	≈5,300	1.0 atm (Air)	(13);13
	900	0 - 0.3	≈40,000	1.0 atm (Air)	(13);13
	1000	0 - 0.3	≈130,000	1.0 atm (Air)	(13);13

TABLE 2.8 (Cont'd)

Alloys; with Selected Reference Materials	5	10	15	20	25	30	Other	Other	Number Page Ref.
Reference Material									
Cr								@ (Cr-100) 0.934	(13);69
Ni - 80 Cr - 20 Nichrome							0.018		
Cr-Ti	0.132	0.675	-	0.983	-	0.195	-	-	(13);69
Cr-V	0.111	7.08	-	10.15	-	6.79	-	-	(13);69
Cr-Mn	0.358	0.266	-	0.711	-	1.01	-	-	(13);69
Cr-Co	0.252	0.249	0.254	0.344	-	0.221	-	-	(13);69
Cr-Ni	0.225	0.217	0.130	0.249	-	0.130	-	-	(13);69
Cr-Zr	0.092	0.253	-	0.513	-	0.664	-	-	(13);69
Cr-Nb(Cb)	0.209	0.251	-	0.286	-	0.424	-	-	(13);69
(Cr-Mo)*	0.112	0.161	0.187	0.098	-	0.030	-	-	(13);69
Cr-Ru	0.212	0.236	-	0.308	-	0.367	-	-	(13);69
Cr-Rh	0.562	0.223	-	1.630	-	0.535	-	-	(13);69
Cr-Pd	0.119	0.097	-	0.064	-	0.060	-	@ Pd-40 0.105	(13);69
Cr-Ta	0.173	0.656	-	0.677	@ Ta-25 0.412	-	@ Ta-35 0.049	-	(13);69
Cr-Re	-	0.195	-	0.0898	-	0.112	-	-	(13);69
Cr-Ir	1.18	0.572	-	0.289	-	0.275	-	-	(13);69
Cr-Pt.	0.201	0.200	-	0.188	-	0.205	-	-	(13);69

Note: a) (*); Very low weight gain of the Cr-Mo Alloys.
i.e. from perhaps (+20% Mo) was due to the rapid volitization of Mo 0_3.

b) Also, it must be noted that the best of the Binary Alloys above still have poorer oxidation resistance than Nichrome (i.e. $\begin{bmatrix}\text{Ni-80}\\\text{Cr-20}\end{bmatrix}$).

TABLE 2.8 (Cont'd)

Alloys - and Ref. Elements	Tempr. (°C)	Atmos- phere	2	4	8	12	16.66	20	40	80	100	200	Ref. Number Page
Cb-20Cr-12Co (Nb)	1090	Air					7.2×10^{-4}	8.67×10^{-4}	1.73×10^{-3}	3.47×10^{-3}	4.38×10^{-3}	8.67×10^{-3}	(13);15, 16, 17
Cb(Nb)	1090	Air	3.1×10^{-2}	5×10^{-2}	7.5×10^{-2}	9.3×10^{-2}	1.097×10^{-1}		2.2×10^{-1}	4.2×10^{-1}	5.3×10^{-1}	1.06	(13);15, 16, 17
Ta-20Cr-12Co	1090	Air	9×10^{-4}	1.81×10^{-3}	3.62×10^{-3}	5.42×10^{-3}	7.52×10^{-3}						(13);15, 16, 17
Ta	1090	Air	2.4×10^{-2}	4×10^{-2}	6.3×10^{-2}	8.1×10^{-2}	1×10^{-1}						(13);15, 16, 17
V-50Ti-15Cr	700	Air			1.7×10^{-3}			3.5×10^{-3}	5.8×10^{-3}	8.7×10^{-2}	9.8×10^{-3}		(13);15, 16, 17
V	700	Air		8×10^{-2}	1.6×10^{-1}								(13);15, 16, 17
W-50Cr	1090	Air					2.17×10^{-3}	2.6×10^{-3}	5.2×10^{-3}	9.7×10^{-3}	1.3×10^{-2}		(13);15, 16, 17
W	1090	Air	3.6×10^{-2}	6.8×10^{-2}	1.39×10^{-1}	2.04×10^{-1}	2.85×10^{-1}						(13);15, 16, 17
Cr	1090	Air	7.1×10^{-4}	1.42×10^{-3}	2.83×10^{-3}	4.25×10^{-3}	5.91×10^{-3}	7.1×10^{-3}					(13);15, 16, 17
Mo	1090	Air	2.04×10^{-1}	4.02×10^{-1}									(13);15, 16, 17

*Note: Nichrome is considerably more oxidation resistant than any of the alloys in above Table, even though the included alloys are the best for the refractory metals as reported, Ref. (13); 17.

TABLE 2.8 (Cont'd)

Alloy	Nominal Composition (Wt. %)	Temperature, (°C)	Time, Hours	Weight Loss, (10^{-2}mg./cm^2)
Reference Pt	Pt-100	1100	20	11
<u>Pt - Pd</u>	Pd-10	900	20	4.6
			200	20.7
	Pt-90	1100	20	12.6
			200	149.5
	Pd-20	900	20	about 4.6
			200	29
	Pt-80	1100	20	about 8
			200	92
	Pd-30	900	20	about 2.5
			200	12.
	Pt-70	1100	20	about 5.
			200	78.
	Pd-40	900	20	≈ 1
			200	11
	Pt-60	1100	20	8 (gain), not loss
			200	58
<u>Pt- Rh</u>	Rh-10	900	20	≈ 2.5
			200	60
	Pt-90	1100	20	28
			200	138
	Rh-20	900	20	8
			200	11
	Pt-80	1100	20	35
			200	155

TABLE 2.8 (Cont'd)

<u>Pt - Rh</u>	Rh-30 Pt-70	900	20	Essentially zero, slight gain
			200	Slight gain ≈ (2 to 4)
		1100	20	about 8
			200	139
	Rh-40 Pt-60	900	20	about 8 (gain)
			200	29 (gain)
		1100	20	9
			200	136
<u>Pt - Ir</u>	Ir-10 Pt-90	900	20	14
			200	-
	Ir-20 Pt-80	900	20	46
			200	-
	Ir-30 Pt-70	900	20	300
			200	-
	Ir-40 Pt-60	900	20	600
			200	

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TABLE 2.20

ESTABLISHED ALLOYS OF HIGH CONDUCTIVITY AND HIGH OXIDATION RESISTANCE

Alloy Type	Application	Characteristics	Reference
4% W-Pt, Thoriated	Electrode of spark plug.	Resistance to corrosion and erosion.	'61-ASM. Metals Handbook, p.1176.
Pt + Ag + Binder	Thermistor-leads.	Nonoxidizing.	Ibid, p. 1176.
Rh-Pt, Thoriated	Glow-plug of jet engine.	Relight on flameout (Req't).	Ibid, p. 1176.
Pt-clad base metal	High-temperature wiring.	High conductivity, oxidation resistance, and low contact resistance.	Ibid, p. 1176.
Solid Ag	High-temperature wiring.	Same as above.	Ibid, p. 1176.
Ag-Mg-Ni (Internal oxidation - hardened type of alloy)	High-temperature wiring.	Same as above.	Ibid, p. 1176.
Ag-Au	Fuse	High conductivity and oxidation resistance.	Ibid, p. 1176.
Pt			R. F. Vines and E. M. Wise; The Platinum Metals and Their Alloys; Inter. Nickel Co. 1941, p. 12.
Pt-Ir	Fuse		
Pt-Au	Fuse		
Pt-Pd	Fuse		
Pt			
Pt-Ir	Spark plug electrodes.		Vines, ibid, p. 12.
Pt-Rh	Spark plug electrodes.		Vines, ibid, p. 12.
Pt			
Pt-Ir	Electrical Contacts.		Vines, ibid, p. 12.
Pt-Rh	Electrical Contacts.		Vines, ibid, p. 12.
Pt-Ru	Electrical Contacts.		Vines, ibid, p. 12.
Pt-Ag	Electrical Contacts.		Vines, ibid, p. 12.
Pd			
Pd-Ag	Electrical Contacts.		Vines, ibid, p. 12.

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12.1 Saarivirta, M., High Conductivity Copper-Rich Cu-Zr Alloys; Transactions A.I.M.E.; Vol. 218; pp. 431-437; 1960.

12.2 Saarivirta, M. J., and Taubenblat, P. P. Some High Temperature Properties of Copper-Zirconium and Copper-Chromium High Conductivity Alloys; Transactions A.I.M.E.; Vol. 218; pp. 935-939; 1960.

12.3 Klokholm, E., and Hyatt, B.; The Effect of Plastic Deformation on The Resistivity of Copper-Palladium Alloys; Transactions A.I.M.E.; Vol. 215; pp. 792-794; 1959.

12.4 Pollock, D. D., and Finch, D. I.; Electrical Properties of Cu-Mn-Al-In-Fe and Cu-Mn-Al-In-Ni-Fe Alloys; Transactions A.I.M.E.; Vol. 212; p 841 (1958).

12.5 Robinson, A. T., and Dorn, J. E., Effect of Alloying Elements on the Electrical Resistivity of Aluminum Alloys; Transactions A.I.M.E.; Vol. 191; pp. 457-460; 1951.

12.6 Hodge, W., Jaffee, R. I. Dunleavy, J. G., and Ogden, H. R.; A. High-Strength-High Conductivity Copper-Silver Alloy Wire; Transactions A.I.M.E.; Vol. 180; pp. 15-31; 1949.

12.7 Hibbard, W. R. Jr., Rosi, F. D.; Clark, H. T.; and O'Herron, R. L.; The Constitution and Properties of Copper-rich Copper-chromium and Copper-nickel-chromium Alloys; Transactions A.I.M.E.; Vol. 175; pp. 283-295; 1948.

12.8 Hodge, W.; Jaffee, R. I.; Dunleavy, J. G.; and Ogden, H. R.; A Copper-Base Alloy Containing Iron As A High-Strength, High-Conductivity Wire Material; Transactions A.I.M.E.; Vol. 180; pp. 32-41; 1949.

12.9 Hibbard, W. R. Jr.; Electrical Resistivity of Dilute Binary Terminal Solid Solutions; Transactions A.I.M.E.; Vol. 200; pp. 594-602; 1954.

12.10 Hansen, M., Johnson, W. R.; and Parks, J. M.; Correlation Between Electrical Conductivity and Temperature Coefficient of Resistance of Solid-Solution Alloys; Transactions A.I.M.E.; Vol. 191; pp. 1184-1189; 1951.

12.11 Pollock, D. D., and Finch, D. I.; Effects of Alloying Elements on the Electrical Properties of Manganin-Type Alloys; Transactions A.I.M.E.; Vol. 206; pp. 203-210; 1956.

12.12 Hodge, W.; Some Properties of Certain High-Conductivity Copper-Base Alloys; Transactions A.I.M.E.; Vol. 209; pp. 408-412; 1181; 1311; 1957.

12.13 Hensel, F. R., and Larsen, E. I.; Certain Characteristics of Silver-base Powder Metallurgical Products; Transactions A.I.M.E.; Vol. 161: pp. 569-579; 1945.

12.14 Borough, J. W.; Trans. A.I.M.E.; Vol. 221; 1274, 1275; 1961.

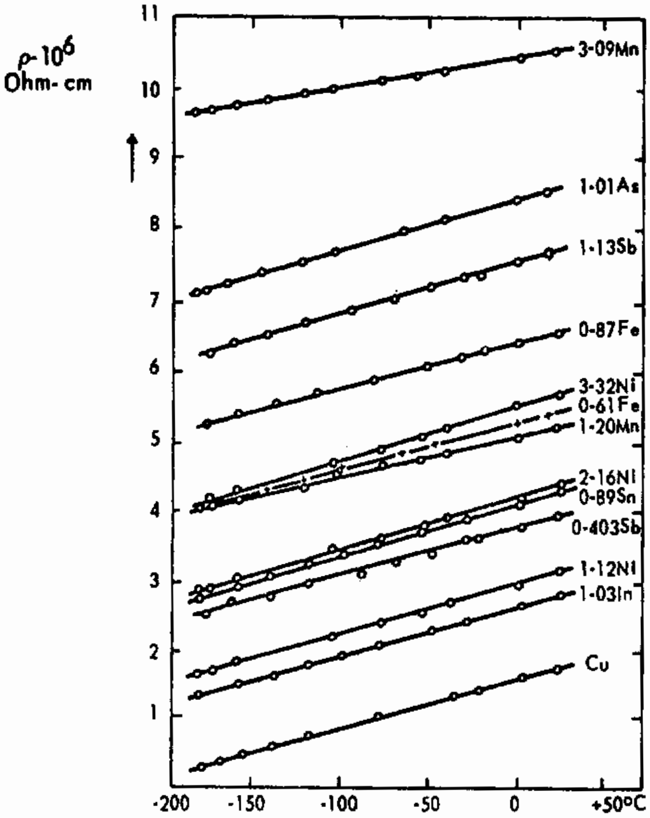


Figure 10. Resistance-Temperature Curves of Copper Alloys

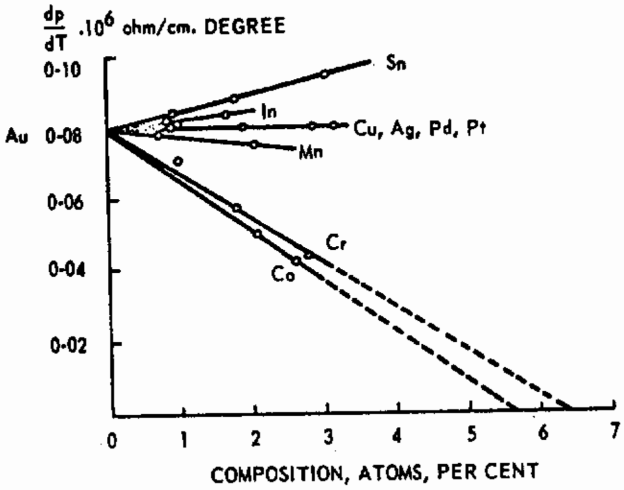


Figure 11. Change in $d\rho/dT$ with Composition for Some Gold Alloys

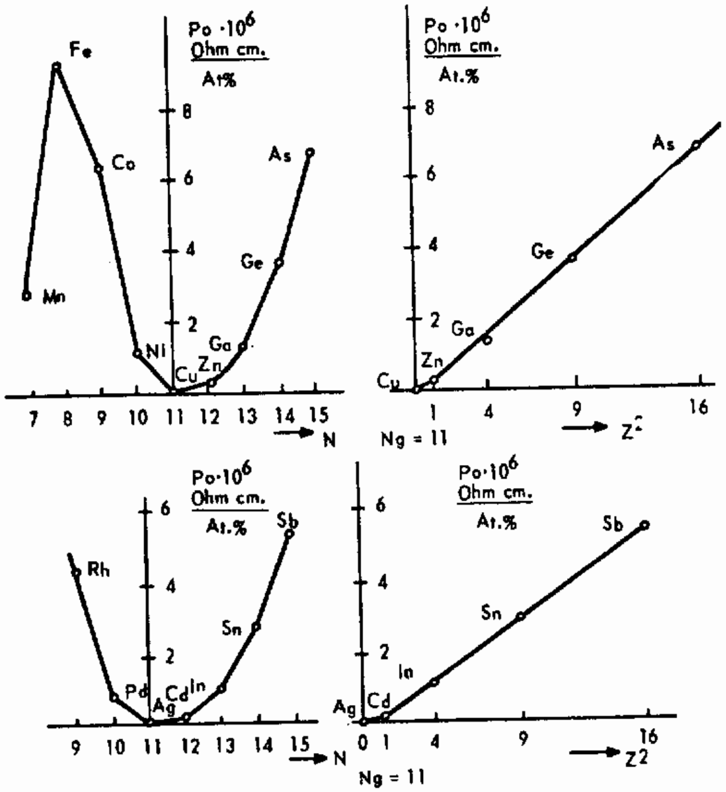


Figure 12. Increase in the Resistance of Copper Due to One Atomic Per Cent of Various Metals in Solid Solution

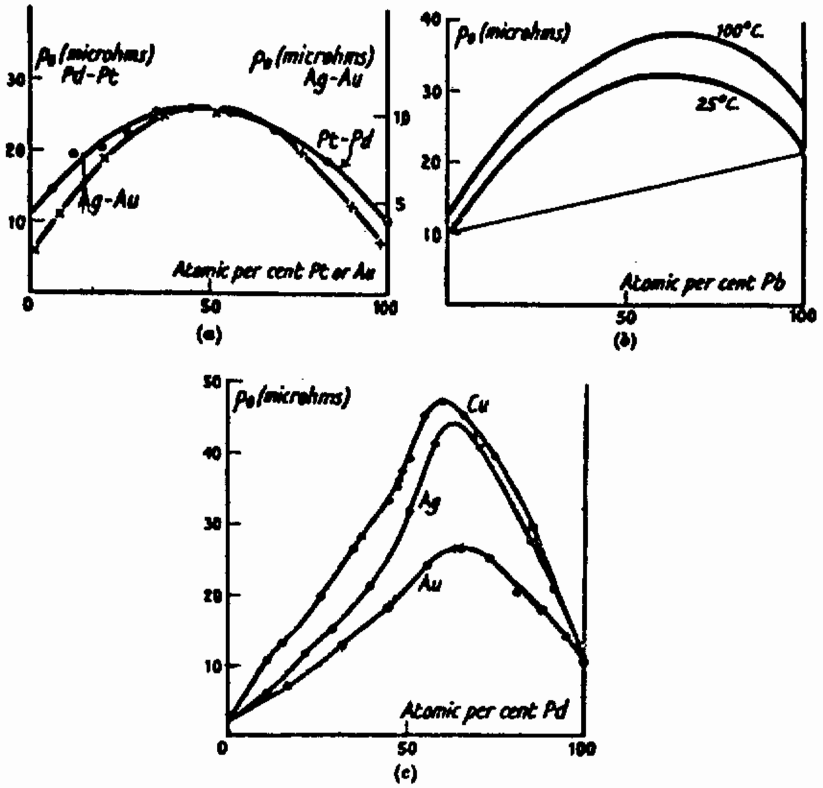


Figure 13. Resistivity of Alloys Where Continuous Range of Solid Solutions is Formed

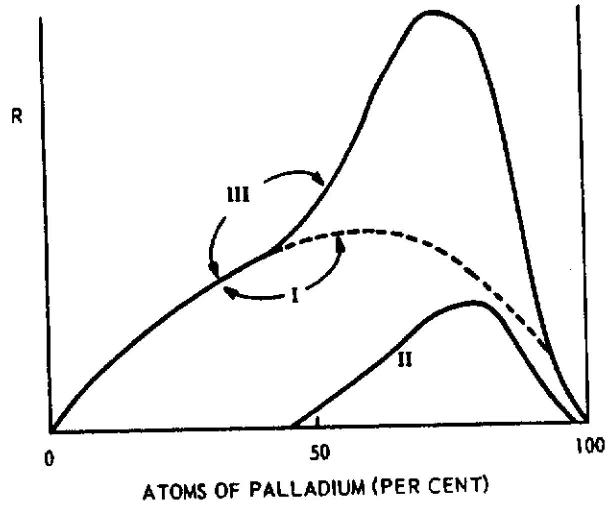
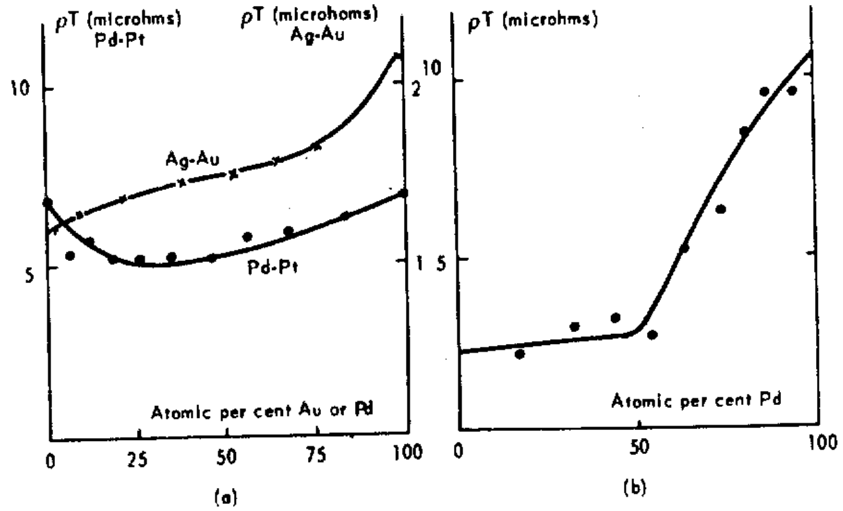


Figure 14. Theoretical Curve for the Resistance, at 0°K, of Ag-Pd Alloys



(a)

(b)

Figure 15. ρ_T (= Td ρ/dT) for Various Alloys in the Range 0° - 100°C

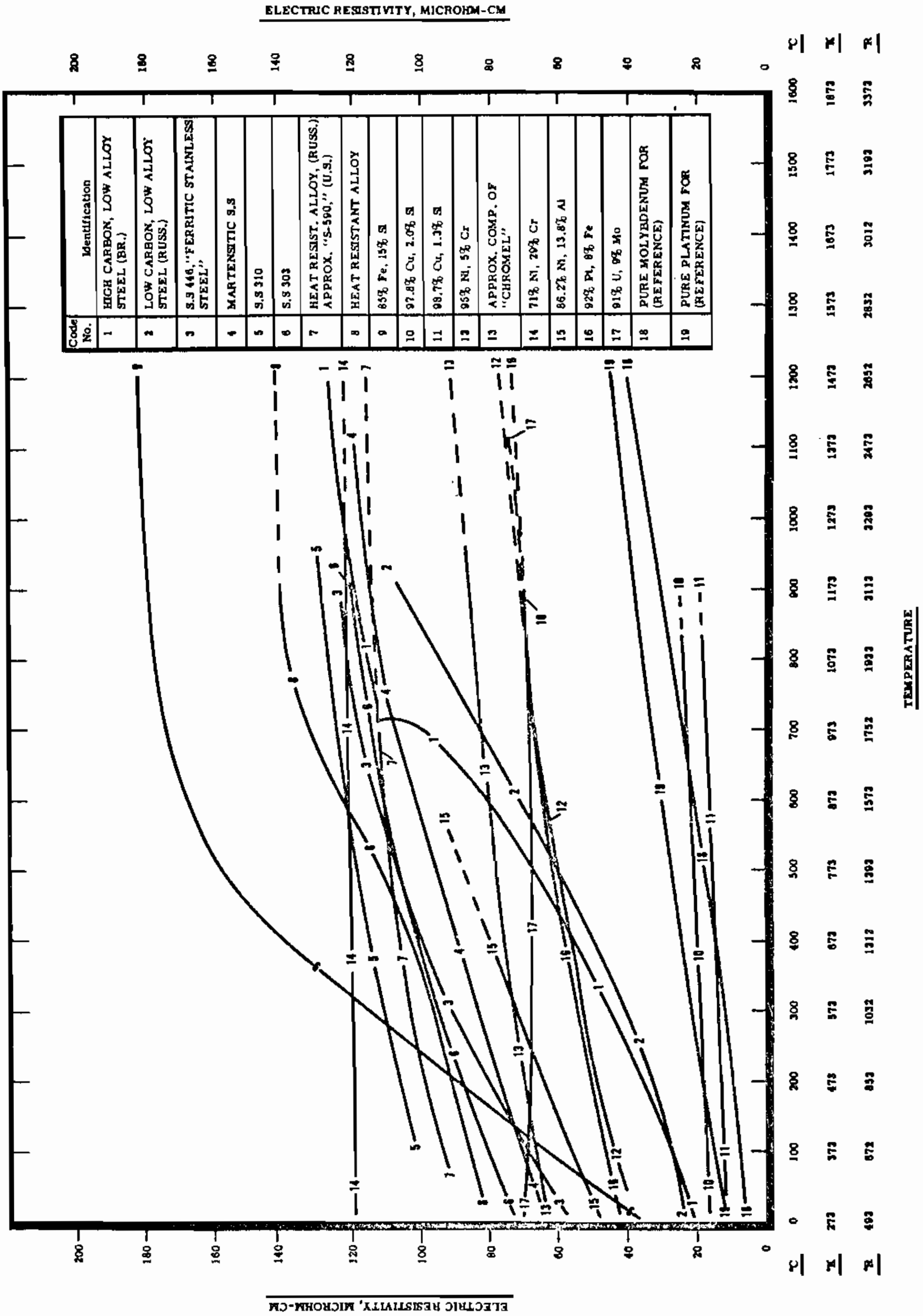


Figure 16. Electrical Resistivity vs. Temperature Characteristics of Selected Metallic Alloys

IDENTIFICATION OF SELECTED ALLOYS: (OF FIGURE 10)

Curve (Code No.)	System (Nominal) Composition (Weight %)	Crystallographic* Structure	Possible* "Ordered Structure"	Physical and/or Heat Treatment	Common Designation:	Investigator	Reference-(Source Data) for Resistivity Vs. Temperature	Remarks
1	Fe-C-Mn-Si-Ni-Cr. Steel	1) Austenite (F.C.C.);(927° to 1288°C 2) Austenite + Cementite; 723° to 927°C 3) Pearlite + Cementite;R.T. to 723°C	None	Annealed at 800°C to 930°C	High Carbon Low Alloy Steel, (British)	Powell, R. W.	WADC-Tech Report 58-476, p. II-C-2	Annealed in Austenite - and Cementite phase fields.
2	Fe-Cr-Mo-Mn-Si-;0.15%C	1) Austenite (838°C to 148°C) 2) Austenite + Ferrite (723°C to 838°C) 3) Pearlite + Ferrite (R.T. to 723°C)	None	Normalized and Annealed	Low carbon, low Alloy Steel. (Russian).	Neimark, B.E.	Ibid; p. II-C-7	
3	Fe, 26% Cr-Mn-Si;0.13%C	Single phase (α),>815°C. <815°C, $\alpha + \sigma$; σ = Tetragonal (FeCr)	Possibly-Small degree in ($\alpha + \sigma$) field below 815°C, due to FeCr.		Stainless Steel 446, "Ferritic Stainless Steel"	Hogan, C.L. and Sawyer, R.B.	Ibid; p. II-D-1	α, (Solid Solution of Cr. in B.C.C. Fe). Solidus≈1500°C
4	Fe, 13% Cr., 0.2%C	Martensite, Body centered Tetragonal lattice, supersaturated solid Soln. of C in Iron.	None	Tempered	Martensitic Stainless Steel.	Neimark, B.E.	Ibid; p. II-D-1	Acicular Needles; Martensite
5	50.98% Fe; 25.54% Cr; 20.68% Ni, 1.83% Mn; 0.84% Si; 0.10%C;S.P.	Austenitic Stainless Steel; (F.C.C.)	None		Stainless Steel 310	Hogan, C.L. and Sawyer, R.B.	Ibid; p. II-D-2	
6	18.42% Cr; 8.97% Ni 0.61% Mn; 0.57% Si; & 0.17% C.	Austenitic Stainless Steel; (F.C.C.)	None		Stainless Steel 303	Ibid	Ibid; p. II-D-2	
7	40% Fe, 20% Cr, 20% Ni, & 20% Co.	Precipitation Hardening Type of Hi-Speed Tool Steel	None	Forged Sample. Quenched in oil from 1200°C. Aged 70 hrs at 760°C.	Heat Resist. Alloy, (Russ.) Approx. "S-590," (U.S.)	Perova, V.I. and Knoroz, L. I.	Ibid., p. II-D-3-a.	Aging Treatment to precipate hardening agents & stress relief.
8	82.4% Fe, 17.6% Al.	β_1 phase, cubic, Solidus about at 1400°C.	Super-Lattice, ordered Fe_3Al, <550°C to R.T.		Heat Resistant Alloy	Bennett, W. D.	Ibid; p. II-D-7	Fe_3Al (or β_1 phase) is Cubic of $Bi_3F_1(DO_3)$ type.
9	85% Fe; 15% Si.	α' phase; to Solidus at 1240°C Curie Point at 530°C	α' phase-ordered - i.e. Fe_3Si; Cubic, Type $BiF_{30}(DO_3)$.			Glaser, F.W. and Ivanick, W.	Ibid; p. II-D	

NOTE: * Authorities for crystallographic structures and/or "ordered structures" are:

1), M. Hansen and K. Anderko; Constitution of Binary Alloys; McGraw-Hill - Hill Book Co. Inc., N.Y., 1958 Edition.;

2), and C. J. Smithells, Metal Reference Book, Vol. I, London, Butterworths Scientific Publications 1956 Edition.

IDENTIFICATION OF SELECTED ALLOYS: (OF FIGURE 10) (Continued)

Curve (Code No.)	System (Nominal) Composition (Weight %)	Crystallographic* Structure	Possible* "Ordered Structure"	Physical and/or Heat Treatment	Common Designation	Investigator	Reference-(Source Data) for Resistivity Vs. Temperature	Remarks
10	97.97% Cu; 2.32% Si	α cu; Si in Solid Soln. with Cu; structure - (F.C.C.); Solidus at 1000°C	None	Melted in graphite crucible under vaccum. Homogenized 18 hr. just below the M.P.		Domenicalli, C.A.	Ibid; p. III-F	
11	98.68% Cu; 1.32% Si.	α Cu; Solid Solution of Si in Cu; (F.C.C.); to Solidus of about 1000°C	None	Same as above		Ibid	Ibid, p. III-F	
12	95% Ni., 5% Cr.	γ Ni = Solid Solution, F.C.C. to Solidus at 1420°C, Curie Point about 100°C	None	Vacuum melted, forged rolled, & cold drawn into 0.4 mm diameter wires.		Thomas, H.	Ibid; p. IV-A-5	
13	91% Ni., 9% Cr.	Same as above, except Curie point <0°C.	None identified	Same as above	Approximate composition of "Chromel"	Ibid	Ibid; p. IV-A-5	
14	71% Ni, 29% Cr.	γ Nickel above 540°C; with possible & limited order structure of CrNi$_3$.	Probable - below 540°C as CrNi$_3$; (F.C.C.).	Work of Thomas. Same as above, Work of Nordheim and Grant(long period deoxidation & decarburization and ρ values are at equilibrium.)		1)Thomas, H. 2)Nordheim, R. & Grant, N. J.	Ibid, p. IV-A-5	
15	86.2% Ni., 13.8% Al.	Phase field, α, to Solidus of 1385°C; α Ni + Ni$_3$Al.	Super structure - ordered Ni$_3$Al; (F.C.C.)	Heat Treated 72 hours at 1100°C; Furnace Cooled.		Liv, T.S. & Bobane, R.	Ibid; p. IV-A	Order Superstructure Ni$_3$Al-Cubic of A-1 (Cu) Type-F.C.C.
16	92% Pt, 8% Fe	Above 710°C, disordered γ Pt (Cubic) to Solidus at 1600°C	Partially ordered, as FePt$_3$, below 710°C	Induction Melted in Mg0 crucible· Tempered.		Kussman, A, & Rittberg, G. Grfn.	Ibid, p. VI-C	Superstructure (ordered FePt$_3$) is of A-1 (Cu) type (F.C.C.)(α) Nickel, F.C.C.
17	91% U; 9% Mo.	γ U, (B.C.C.); Stable from 575°C to Solidus at 1150°C. <575°C, α u + γ u phases.	None	γ- quenched		Bostrom, W.R. & Halterman, E. K.	Ibid, p. VI-F-2	γ Uranium alloy - B.C.C α Uranium alloy - Orthorhombic
18	Pure Molybdenum for (Reference)	Body Centered Cubic	None	Annealed State			Table 12 of present study report.	Derived Mean value of ρ vs. Temperature
19	Pure Platinum for (Reference)	Face Centered Cubic	None	Annealed State			Ibid, Table 12......	Same as above.

NOTE: * Authorities for crystallographic structures and/or "ordered structures" are:

1), M. Hansen and K. Anderko; Constitution of Binary Alloys; McGraw-Hill - Hill Book Co. Inc., N.Y., 1958 Edition.;

2), and C. J. Smithells, Metal Reference Book, Vol. 1, London, Butterworths Scientific Publications; 1956 Edition.

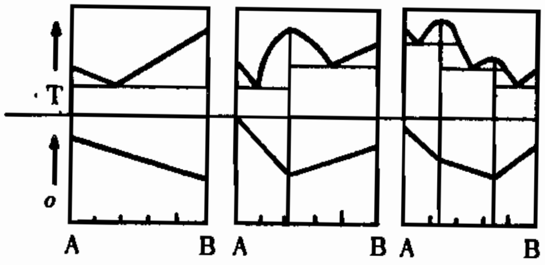


Figure 17. Electrical Conductivity of Binary Alloys vs. the Concentration of One Component in Percent Volume, for Alloys Immiscible in Solid State

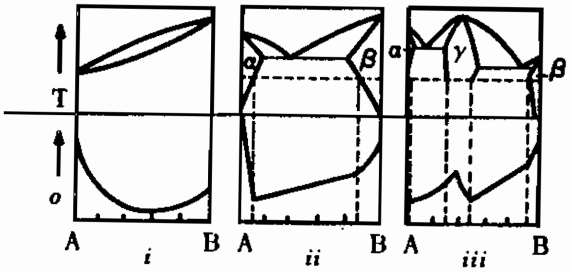


Figure 18. Electrical Conductivity of Binary Alloys vs. the Concentration of One Component in Percent Volume, for (1) Continuous Series of Solid Solutions; (2) Miscibility Gap Between Primary Solid Solutions; (3) Primary Solid Solutions and Intermediate Phase of Variable Composition

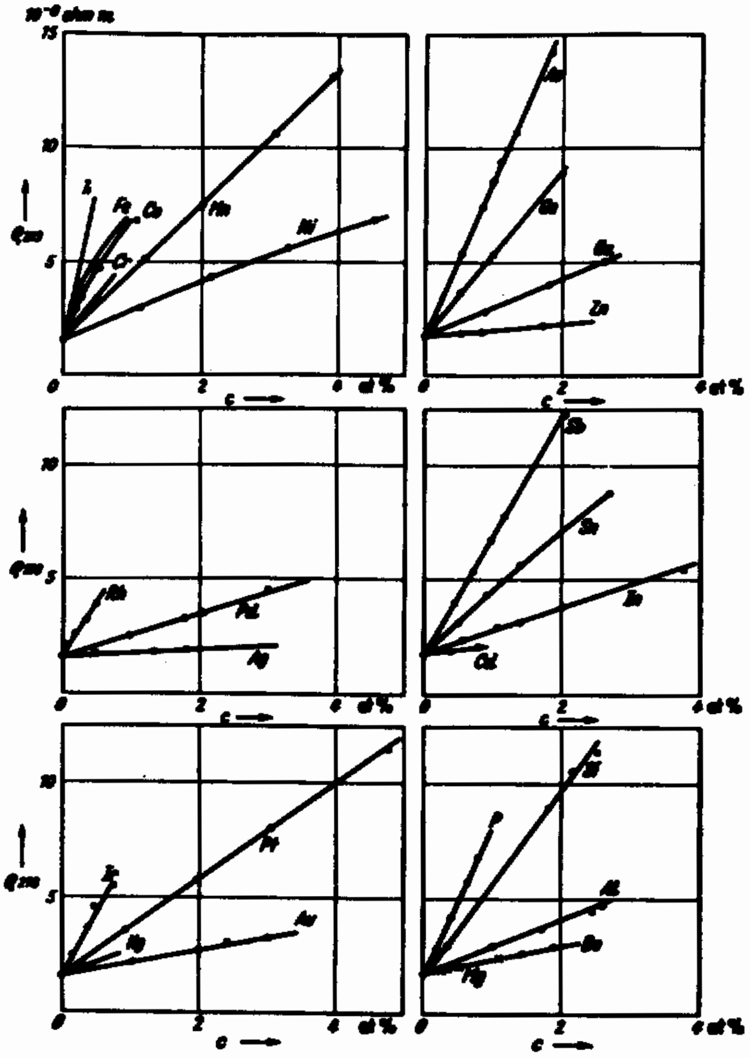


Figure 19. Resistivity at 273°K for Copper Base Binary Alloys as a Function of the Concentration of the Second Component

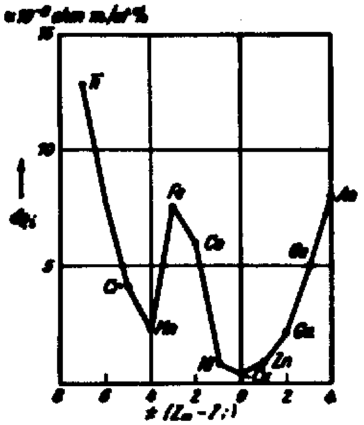


Figure 20. $\delta\rho_i$ for Alloys With Gold as a Base Metal Against Z_m-Z_i

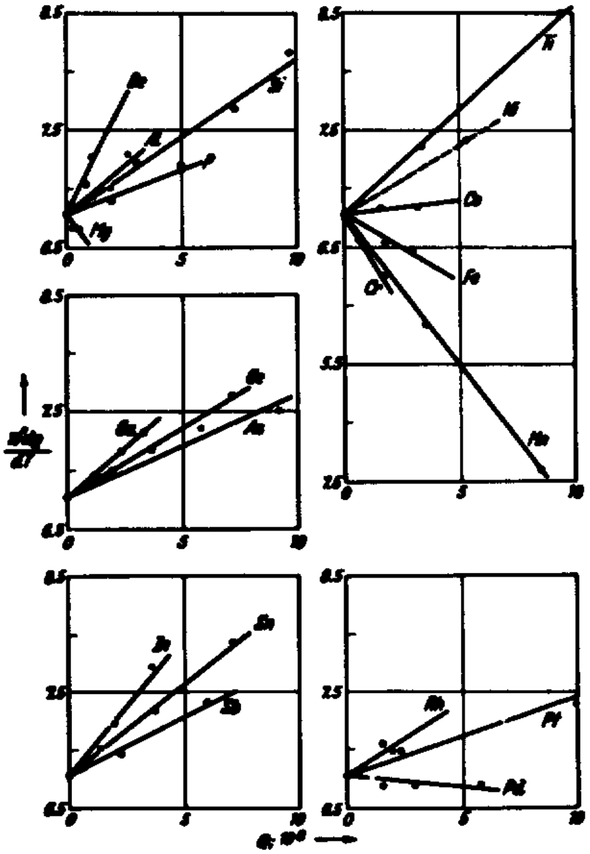


Figure 21. $\delta\rho/\delta$ T in Ohm m/degree Against ρi for Several Copper Base Alloys

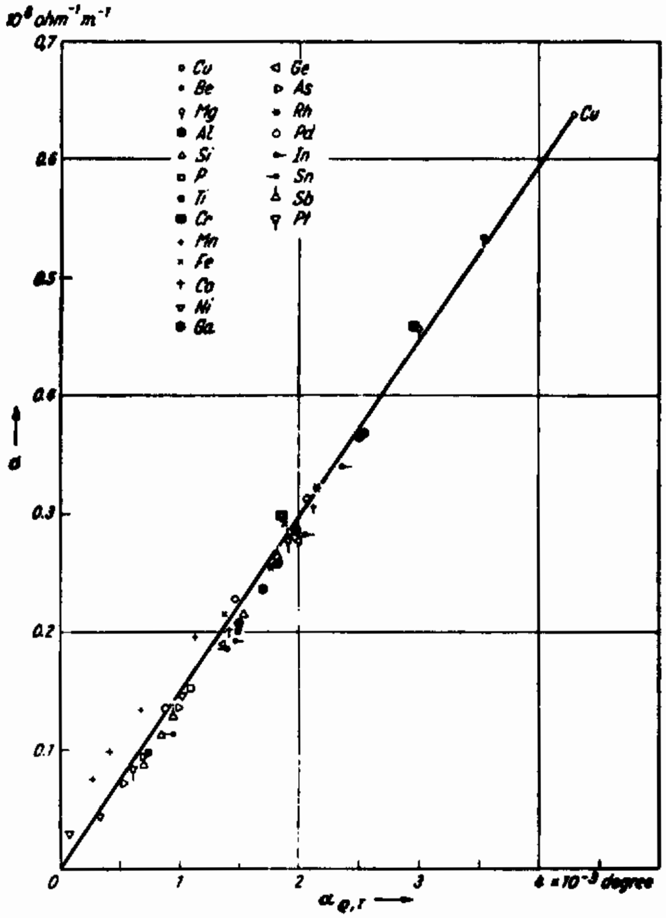


Figure 22. Conductivity of Copper Base Alloys Against the Temperature Coefficient of Resistivity (in 10^{-3} degree^{-1})

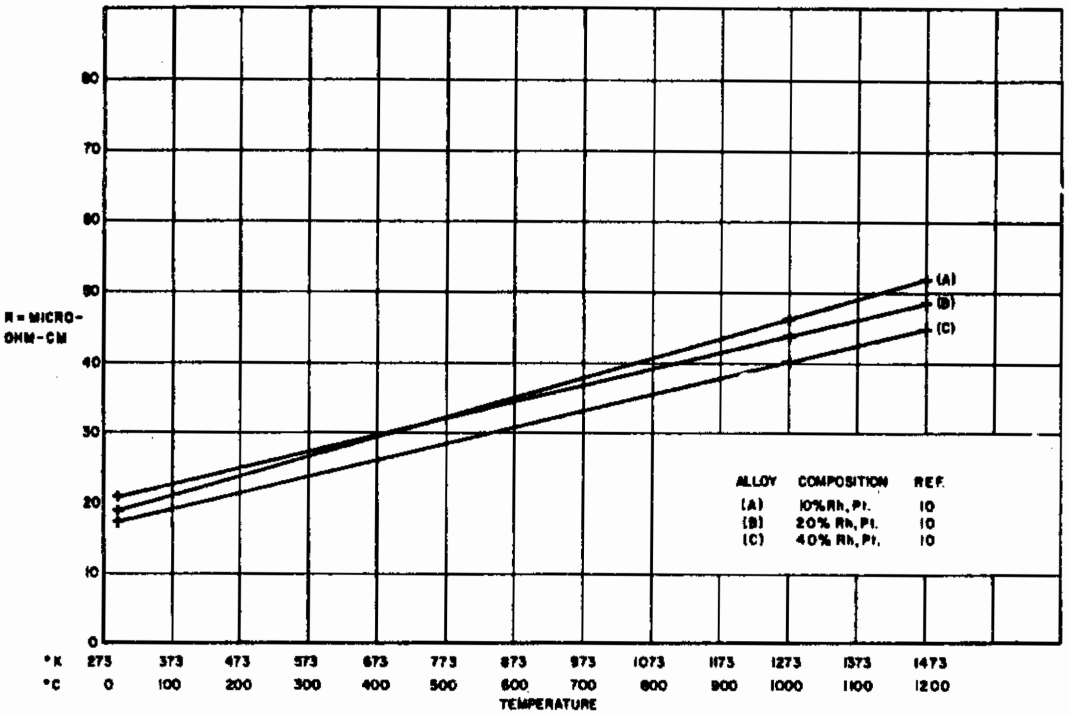


Figure 23. Resistivity of Selected Precious Metal Alloys vs. Temperature

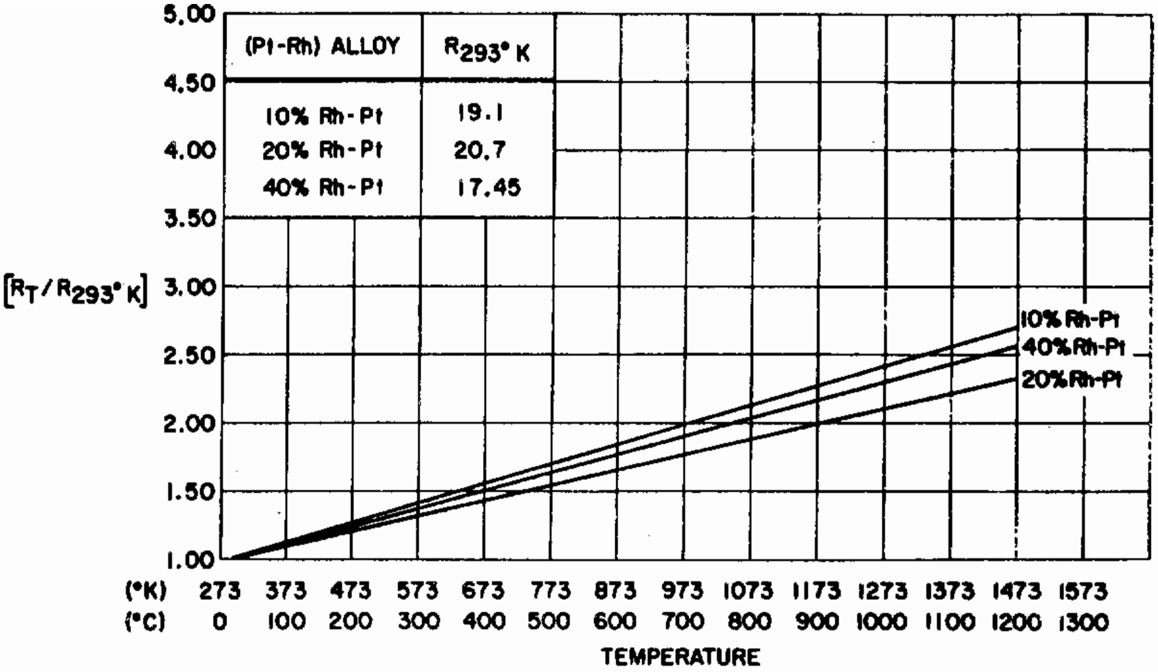


Figure 24. Relative Resistances of Selected (Pt-Rh) Alloys vs. Temperatures

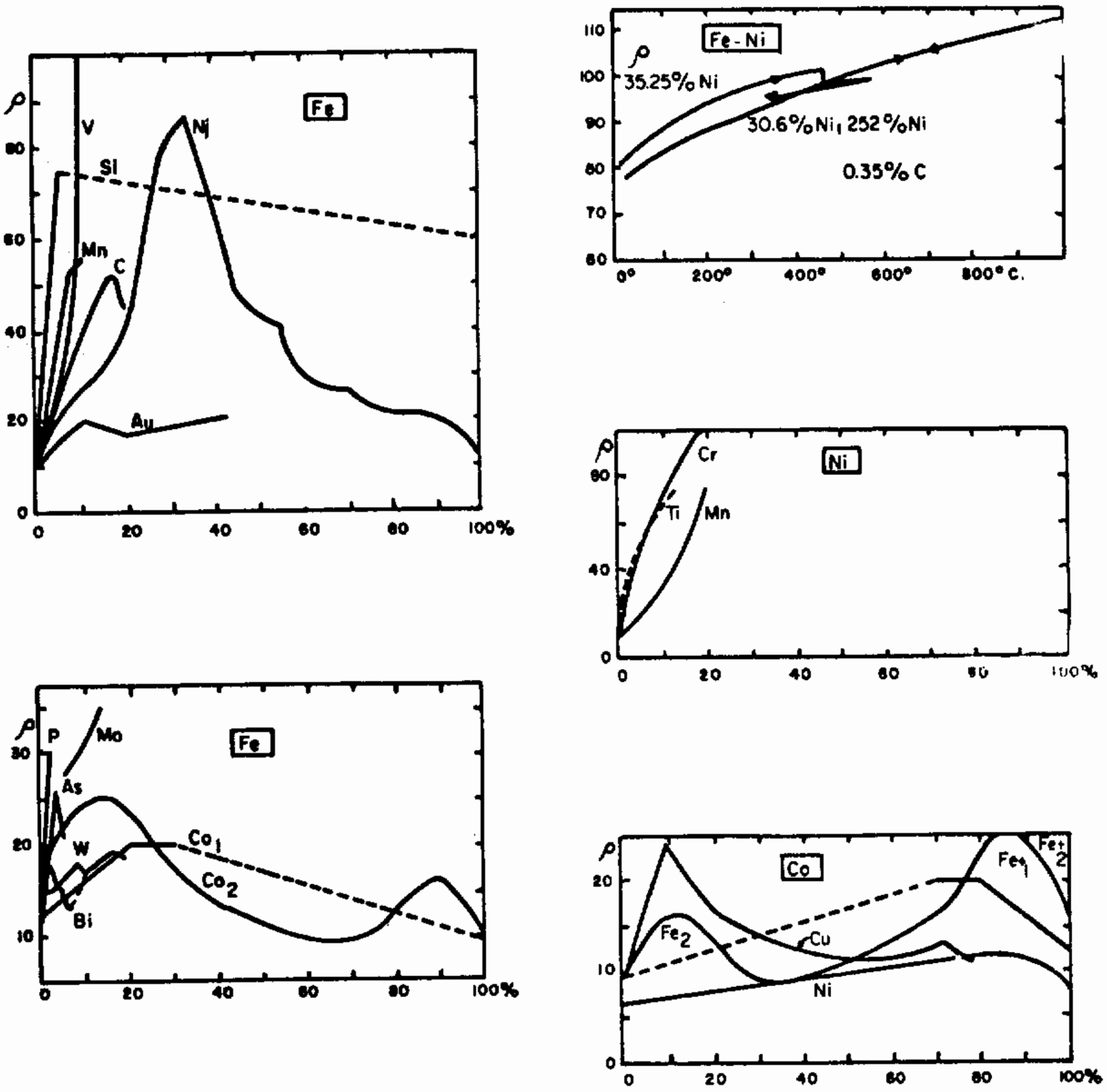


Figure 25. Resistivity (ρ) of Some Binary Alloys

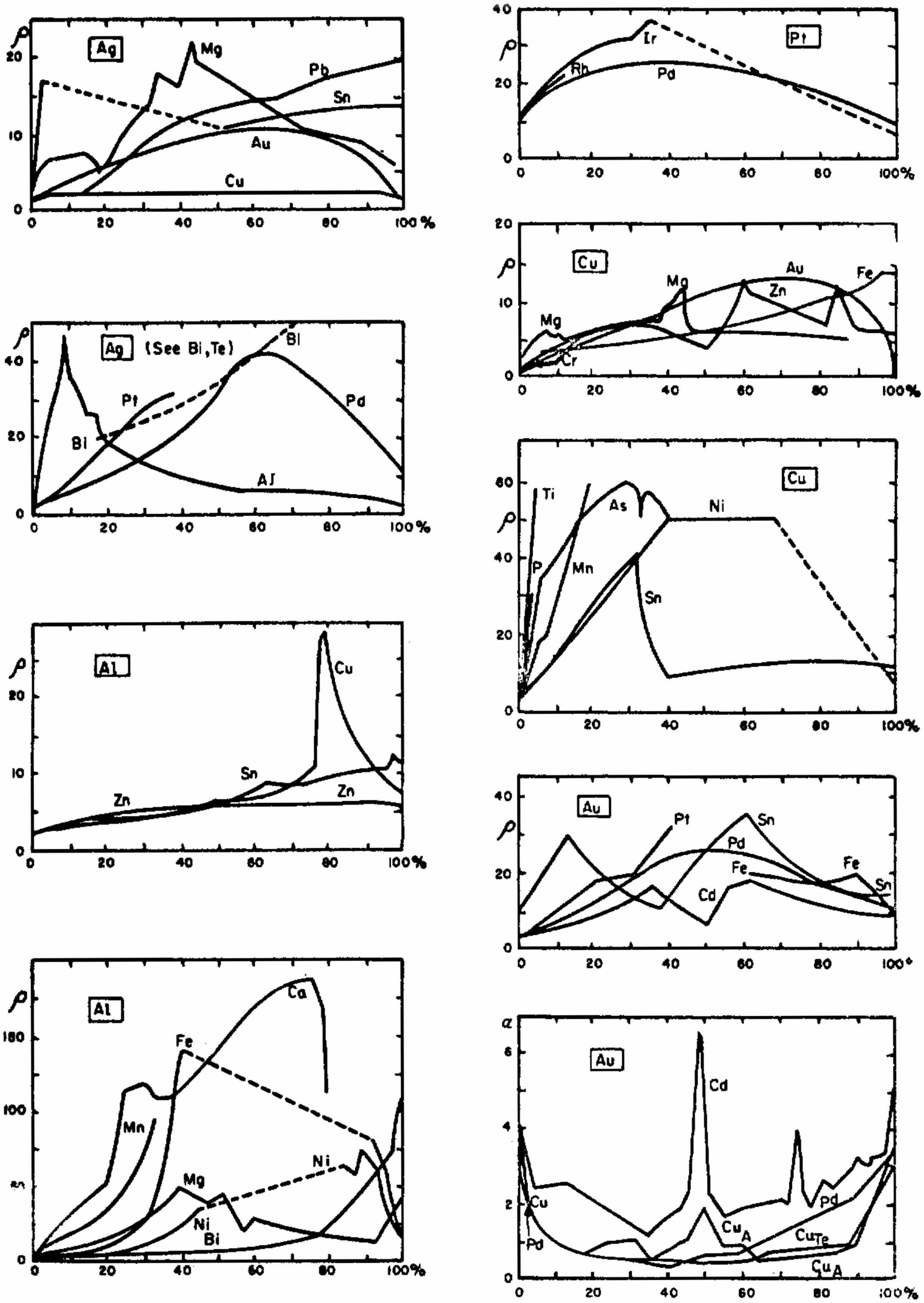


Figure 26. Resistivity (ρ) of Some Binary Alloys

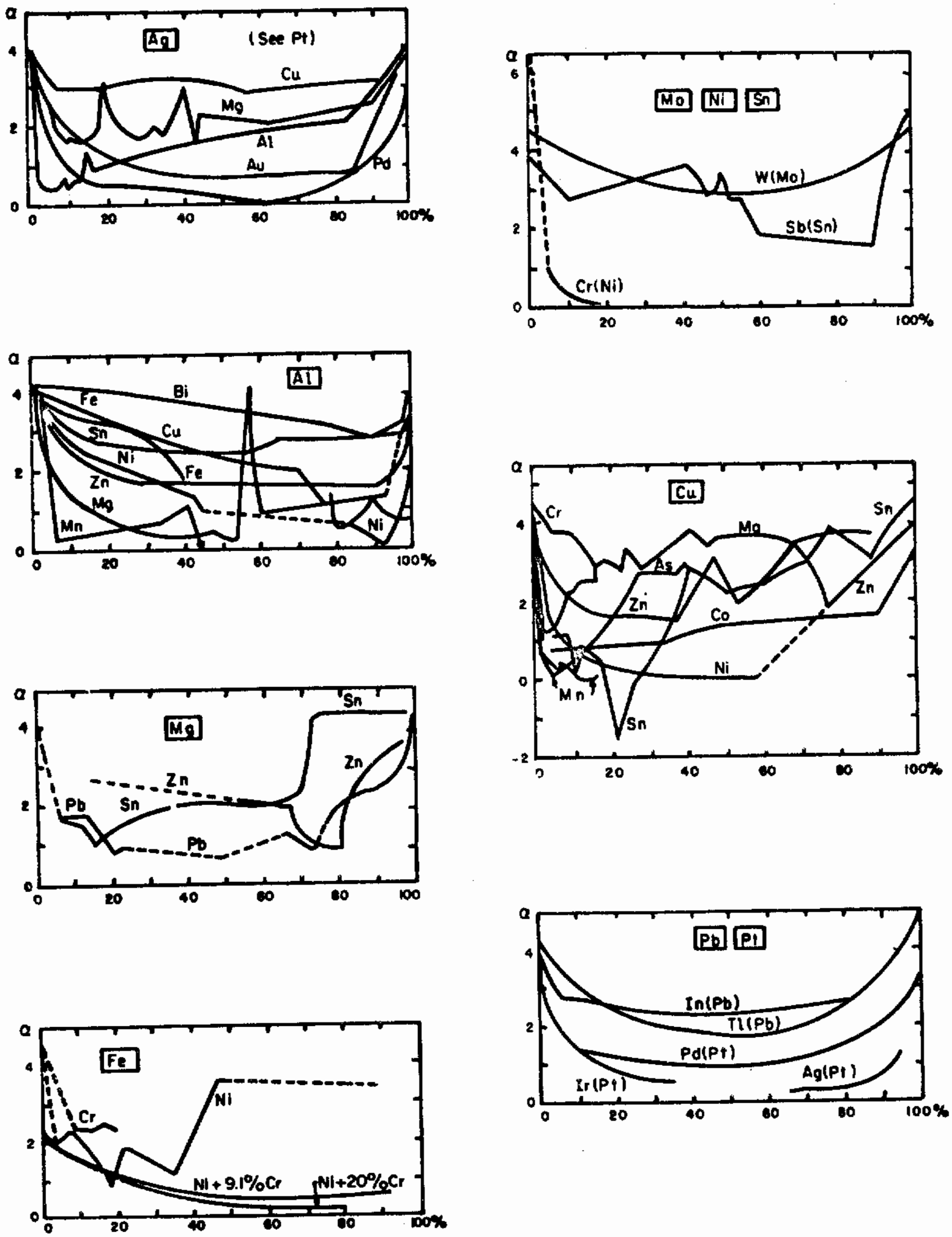


Figure 27. The Symbol of Metal Common to the Alloys of a Chart is Enclosed in a Square, and the Material Abscissae = Wt. % of the Other Metal

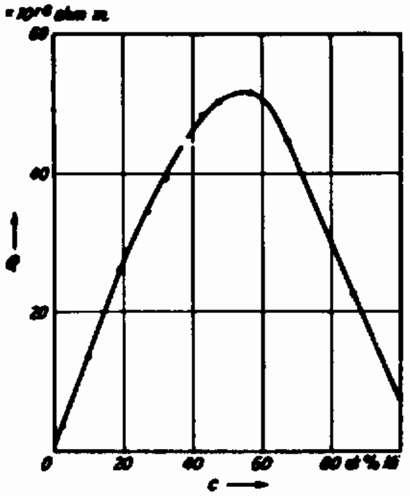


Figure 28. Resistivity of Copper-Nickel Alloys as a Function of Nickel Concentration in Atom Percent

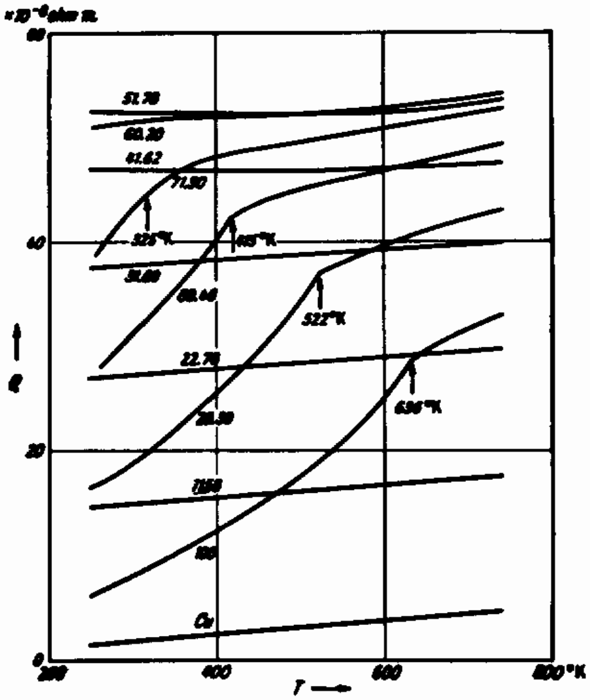


Figure 29. Resistivity as a Function of Temperature for Several Copper-Nickel Alloys

3. METALLIC BINARY COMPOUNDS

3.1 Introduction

The highest ratios of melting point to resistivity are to be found in certain binary compounds which exhibit metallic conductivity. From an electronic standpoint, such compounds may be considered as metals since they contain partially filled conduction bands. We may expect some of these compounds to have a band structure similar to monovalent metals in which there is no band overlap, but one band is incompletely filled with electrons. Other compounds may be expected to have overlapping bands, where one or more bands are not completely filled because of the band overlap. The latter compounds are analogous to the divalent and transition metals. If more data were available on the electrical conductivity of the large number of metallic compounds, it is probable that the conductivities of different compounds would fall into a number of distinct ranges, analogous to the breakdown of conductivity values for pure metals presented in section 1.1.2 for monovalent metals, divalent metals and transition metals. Theoretical study has shown no reason why a binary compound of higher conductivity than Ag, Cu, or Au, at elevated temperatures should not be found. Such a compound should exhibit a considerably higher melting point-to-conductivity ratio than the monovalent metals.

To form a metallic compound, we need a molecule which has metallic bonding and more than zero electrons per atom, free to enter into one of the energy bands of the solid at 0°K, but insufficient to fill all the available energy states in that band. That is, a metallic conductor must have at least one partially filled band at 0°K. In monovalent metals, 0.6 to 1 electrons per atom are available for entering the conduction band and thus occupy less than half the available energy states required to fill the band. Ideally, the highest conductivity may be expected when there are more than one but significantly less than two (say 1.4) electrons per atom available to enter a band which would be filled by two electrons per atom. This situation is not obtained in pure metals, but it might be achievable in metallic compounds. Thus, both TiN and $NbSi_2$ have a room-temperature conductivity as low as 6.3 microhm-cm at room temperature in very impure and highly strained samples. This resistivity is to be compared with that of 2.4 and 10.6 microhm-cm for pure and strain-free gold and platinum, respectively. Practically nothing is known about the band structure of metallic compounds. Thus, a direction to proceed is to correlate, as far as possible, the data on high-conductivity compounds, and to determine which features are shared; e.g., a particular crystallographic structure or molecular formula (AB or AB_2, etc.) with reference to the electronic configurations of the component atoms. However, this approach cannot be applied without considerably more information concerning the structural and electrical properties of different classes of metallic compounds. This work should not only involve ordinary electrical and crystallographic investigations, but also should include investigation of energy band structures by soft X-ray spectra, magnetic, and thermal measurements.

While the data compiled on metallic compounds in this report may seem extensive, it consists, however, of only a small fraction of the minimum amount of data required for proper analysis of possibly useful alloy and compound systems. Due to a lack of interest in the electrical properties of compounds in the past, especially at high temperatures, very little basic data exists in this field. In order to explore quantitatively the areas in which no information exists, a thorough analysis has been made of Hansen's "Constitution of Binary Alloys". In table 3.1 are listed the well-defined binary compounds which have melting points greater than 1000°C, together with thermal data and crystallographic structure data. Also included are references to electrical data in the tables of this investigation. It will be observed that some electrical data exists on 8% of the systems in table 3.1, but this data only rarely involves the temperature variation of conductivity. In table 3.1, the compounds on which room-temperature resistivity data exists are underlined once. Those on which temperature variation data exists are underlined twice. Clearly, much further work needs to be accomplished on the electrical and associated properties of metallic compounds.

It is well known that several high-melting-point binary compounds exhibit superconductivity at very low temperatures. It is thus of interest to explore the conductivity of the superconducting compounds at normal temperatures. A list of selected compounds which exhibit superconductivity is given in table 3.2 together with their room temperature resistivities. Of course, these compounds do not, in general, exhibit the lowest values of resistivity at elevated temperatures, any more than the superconductor tantalum is expected to have a lower normal resistivity than the nonsuperconductor, copper.

In the following parts of this section, the data on the electrical, oxidation-resistant, mechanical, crystallographic and thermal properties of metallic binary compounds is presented and discussed. Techniques of fabrication are also considered in sections 3.4 and 3.5.

3.2 Compilation and Treatment of Data

The basic data on the resistivity at 20°C, temperature coefficient of resistivity, melting point, crystallography, and oxidation-resistance at elevated temperature of binary metallic compounds is presented in table 3.4. The references to the source of the data are also given in this table and refer to the list of references following table 3.5. In table 3.5 is presented the resistivity of metallic compounds as a function of temperature from 0°C to 1200°C where this data exists, together with the temperature coefficient of resistivity, weight percent composition, references and relevant remarks. The reference list for these data follows the table. The results for resistivity at various temperatures were obtained from smoothed plots of the original data. The values at 0°C, 20°C, and 100 degree intervals up to 1200°C were obtained from the smoothed curves. This method of presentation has the advantage of unifying the presentation of much diversified data under a common system of presentation. In addition, it enables the design engineer to compare and select metallic compounds for conductivity applications at any specific temperature from 0°C to 1200°C. It also indicates to the research worker where data on the electrical conductivities from 0°C to 1200°C is incomplete. This data is also in a form which will facilitate calculation of the coefficients in the resistivity polynomial:

$$\rho = a + bT + cT^2 + dT^3 + \text{etc.}$$

which is useful as an interpolation formula and for the theoretical analysis of the data.

3.3 Discussion of Results

It will be observed from tables 3.4 and 3.5 that many of the compounds having low resistivity exhibit relatively high temperature coefficient of resistivity. However, in the absence of considerably more high-temperature data, a selection of compounds of interest for possible application or further work is best accomplished using the more extensive data available at room temperature. This selection has been made in table 3.3 from the data presented in tables 3.4 and 3.5. Table 3.3 lists those compounds which are known to have room temperature resistivities less than 22 microhm-cm within the probable experimental error. This value of room temperature resistivity was made the basis of selection of metallic compounds of interest because it is the value of resistivity, at 20°C, from standard Pt-20% Rh alloy used widely in high temperature conductor applications. Data on compounds of higher resistivity are listed in tables 3.4 and 3.5. Table 3.3 lists:

a. The compound of interest together with its molecular formula and nominal wt. % composition.

b. Melting point in °C.

c. Resistivity at 20°C and at T_n °C, the highest temperature at which resistivity values are available.

d. The temperature coefficient of resistivity together with the temperature range over which the value tabulated is given.

e. The upper temperature limit for resistance to oxidation.

f. The crystal structure, for the purpose of giving an indication of the probable mechanical properties of the compound.

g. Miscellaneous remarks and notes of relevance.

h. The reference to the tables from which the data was derived which in turn refer to the original source of data.

Many of these compounds not only have very high melting points but also exhibit an electrical conductivity comparable with Pt and Pt-Rh alloys at 20°C and good resistance to oxidation up to temperatures of 1000°C or higher. Generally, the compounds with face-centered cubic structures can be expected to exhibit reasonably good mechanical properties, the other structures being normally brittle. It should be stressed that many of these metallic compounds exhibit high-temperature coefficients of resistivity, and an estimation of resistivity at high temperature from room temperature data should not be made when this can be avoided. This, however, cannot be accomplished in most cases due to the absence of high-temperature data.

The systems which are of most interest for further investigation are now discussed. These include $NbSi_2$, $TaSi_2$, VSi_2, and ZrB_2 which exhibit room temperature resistivities of 6.3, 6.3, 9.5, and 9.2 microhm-cm at room temperature compared with 10.6 and 21 microhm-cm for platinum, and platinum-20% rhodium alloy, respectively. These systems should have upper limits to resistance to oxidation of the order of 1000°C. Of somewhat higher oxidation resistance are $MoSi_2$ (1700°C;22), CrB_2 (1300°C;21), TiB_2 (1300°C;15), ZrN (1200°C;12), TaC (1100°C;30) and HfB_2 (1100°C;22.) Here, the temperature of the upper limit to good resistance to oxidation is given by the first number in the parentheses, and the resistivity in microhm-cm at 20°C is given by the second number. The face-centered cubic structures which are likely to have more adequate mechanical properties for high-temperature conductor applications are ZrN (1200°C;12), TiN (unestimated; 11), and TaC (1100°C;30). Compounds of the face-centered cubic type not included in table 3.3 are given in tables 3.4 and 3.5. These include: HfB, HfN, TiC (60), ZrC (63), Hfc (109), VC (150), NbC (74), ZrB (30), and ZrB_2 (60), where the resistivity is given in microhm-cm in the parentheses when this is known.

It is likely that compounds other than the face-entered cubic structures can be used to form useful conductors, in spite of their normally poor mechanical properties. This may be accomplished by vapor-plating onto a suitable mechanical substrate or by sintering the compounds to form useful shapes for high-temperature conductor components. The most outstanding compounds in regard to oxidation resistance are probably $MoSi_2$, CrB_2, and TiB_2. Since these compounds are not of the face-centered cubic structure, they would be best utilized for high-temperature conductor applications by using the vapor-plating or sintering techniques. These techniques of fabrication are discussed in sections 3.4 and 3.5.

It should be emphasized that the technology of the highly refractory borides, carbides, nitrides, and silicides is still in its infancy. Directed research into improving the electrical conductivities of many of the metallic compounds already known to be good conductors should result in considerably lower conductivities than those reported. In addition, it is probable that new compounds and known compounds of unknown electrical properties will be found on further study to have room-temperature and elevated-temperature conductivities less than platinum or platinum-rhodium alloys. Because the melting points of many of the metallic compounds far exceed the melting points of these metals and alloys, it is possible that they may be used for high-temperature conductors at temperatures considerably in excess of 1200°C.

3.4 Supplemental Data: Selected Bibliography on the Properties and Uses of Borides, Carbides, Nitrides and Silicides

The literature on boride, carbide, nitride and silicide compounds includes several books as well as technical papers from government and industry, trade literature, and patent disclosures. For the purpose of this paper many of these sources were covered — with the exception of patents. Many of these books and papers include additional references; therefore, interested researchers and engineers will find a rather complete coverage of the field in this bibliography. Data and information is available on all phases of work in this field: synthesis, analysis, structure, properties, fabrication and uses.

Useful borides, carbides, nitrides and silicides cover these compounds of several of the elements in the periodic table. Compounds of the transition metals are usually classed as refractory hard metals because of their general physical characteristics. Those of other groups have varying properties but many are quite refractory. Some of these refractory materials, especially some of the carbides and nitrides, are unstable in moist air. This limits their usefulness in other than specialized applications. Present day applications for many of the borides, carbides, nitrides and silicides are ever-increasing, because of their unique properties.

History

Much of the original work in the synthesis and study of these compounds was done in the second half of the 19th century. This work, by the French chemist Moissan, was published in 1897.(15) Because of the completeness and systematic procedures used by Moissan, little has been added to our basic knowledge of these materials. Electric arc fusion techniques were used to obtain the high temperatures required to melt his materials. The compounds thus formed were usually very impure due to contamination from the electrodes and surrounding refractories as well as from relatively impure starting materials. The impetus for this early research was the discovery of cemintite (Fe_3C) and its application to tool materials. Work of Moissan and others was chiefly basic in nature, and it was not until later that some of these materials found applications. Other researchers have improved or added to the basic work of Moissan. They include Honigschmid(14), in 1914, who improved upon the synthesis techniques. Hagg, Kiessling(1),(31),(51) and others have done considerable work on X-ray and structural analysis of these materials. Since the time of these early discoveries, applications for their use have greatly expanded, and newer uses are constantly being found. Early uses, for the carbides especially, was in tool materials — followed by lamp filaments and refractories.

Synthesis

The general synthesis techniques for forming these compounds are varied(1),(3),(4),(14),(15). Many of the techniques are applicable to synthesis of most of the borides, carbides, nitrides and silicides. Some of these, such as vapor phase deposition, are useful in forming very pure thin films while most of the others produce powders or massive forms of the compounds. Most of these processes require high temperatures and the use of a protective atmosphere or vacuum. The techniques might be classed as shown

1. Direct combination of the elements.
2. Reduction of oxides or other compounds.
3. Chemical isolation from alloys.
4. Fused salt electrolysis.
5. Vapor phase deposition.

Most of the compounds can be formed by direct chemical combination at elevated temperatures. Carbides, borides and silicides can be formed by fusion or reactive sintering of the elements. The reactive sintering usually produces a more nearly pure product and requires lower temperatures. The use of a gaseous phase such as nitrogen or ammonia to form nitrides or a hydrocarbon to form carbides also can be accomplished at lower temperatures and will yield a relatively pure material. Usually, however, long periods of time at high temperature are required for complete nitriding or carburizing.

Reduction of the metal oxide or other compounds of the metal can be used to produce many of these materials.(1),(3),(40) Borides and silicides can be made by reduction of an oxide or mixture of oxides in the presence of carbon or metals such as silicon, aluminum, or magnesium. Carbides are made commercially by reduction of the metal oxide with carbon. Many nitrides are made by reduction of the metal oxide with carbon in the presence of nitrogen or dissociated ammonia. Decomposition of compounds such as the chlorides or oxychlorides with ammonia is still another technique used to produce nitrides.

The menstruum process, or chemical isolation from metals or alloys, is used to produce many carbides and silicides.(1),(3) In this process the carbide or silicide is formed in a melt of a given metal. Hydrochloric, nitric or other acids are then used to dissolve away the metal leaving the crystals of carbide or silicide. Rather pure crystals of materials can be formed by this process.

Fused salt electrolysis techniques have been used to produce certain borides, carbides and silicides.(1),(3) Complex baths of salts and the metal oxide are fused usually in graphite crucibles. Carbonates are generally used for carbides, B_2O_3 for the borides, and alkali fluorosilicates for the silicides. The respective boride, carbide, or silicide is deposited on a graphite cathode by application of the proper current density. High temperatures are required to maintain solubility of the oxide in these melts, making this process rather difficult to use.

Many of these high-temperature compounds can be produced by vapor phase deposition.(1),(3),(4) The materials produced by this method are more nearly pure than those produced by any other method discussed in this paper. Because of the nature of this type synthesis; it is difficult, if not impossible to build up more than a thin film of the material on a suitable substrate. This technique normally involves the simultaneous decomposition and reaction of vapor of the metal halide and a reacting carrier gas with subsequent deposition on a hot substrate. To produce carbides, carbon monoxide or a hydrocarbon gas is used as a carrier gas; for nitrides, nitrogen or ammonia is used; and for borides, a boron halide vapor is employed. Silicides are usually formed by reacting a silicon halide with a hot metal powder or a metal halide with a hot silicon powder.

Fabrication

Powder metallurgical techniques are those chiefly used to fabricate parts from the carbide and other powders.(6),(7) Compaction of the powders followed by sintering in a suitable atmosphere is the method most widely used.(24),(28) (60),(61) In this method the powder is pressed to shape in hardened steel dies. Isostatic pressing is also finding increased usage for uniform and high compaction of these hard materials. Various parameters such as particle size, size distribution, lubrication and binders for the particles, pressure, size and shape of the compact, as well as others, must be considered for optimum results. The pressed compacts are then sintered to temperatures below the melting point in a vacuum or suitable atmosphere. In many cases, small quantities of metals or other materials are added as cementing or sintering aids. This process will generally produce a suitable finished product although, in some cases, parts must be ground to closer tolerances.

A second method of forming that is finding increasing usage today is hot pressing.(42),(59) In this method the powders are heated and compacted simultaneously. The dies are usually heated by resistance or induction techniques. Normally, graphite dies are used in forming the parts. The use of induction heating allows rapid heating and cooling of the die and compact. This technique is also desirable because compacts can be made that are much closer to theoretical density than those made by any other method.

A third method, which is not used to any great extent because of the problems involved, is fusion casting. The materials are heated in graphite molds by an electric arc until molten. After cooling and solidification, the part is removed and finished by grinding. Among other problems, such as the very high temperatures and protective atmospheres required to melt them. Some materials will sublime considerably or will change drastically in composition at these temperatures.

A fourth method of fabrication consists of vapor plating. This is discussed in section 3.5.

Properties

In general, the various borides, carbides, nitrides and silicides have similar physical properties.(1),(3),(12),(23),(42),(43) These are: (1) a high melting temperature, (2) high hardness, (3) brittleness, (4) electrical conductivity, (5) high strength at room and elevated temperatures, (6) fair-to-good chemical stability and (7) fair oxidation resistance.

Many carbides and borides have melting temperatures in excess of 2500°C with some much higher. Hafnium and zirconium diborides melt at about 3100°C, and hafnium and tantalum carbides at about 3800°C. Most of the nitrides melt slightly lower than the carbides and borides with the silicides still lower. In any event, most of the useful materials melt at temperatures in excess of about 2000°C. Vapor pressure and reaction rates must be considered when discussing melting temperatures of these materials.

All of these compounds are very hard and brittle. Many are well above 8 or 9 on the Moh's scale with a few of the borides and carbides such as boron carbide and titanium diboride approaching the hardness of diamond.

Most of the materials are electrically conductive. Conductivity will vary considerably with the particular compound and its purity. Some of these materials, such as silicon carbide and molybdenum disilicide, because of their conductivity and oxidation resistance, are used as resistance heating elements. A few of the nitrides, notably boron nitride and aluminum nitride and a few others, are nonmetallic in nature and are excellent electrical insulators rather than conductors.

High strength at ambient and elevated temperatures is another important property of these materials. The carbides, especially, are noted for their retention of mechanical properties at very high temperatures provided they are protected from oxidation. Although most of these materials are very strong, their extreme hardness and brittleness greatly limit their usefulness in mechanical applications.

Most of the compounds have fair-to-good chemical stability; however, this property varies with the particular compound. While most of the borides, carbides and silicides react only slightly with strong acids, some of the carbides and nitrides will react with moisture in the air to hydrolyze. Notable among these are some of the alkalies and some of the rare earth group of elements. Of the four classes of compounds, the nitrides are probably the least resistant to chemical attack. The general chemical inertness causes some difficulties in preparing these materials for chemical analysis. For use in vacuums and under elevated temperature condition, the borides are the most stable -- followed by the carbides and silicides. The nitrides are quite unstable under vacuum conditions because of their high vapor pressures. Most of the compounds containing boron are fairly oxidation-resistant at high temperatures. Several of the borides and boron silicides are notable in this respect.

Other silicides are also rather resistant to oxidation at elevated temperatures, because of the formation of a silica layer which, in effect, glazes the surface to slow further oxidation. Probably the least oxidation resistant, are in general, the nitrides. The properties of all these materials can be varied to a degree by the use of metals or other bonding agents when forming the ware. Both oxidation and thermal shock resistance as well as electrical properties can be improved or tailored to use.

Present and Future Uses

The uses for these materials vary considerably. Probably the bulk of the materials produced in this country are used in abrasives, tool materials, and special refractories. The well-known silicon carbide is used considerably in abrasives and refractories, and other carbides such as tungsten and titanium are used for tool materials. Silicon carbide and molybdenum disilicide are being used to a great extent as heating elements. Other materials may find future use in this application. The nuclear field has considerable interest in these various compounds as refractory and fuel materials as well as for crucibles to contain highly corrosive melts. Coatings of some of these materials are being used for oxidation protection, hard facing for bearing surfaces, and chemical resistance.

Some of the newer and speculated uses of the various borides, carbides, nitrides and silicides are in the electronics and space fields. They are being used or considered for thermoelectrics, thermionic emitters,(35) semiconductors and others. Boron nitride in a machinable form is being used for high-temperature tuning capacitors and other dielectrics. Some of the other materials should find new metallurgical and chemical usage such as hardening in alloys, and catalysts or catalyst supports. Other materials may find use in magnetic applications.

Some of the rare earth compounds are felt to have interesting properties as emitters, thermoelectrics, semiconductors and others. Research in these and other new compounds should prove both interesting and fruitful.

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3.5 Supplemental Data: Vapor Plating of Metallic Compounds*

Vapor plating has been successfully employed for the deposition of a variety of compound coatings. This method is of particular value for the deposition of refractory materials of high purity. However, the less refractory materials, such as copper, can also be deposited by this method and may offer some advantages (such as greater crystallinity) over more conventional methods, such as electroplating.

The degree of crystallinity of the coating obtained by vapor plating generally depends upon the deposition or substrate temperature; the higher the temperature the greater the crystallinity. In general, it may be expected that a more stable starting compound requires a higher decomposition or substrate temperature, and that the resulting coating should be more crystalline than that obtained from a less stable starting compound. One can, therefore, in a sense, control the physical properties of the coatings obtained by vapor plating by judicious selection of the starting compound as well as the deposition conditions.

The conducting compounds of interest here are the carbides, nitrides, borides, and silicides.

Carbides (TaC): Tantalum carbide (TaC) has been vapor deposited by reduction of tantalum pentachloride with hydrogen in the presence of toluene vapor at 700-1000° followed by heating to 2500° to convert the dicarbide to the monocarbide. Other sources of carbon for the preparation of tantalum carbide deposits have included pentane (35-60° petroleum ether) and graphi (as the substrate).

An alternate approach to tantalum carbide would consist of employing an organometallic derivative capable of decomposition to tantalum carbide. Specific possibilities for this purpose include the novel π-methlcyclopentadienyl tantalum tetracarbonyl, bis-π-methylcyclopentadienyltantalum, and bis-π-benzene tantalum methyl. In each case, however, there is a possibility that various carbides of tantalum including TaC may be formed. A subsequent heat treatment may therefore be necessary.

Nitrides (ZrN): Zirconium nitride has been vapor deposited by reduction of zirconium tetrachloride with a 3:1 mole ratio of nitrogen to hydrogen at a specimen temperature of 2000-2500°.

A more direct route to ZrN would be via thermal decomposition of zirconium tetra-kis diethylamide, Zr $(NEt_2)_4$.

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*Powell, Campbell, Gonser, "Vapor-Plating", John Wiley & Sons, Inc., New York, 1955.

Another approach of interest, primarily because it would provide a more volatile source of zirconium, is the thermal decomposition of zirconium acetylacetonate (preferably the hexafluoroacetylacetonate derivative) or bis-π-methylcyclopentadienylzirconium dicarbonyl in the presence of ammonia, e.g.,

$$Zr(AA)_4 + \frac{4}{3} NH_3 \longrightarrow ZrN + 4AAH + 1/6N_2$$

$$(\pi\text{-}CH_3Cy)_2\, Zr(CO)_2 + NH_3 \longrightarrow ZrN + 2\, CH_3CyH + 2CO + 1/2H_2$$

Borides (TiB_2, Zr, B_2, HfB_2, CrB_2): In the case of the first three borides, these have been deposited by reduction of the metal chloride ($TiCl_4$), $ZrCl_4$), or $HfCl_4$) and boron trichloride or tribromide with hydrogen at temperatures generally above 1000°. In the case of HfB_2, a specimen temperature of 1900-2700°, has been used. In the case of CrB_2, the method generally employed has consisted of boriding chromium with boron trichloride in the presence of hydrogen.

Two other approaches appear worthy of study. They are (1) reduction of the acetylacetonate derivatives with hydrogen in the presence of boron trichloride and (2) thermal decomposition of the borohydrides, particularly in the case of TiB_2, ZrB_2, and HfB_2. Use of the volatile hexafluoroacetylacetonate derivatives is of particular interest in the first of these approaches.

Silicides (VSi_2, $NbSi_2$, $TaSi_2$, $MoSi_2$): Silicide deposits have been produced by two methods.

1. Codeposition by reduction or thermal decomposition of a mixture of metal halide vapor and silicon tetrachloride, and

2. Silicon diffusion or siliconizing by deposition of free silicon by displacement of reduction from its halide vapor followed by diffusion into the metal sublayer.

Since silicon diffused very readily into most metals at relatively low temperatures, the second method has been most generally utilized for preparing silicide coatings. Vanadium, niobium, tantalum, and, in particular, molybdenum silicides have been produced by this method.

Further study of the first method would be of interest to produce the pure disilicides. For this purpose, use of more volatile sources of the metal (V, Nb, Ta, Mo) such as the hexafluoroacetylacetonate or carbonyl derivative (e.g., $\pi\text{-}CyV(CO)_4$) would appear desirable.

Notes and Abbreviations, Table 3.1

Table 3.1 is an alphabetical listing of well-defined binary compounds which have melting points of greater than 1000°C. Specific melting points are listed as well as the crystal structure, and references to electrical measurements are given if reported. In some instances no melting point has been reported.

An asterisk (*) indicates that the compound is formed peritectical or by a eutectoid decomposition, and it is improbable, in most instances, that a single phase compound could be produced of these compounds. Those compounds not indexed by an asterisk can be formed from the melt. The melting points of the constituent elements in the compound are given in the second column of the table. Those compounds for which resistivity data at room temperature only has been found are underlined once. Underlined twice are those compounds for which resistivity data as a function of temperature has been found.

The following abbreviations are used to indicate crystal structure types: b.c.c., body-centered cubic; c.p. close packed structure; f.c.c., face-centered cubic; hex., hexagonal; monocl., monoclinic; rhbdr., rhombohedral rhomb., rhombic; teter., tetragonal. (The data for this compilation was taken from "Constitution of Binary Alloys", 2nd Ed., McGraw-Hill Co. (1958), by Max Hansen, from which additional information may be obtained.)

TABLE 3.1

WELL-DEFINED BINARY COMPOUNDS WITH M.P. GREATER THAN 1000°C

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structure (1)	(2)	(3)
Ag-Ce	960.5-800	$CeAg_3$ 990	$CeAg_2$ 865*	CeAg 855				
Ag-Th	960.5-1845	$ThAg_3$ 1120	Th_3Ag_5 1035					
Ag-Ti	960.5-1720	TiAg 1040*						
Ag-Zr	960.5-1860	ZrAg 1135*	Zr_2Ag? ~ 1400	Zr_3Ag? 1250*		Tetr.		Tetr.
Al-As	660	AlAs > 1600						
Al-Au	660-1063	$AuAl_2$ 1060	Others < 1000			Cubic		
Al-Ba	660-715	$BaAl_4$ ~ 1050	Others < 1000			Tetr. b.c.		
Al-Ca	660-816	$CaAl_2$ 1079				Tetr. b.c.		
Al-Ce	660-804	$CeAl_4$ 1250*	$CeAl_2$ 1465	Others < 1000		Tetr. b.c.	f.c.c.	
Al-Co	660-1495	Co_2Al_5 1170*	CoAl 1645	Others < 1000		Hex.	b.c.c.	
Al-Cr	660-1890	Cr_4Al_9 1170*	Cr_5Al_8 1350*	Others > 1000*		b.c.c.	Rhbdr.	
Al-Fe	660-1534	Fe_2Al_5 1173	Others 1000*			monocl		
Al-La	660-812	$LaAl_4$ 1222*	$LaAl_2$ 1424	Others < 1000		Tetr.	f.c.c.	
Al-Mn	660-1245	MnAl 1160*	Others < 1000*				b.c.c.	
Al-Mo	660-2620	Mo_3Al ~ 2150	Others? < 1000					

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Al-Ni	660-1453	Ni_2Al_3 1133*	NiAl 1638	Ni_3Al 1385	Table 3.4	b.c.c.	b.c.c.	f.c.c.
Al-Pd	660-1558	PdAl 1645	Pd_2Al 1430	Others < 1000*		b.c.c.		
Al-Pr	660-932	$PrAl_4$ 1244*	$PrAl_2$ 1442	Others < 1000*			cubic	
Al-Sb	660-6305	AlSb ~1065				cubic		
Al-Ti	660-1720	TiAl 1460	$TiAl_3$ 1340*		Table 3.4	Tetr f.c.	Tetr	
Al-U	660-1150	UAl_4 730*	UAl_3 1350*	UAl_2 ~1590		Rhomb b.c.	f.c.c.	f.c.c.
Al-V	660-1870	VAl_6 or Al_5 ~1210*	VAl_3 ~1370*	V_5Al_8 1670*		cubic	Tetr	b.c.c.
Al-Zr	660-1852	Zr_4Al_3 1530	$ZrAl_2$ 1645	$ZrAl_3$ 1580			Rhomb	Tetr
As-Co	-1495	Co_3As_2 1014*	CoAs 1180	Others 1000			Rhomb	
As-Fe	-1528	Fe_2As 919	Fe_3As_2? 1004*	FeAs 1030		Tetr		Rhomb
As-Mn	-1245	Mn_3As 940*	Mn_2As 1029	MnAs 935			Tetr	Hex
As-Pt	-1769	Pt_2As_3? ~1450	$PrAs_2$ ~1400					
As-Si	-1415	SiAs 1083	$SiAs_2$ 944*					
As-Zn	-817	Zn_3As_2 1015	$ZnAs_2$ 771			Tetr	Rhomb	
Au-Ca	1063-845	CaAu? 1015*	Other ~1000					

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Au-Ce	1063-780	$CeAu_3$ 1150	$CeAu_2$ 1130	CeAu $\sim$1320				
Au-La	1063-812	$LaAu_3$ 1204	$LaAu_2$ 1214	LaAu 1360				
Au-Mg	1063-649	MgAu 1150*	Others $<$1000			Cubic		
Au-Mn	1063-1244	Mn_3Au 1095*	MnAu 1260*	Others 1000	Table 3.4	Tetr		
Au-Pr	1063-950	$PrAu_3$ $\sim$1135	$PrAu_2$ $\sim$1205	PrAu $\sim$1350				
Au-Th	1063-1845	$ThAu_3$ $\sim$1460	Th_3Au_5 $\sim$1450	Th_2Au ?				Tetr
Au-Ti	1063-1800	$TiAu_6$ 1190*	$TiAu_2$ 1480	Others 1000		f.c. Tetr	f.c. Tetr	
Au-U	1063-1133	U_2Au_3 1216*	UAu_3 $>$1450					
Au-Zr	1063-1857	$ZrAu_3$ $\sim$1560	Diagram Incomplete					
B-Ce	-804	CeB_6 Not Reported	CeB_4 Not Reported					
B-Co	-1495	Co_2B 1265				Tetr b.c.		
B-Cr	-1890	CrB $\sim$1550	CrB_2 $\sim$1850	Others $>$1000	Table 3.4	Rhomb	Hex	
B-Fe	-1534	Fe_2B 1389	FeB $\sim$1550			Tetr b.c.	Rhomb	
B-Hf	-1700	H_fB	H_fB_2 $\sim$3250		Table 3.4	f.c.c.	Hex	
B-Mn	-1244	Mn_2B	MnB	Others				

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
B-Mo	-2620	Mo_2B ~2070*	MoB ~2180*	Others >1000*	Table 3.4	Tetr	Tetr	
B-Nb	-2500	NbB	Nb_3B?	Nb_2B ~2800	Table 3.4	Rhomb	Rhomb	Hex
B-Ni	-1453	Ni_2B ~1220	Ni_3B_2 ~1160	NiB ~1020		Tetr b.c.	?	Rhomb
B-Pt	-1769	Pt_3B_2?	PtB?					
B-Rh	-1966	Rh_2B	RhB	Rh_2B		Rhomb		
B-Ru	-2450	Ru_2B_3	RuB	and others			Cubic	
B-Ta	-2996	TaB_2 >3000	TaB >1000	Others >1000	Table 3.4	Hex	Rhomb	
B-Th	-1845	ThB_6	ThB_4 >2500*					f.c.c.
B-Ti	-1760	Ti_2B 1800*	TiB 2060*	TiB_2 2790	Table 3.5	Tetr	Rhomb	Hex
B-U	-1133	UB_2 ~1132	UB_4 ~1565	UB_{12}		Hex	Tetr	f.c.c.
B-V	-1870	VB ~1780	VB_2 ~2100		Table 3.4	Rhomb	Hex	
B-W	-3370	WB ~2860	W_2B ~2770	W_2B_5 ~2980	Table 3.4	Tetr	Tetr	Hex
B-Zr	-1857	ZrB ~1250	ZrB_2 ~3040	ZrB_{12} ~2680	Table 3.5	f.c.c.	Hex	f.c.c.
					Table 3.4			
Ba-S	676-	BaS >2000	BaS_3	Others		Cubic	Rhomb	
Be-C	1280-3550	Be_2C 2400				Cubic		
Be-Co	1280-149[illegible]	BeCo [illegible]	$Be_{12}Co_5$			Cubic		

TABLE 3.1 (Continued)

System	M.P.°C	M.P.°C Compounds			Resistivity References	Crystal Structures		
(A) (B)	(A) (B)	(1)	(2)	(3)		(1)	(2)	(3)
Be-Cr	1280-1845	Be_2Cr ~1840				Hex		
Be-Cu	1280-1083	Be_3Cu 1239*				f.c.c.		
Be-Fe	1280-1539	Be_2Fe 1480*	Be_5Fe 1375*	$Be_{11}Fe$? 1225*		Hex	Cubic	Hex
Be-Ir	1280-2454	Be_2Ir						
Be-Mn	1280-1245	Be_2Mn				Hex		
Be-Mo	1280-2620	$BE_{12}Mo$	Be_2Mo ~1870			Tetr b.c.		
Be-N	1280-	Be_3N_2 ~2200				Cubic		
Be-Ni	1280-1452	BeNi 1472	$Be_{21}Ni_5$ 1264			Cubic	Cubic	
Be-Np	1280-640	$Be_{13}Np$ >1400				f.c.c.		
Be-O	1280-	BeO ~2500						
Be-Os	1280-2700	Be_2Os						
Be-Pd	1280-1552	$BePd_2$ 1090*	BePd 1465	Others >1000*			Cubic	
Be-Pt	1280-1773	Pt_5-Be_{21}				?		
Be-Pu	1280- ?	$Be_{13}Pu$ ~1690				Cubic		
Be-Re	1280-3167	Be_2Re				Hex		
Be-Rh	1280-1966	Be_2Rh				?		
Be-Ru	1280-2540	Be_2Ru						
Be-Th	1280-1845	$Be_{13}Th$ ~1215				Cubic		

TABLE 3.1 (Continued)

System	M.P.°C	M.P.°C Compounds			Resistivity References	Crystal Structures		
(A) (B)	(A) (B)	(1)	(2)	(3)		(1)	(2)	(3)
Be-Ti	660-1720	Be_2Ti	BeTi	Others		f.c.c.	?	
Be-U	1280-1133	$Be_{13}U$ ~2000				Cubic		
Be-V	1280-1870	Be_2V >1650				Hex		
Be-W	1280-3370	B_2W	$Be_{13}W$			Hex	Tetr	
Be-Zr	1280-1850	$Be_{13}Zr$ ~1800	Be_7Zr ~1790	Others >1000		Cubic		
Bi-Ca	271-816	Ca_3Bi_2? >1200	$CaBi_3$ 507*					
Bi-Ce	271-830	Ce_3Bi 1400*	Ce_4Bi_3 ~1630	CeBi ~1525*				Cubic
Bi-Ir	271-2454	IrBi 1420	Ir_2Bi 1440					
Bi-Li	271-186	Li_3Bi 1145	LiBi 400*		2	Cubic	Tetr	
Bi-Mn	271-1245	MnBi ~1043*				Hex		
Bi-Pt	271-1245	PtBi	$PtBi_2$	$PtBi_3$?		Hex	Cubic	
Bi-Th	271-1700	Th_2Bi 1800	Th_3Bi_5 ~1350					
Bi-U	271-1133	UBi_2 1010*	U_3B_4 ~1150*	UBi >1400*		Tetr	Cubic	Cubic
C-Cr	3550-1930	$Cr_{23}C_6$ 1518*	Cr_7C_3 1782*	Cr_3C_2 1900*	Table 3.4	f.c.c.	Hex	f.c.c.
C-Fe	3550-1534	Fe_3C ~1130*						
C-Hf	3550-1700	HfC ~3890?			Table 3.4	f.c.c.		
C-La	3550-812	LaC_2				Tetr		
C-Mn	3550-1245	$Mn_{23}C_6$ ~1010*	Mn_7C_3 1340*			Cubic	Hex	

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	 (2)	 (3)	Resistivity References	Crystal Structures (1)	 (2)	 (3)
C-Mo	3550-2620	$\underline{Mo_2C}$ ~2400*	MoC 2650		Table 3.4	f.c.c.	Hex	
C-Nb	3550-2500	$\underline{\underline{NbC}}$ >3700	Nb_2C		Table 3.5	f.c.c.	Hex	
C-Si	3550-1430	$\underline{SiC}$ ~2700			Table 3.4	Hex or Cubic		
C-Ta	3550-2996	Ta_2C ~3400*	$\underline{\underline{TaC}}$ 3800		Table 3.5	Hex	f.c.c.	
C-Th	3550-1845	ThC ~2625	ThC_2 ~2660			Cubic	Rhomb	
C-Ti	3550-1720	$\underline{\underline{TiC}}$ 3250			Table 3.5	f.c.c.		
C-U	3550-1133	UC 2390	U_2C_3 1775*	UC_2 >2500*		f.c.c.	b.c.c.	Tetr b.c.
C-V	3550-1900	V_2C ~1650*	$\underline{\underline{VC}}$ >2800		Table 3.5	Hex C.P.	f.c.c.	
C-W	3550-3370	$\underline{W_2C}$ ~2750	WC ~2600*		Table 3.4	f.c.c. or Hex	Hex	
C-Zr	3550-1857	$\underline{ZrC}$ >3200			Table 3.4	f.c.c.		
Ca-N	816-	Ca_3N_2 ~1195				Hex		
Ca-Pb	816-327.3	Ca_2Pb ~1110	CaPb ~950	$CaPb_3$ ~660	3			Tetr
Ca-Si	816-1430	Ca_2Si 910*	CaSi ~1245	$CaSi_2$ 1020		f.c.c.	Rhomb	Rhomb
Ca-Sn	816-232	Ca_2Sn ~1120	CaSn 987	$CaSn_3$ 627		Tetr	Rhomb	Tetr
Ce-Co	780-1495	$CeCo_5$ 1205*	$CeCo_2$ 1035*	Others >1000*		Hex	f.c.c.	

TABLE 3.1 (Continued)

System (A)	System (B)	M.P. °C (A)	M.P. °C (B)	M.P. °C Compounds (1)	M.P. °C Compounds (2)	M.P. °C Compounds (3)	Resistivity References	Crystal Structures (1)	Crystal Structures (2)	Crystal Structures (3)
Ce	Fe	775	1528	$CeFe_5$ 1060*	$CeFe_2$ 773*			Hex	f.c.c.	
Ce	In	800	156	CeIn 1160	$CeIn_3$ 1215	Others >1000			f.c.c.	
Ce	Ni	780	1453	$CeNi_5$ 1315	$CeNi_3$ 1065*	Others >1000*		Hex		
Ce	Pb	777	327	Ce_2Pb ~1380	CePb ?	$CePb_3$ 1170			b.c.c.	Tetr
Ce	Pt	780	1773	$CePt_2$				f.c.c.		
Ce	Si	780	1430	$CeSi_2$ 1440	Others >1000					
Ce	Sn	830	232	Ce_2Sn 1400	Ce_2Sn_3 1165	$CeSn_3$ 1162		Tetr		
Ce	Tl	775	302	$CeTl_3$ 1080	CeTi 1240	Ce_2Tl 945*				
Co	Ge	1495	958	Co_2Ge 1200	Others <1000*			Rhomb b.c.		
Co	Mo	1495	2620	MoCo 1020*	Mo_6Co_7 ~1450*			Hex C.P.	Rhomb	
Co	Na	1495	97.5	$NbCo_2$ ~1500	Nb_2Co_5? ~1550			Cubic or Hex		
Co	O	1495		CoO >1810	Co_3O_4 900*			f.c.c.		
Co	P	1495	41.1	Co_2P 1386	CoP	CoP_3		Rhomb	Rhomb	Tetr
Co	Pu	1495	640	Pu_6Co	Pu_2Co	Others		Tetr b.c.	Hex	
Co	S	1495	120	CoS 1182	CoS_2 ?	Other <1000		Hex	Rhomb	
Co	Sb	1495	630.5	CoSb ~1195	$CoSb_2$ ~902*	$CoSb_3$ ~770*		Hex	Rhomb or Cubic	

TABLE 3.1 (Continued)

System	M.P. °C	M.P. °C Compounds			Resistivity References	Crystal Structures		
(A) (B)	(A) (B)	(1)	(2)	(3)		(1)	(2)	(3)
Co-Se	1495-220	CoSe	$CoSe_2$			Hex	Rhomb or Cubic	
Co-Si	1495-1430	Co_2Si 1332	CoSi 1460	$CoSi_2$ 1326		Rhomb	Cubic	Cubic
Co-Sn	1495-232	Co_2Sn ~1170	CoSn ~936*	$CoSn_2$ ~525*		Hex	Hex	Tetr
Co-Ta	1495-2996	$TaCo_2$ 1593*				Cubic or Hex		
Co-Te	1495-452	CoTe	$CoTe_2$			Hex	Hex	
Co-Th	1495-1845	$ThCo_5$	ThCo	Th_7Co_3		Hex	Rhomb	Hex
Co-Ti	1495-1720	$TiCo_2$ ~1250*	TiCo	Ti_2Co?			b.c.c.	
Co-U	1495-1133	UCo_2 1770	UCo 805*	U_6Co 826*		f.c.c.	b.c.c.	Tetr b.c.
Co-V	1495-1870	VCo_3 1070	VCo ~1240*	V_3Co ~1125*				
Co-W	1495-3370	WCo_3 ~1480*	W_6Co_7 ~1630*			Hex	Rhomb	
Co-Zr	1495-1857	$ZrCo_4$?	$ZrCo_2$ 1560				f.c.c.	
Cr-Ge	1830-936	CrGe	Cr_3Ge	Cr_3Ge_2		Tetr	Tetr	Tetr
Cr-Mn	1830-1245	$CrMn_2$? ~600*	$CrMn_3$ 1310*					
Cr-Nb	1830-2500	$NbCr_2$ >1900*				Cubic		
Cr-O	1850-	Cr_3O_4? ~2100*				Rhomb		
Cr-Os	1850-2700	Cr_3Os	Cr_2Os			Cubic	Tetr	
Cr-P	1860-41.1	Cr_3P 1510*	Cr_2P? ~1650	CrP ?		Tetr	?	Rhomb

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Cr-Pd	1890-1554	Cr_3Pd_2? 1398			4	f.c.c.		
Cr-Pt	1860-1773	Cr_3Pt >1500	CrPt?			?		
Cr-S	1850-120	CrS ~1565	Cr_3S_4	Cr_2S_3	5	Hex		
Cr-Sb	1880-630	CrSb 1110	$CrSb_2$ 676*			Hex	Rhomb	
Cr-Se	1880-220	CrSe	Cr_2Se_3			Hex		
Cr-Si	1880-1430	Cr_3Si ~1730	CrSi ~1600	Others ~1500	6 Table 3.4 for $CrSi_2$	Cubic	Cubic	
Cr-Ta	1840-2996	$TaCr_2$ ~1940*				Hex		
Cr-Ti	1880-1720	$TiCr_2$? 1350*				f.c.c.		
Cr-Zr	1850-1960	$ZrCr_2$ ~1675				Hex or Cubic		
Cu-N	1083-	Cu_3N				Cubic		
Cu-O	1083-	Cu_2O 1230*				Cubic		
Cu-P	1083-	Cu_3P 1020			7,8	Hex		
Cu-Pu	1083-640	PuCu	$PuCu_3$	$PuCu_7$				
Cu-S	1083-120	Cu_2S 1129	Cu_6S_5 ?	Other 1000		Hex	Cubic	
Cu-Se	1083-220	Cu_2Se ~1120			8	Cubic		
Cu-Te	1083-453	Cu_2Te 1125	Cu_4Te_3 727*	CuTe 367*		f.c.c.	Tetr	Rhomb

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Cu-Th	1083-1845	$ThCu_6$ 1062	$ThCu_4$ 1062	Others < 1000				
Cu-U	1083-1133	UCu_5 1050				f.c.c.		
Cu-Zr	1083-1857	$ZrCu_3$ ~1115	Zr_2Cu ~1000	Others < 1000			Tetr f.c.	
Fe-Ge	1534-943	Fe_2Ge 1180*	$FeGe_2$ 866*				Hex	
Fe-Hf	1534-1700	$HfFe_2$ ~1650				f.c.c.		
Fe-Nb	1534-2500	$NbFe_2$ 1655				Hex		
Fe-O	1534	Fe_3O_4 1597	Fe_2O_3 1457*			f.c.c.	Rhomb	
Fe-P	1534-41.1	Fe_3P 1166*	Fe_2P 1365	Others > 1000		Tetr b.c.	Hex	
Fe-Pu	1534-640	$PuFe_2$ 1230	Pu_6Fe 410			f.c.c.	Tetr b.c.	
Fe-Re	1534-3440	Re_2Fe_3 > 1550						
Fe-S	1534-120	FeS 1190	FeS_2 ?*			Hex	Cubic or Rhomb	
Fe-Si	1528-1430	Fe_5Si_3 1030*	FeSi 1410	FeSi 1220*	9	Hex	Cubic	
Fe-Ta	1528-2996	$TaFe_2$ 1775				Hex		
Fe-Th	1528-1845	Th_7Fe_3 ~1000	$ThFe_3$	$ThFe_5$		Hex	Hex	
Fe-Ti	1528-1800	$TiFe_2$ 1530	TiFe 1317*	Ti_2Fe? 1085*		Hex	b.c.c.	f.c.c.
Fe-U	1528-1133	UFe_2 1235	U_6Fe ~810*			f.c.c.		

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	 (2)	 (3)	Resistivity References	Crystal Structures (1)	 (2)	 (3)
Fe-W	1528-3370	WFe_2 1040*	W_2Fe_3 1640*	W_6Fe_7		Hex	Hex	
Fe-Zr	1528-1860	$ZrFe_2$ ~1610				f.c.c.		
Ga-Ni	29.8-1453	Ni_2Ga 1211*	Ni_3Ga_2 1220	Others <1000			Hex	
Ga-Pd	29.8-1552	PdGa	Pd_2Ga	Pd_3Ga		Cubic	Rhomb	Cubic
Ga-Pr	29.8-911	PrGa 1044*	$PrGa_2$ 1470	Others <1000*			Hex	
Ga-Pt	29.8-1776	PtGa	$PtGa_2$	Pt_2Ga_3		Cubic	Cubic	Rhomb
Ga-U	29.8-1133	UGa_2?	UGa_3 ~1300				Cubic	
Ge-Mg	936-650	Mg_2Ge 1115				Cubic		
Ge-Ni	936-1453	Ni_3Ge 1200	NiGe 850*			Cubic	Rhomb	
Ge-Ti	936-1720	Ti_5Ge_3	$TiGe_2$					
Ge-U	936-1133	UGe_3 ~1200				Cubic		
Ge-V	936-1710	VGe_3						
Ge-Zr	948-1845	Z_2Ge 1585*	Zr_2Ge ~2275	$ZrGe_2$? 1420*		Hex	Tetr	Tetr
Hf-Mo	1534-2620	$HfMo_2$ >2300				Cubic		
Hf-Si	1534-1430	HfSi	$HfSi_2$			Hex	Rhomb	
Hf-V	1534-1710	HfV_2 >1500				f.c.c.		
In-S	156-120	In_3S_4 840*	In_2S_3 1098	Others <1000		f.c.c.		

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
In-U	156-1133	UIn_3				f.c.c.		
Ir-U	1454-1133	UIr_2				f.c.c.		
Ir-Zr	2454-2230	$ZrIr_2$				Cubic		
La-Ni	812-1453	$LaNi_5$ 1325	$LaNi_4$? 1095*	$LaNi_3$? 975*		Hex	f.c.c.	
La-Pb	812-327	La_2Pb ~1315	LaPb ~1246	$LaPb_3$ ~1030				Cubic
La-Sb	812-630	La_2Sb ~1460*	La_3Sb_2 ~1690*	Others >1000*				
La-Sn	812-232	La_2Sn 1420	La_2Sn_3 1187	$LaSn_3$ 1135				Cubic
La-Tl	812-302	La_2Tl ~1260?	LaTl ~1180	$LaTl_3$ 1096				
Mg-Ni	650-1453	Mg_2Ni 760*	$MgNi_2$ 1145			Hex	Cubic	
Mg-Sb	650-630	Mg_3Sb_2 1228				f.c.c.		
Mg-Si	650-1430	Mg_2Si 1120				Cubic		
Mn-P	1245-41.1	Mn_3P 1105*	Mn_2P 1327	MnP 1147		Tetr b.c.	Hex	
Mn-Pu	1245-640	$PuMn_2$ 1050				f.c.c.		
Mn-S	1245-120	MnS ~1610				Cubic		
Mn-Si	1225-1458	Mn_5Si_3 1285	MnSi 1275			Hex	Cubic	

TABLE 3.1 (Continued)

System (A) (B)	M.P.°C (A) (B)	M.P.°C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Mn-Ti	1245-1660	TiMn? 1175*	$TiMn_2$ 1330			Tetr	Hex	
Mn-U	1245-1132	UMn_2 1120	U_6Mn 745*			f.c.c.	Tetr b.c.	
Mn-Zr	1245-2230	$ZrMn_2$				Hex		
Mo-Ni	2620-1453	MoNi $\sim$1350*	Others $<$1000*		10			
Mo-Si	2620-1430	Mo_3Si $\sim$2120	Mo_3Si_2 2190	$MoSi_2$ 2020	Table 3.5	Cubic		Hex
Mo-Zr	2629-1880	$ZrMo_2$ $\sim$1880*				f.c.c.		
N-Ti	-1660	TiN $\sim$2950			Table 3.5	f.c.c.		
N-Zr	-1880	ZeN $\sim$2980			Table 3.5			
Nb-Ni	2500-1452	$NbNi_3$ 1403	NbNi? 1280*			Hex C.P.		
Nb-Si	2420-1430	Nb_5Si_3 2480	$NbSi_2$ 1930		Table 3.4	Tetr	Hex	
Ni-P	1452-41.1	Ni_3P 1025*	Ni_5P_2 1175	Others				
Ni-Pr	1453-930	$PrNi_5$ $\sim$1365	$PrNi_4$ $\sim$1100*	Other $<$1000		Hex		
Ni-Pu	1453-640	$PuNi_4$ 1225*	$PuNi_5$ $\sim$1420	Pu_2N_{17} 1220*			Hex	Hex
Ni-Sb	1453-630	Ni_3Sb 1097	NiSb 1153	Others $>$ 1000	11	Hex	Hex	

TABLE 3.1 (Continued)

System (A) (B)	M.P. °C (A) (B)	M.P. °C Compounds (1)	 (2)	 (3)	Resistivity References	Crystal Structures (1)	 (2)	 (3)
Ni-Si	1453-1430	Ni_3Si 1165*	Ni_5Si_2 1282	Ni_2Si 1318	Table 3.4	f.c.c.	Hex	Rhomb
Ni-Sn	1453-232	Ni_3Sn 1174	Ni_3Sn_2 1264	Ni_3Sn_4 795*		Hex	Hex	Monocl
Ni-Ta	1453-2996	$TaNi_3$ 1545	$TaNi_2$? 1580*			Hex		
Ni-Th	1453-1845	$ThNi_5$ 1530	ThNi 1200	Others $>$1000		Hex	Rhomb	
Ni-Ti	1453-1720	Ti_2Ni 1015*	TiNi 1240	$TiNi_3$ 1378	12,13	f.c.c.	b.c.c.	Hex
Ni-U	1453-1133	UNi_2 985*	UNi_5 1305	Others $<$1000		Hex	f.c.c.	
Ni-V	1453-1900	VNi_3 1045*	VNi_2 920*	V_3Ni?		Tetr	Monocl	Cubic
Ni-W	1453-3370	WNi_4 $\sim$1510*				Tetr b.c.		
Ni-Zr	1453-1860	Zr_2Ni $\sim$1200	ZrNi $\sim$1470	$ZrNi_3$ $\sim$1600	14			
O-Sn	-232	SnO $\sim$1700*	Sn_3O_4 $\sim$1150*			Tetr	Tetr	
O-Ta	-2996	TaO	Ta_2O_5		15	f.c.c.	Rhomb	
O-Ti	-1720	Ti_2O_3 $\sim$1900	TiO 1770*	Others?		b.c.c.	f.c.c.	
O-V	-1900	VO $\sim$1920*			16,17			
O-W	-3370	WO_2	WO_3	Others		Monocl	Tricl	

TABLE 3.1 (Continued)

System	M.P. °C	M.P. °C Compounds			Resistivity	Crystal Structures		
(A) (B)	(A) (B)	(1)	(2)	(3)	References	(1)	(2)	(3)
O-Zr	-1852	ZrO_2 2700	ZrO			Monocl		
Os-Pu	2700-640	Pu_3Os 680*	Pu_5Os_3 1010*	$PuOs_2$ 1500				Hex
Os-Si	2700-1430	OS_2Si_3	$OsSi_2$			Tetr		
Os-Ti	2700-1720	TiOs	$TiOs_2$	$TiOs_3$		b.c.c.		
Os-U	2700-1133	UOs_2				f.c.c.		
Os-W	2700-3370	W_3Os						
Os-Zr	2700-1880	$ZrOs_2$				Hex		
P-Pd	41.1-1549	Pd_3P 1047	PdP_2 ~1150	Others < 1000*				
P-Pt	41.1-1769	PtP_2 ?						
P-Pu	41.1-635	PPu > 2000				f.c.c.		
P-Rh	41.1-1966	Rh_2P > 1500	Rh_5P_4 ?	RhP_2 ?				
P-Th	41.1-1845	Th_3P	ThP			b.c.c.	f.c.c.	
P-U	41.1-1133	UP	U_3P_4	Up_2		f.c.c.	Cubic	Tetr
P-V	41.1-1900	VP_2	VP				f.c.c.	
Pb-Pd	327-1541	Pd_3Pb 1220	Pd_3Pb_2 830*	Others < 1000*	18	Cubic	f.c.c.	
Pb-Pr	327-890	$PrPb_3$ ~1115	PrPb ~1185	Pr_2Pb ~1315		f.c.c.		
Pb-S	327-120	PbS 1103				f.c.c.		

TABLE 3.1 (Continued)

System	M.P. °C	M.P. °C Compounds			Resistivity	Crystal Structures		
(A) (B)	(A) (B)	(1)	(2)	(3)	References	(1)	(2)	(3)
Pb-Se	327-220	PbSe 1088				f.c.c.		
Pb-Ti	327-1665	Ti_4Pb 1305*	Ti_2Pb? ~1240					
Pb-U	327-1133	UPb_3 ~1220	UPb 1210*		19	f.c.c.	Tetr	
Pd-Sb	1549-630	Pd_3Sb ~1200	Others <1000					
Pd-Si	1552-1430	Pd_2Si 1250	PdSi ~1100			Hex	Rhomb	
Pd-U	1552-1133	UPd 1047*	U_5Pd_6 1110*	UPd_3 ~1640				Hex
Pr-Sn	890-232	Pr_2Sn ~1415	Pr_2Sn_3 ~1165	$PrSn_3$ ~1145				f.c.c.
Pr-Tl	890-302	Pr_2Tl ~980*	PrTl ~1150	$PrTl_3$ ~1050				
Pt-Sb	1769-630	PtSb 1045*	$PtSb_2$ 1226	Pt_4Sb 753*		Hex		
Pt-Si	1769-1412	Pt_5Si_2 986*	Pt_5Si_2 1100	PtSi 1229			Tetr	Rhomb
Pt-Sn	1773-232	Pt_3Sn ~1365	PtSn ~1305	Others <1000*		f.c.c.	Hex	
Pt-Ti	1769-1665	$TiPt_3$	Ti_2Pt_3	Others		Cubic		
Pt-U	1769-1133	UPt_3	UPt_2					
Re-Ti	3167-1665	Ti_5Re_{24} ~1700				Cubic		
S-V	120-1900	VS >1600				Hex		
Sb-Zr	630-1830	Zr_2Sb ~1900				Hex		

TABLE 3.1 (Continued)

System (A) (B)	M.P.°C (A) (B)	M.P.°C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Se-Th	220-1800	ThSe 1880	Others >1000			f.c.c.		
Si-Ta	1405-2996	$TaSi_2$ $\sim$2200	Ta_2Si $\sim$2475	Ta_5Si_3 $\sim$2500	Table 3.4	Hex	Tetr	Tetr
Si-Th	1430-1800	$ThSi_2$ $\sim$1600	ThSi >1450			Hex	Rhomb	
Si-Ti	1430-1665	Ti_5Si_3 2120	TiSi 1760*	$TiSi_2$ 1540	20 Table 3.5	Hex	Rhomb	Rhomb
Si-U	1430-1133	USi_2 $\sim$1700	U_3Si_2 $\sim$1665	Others	Table 3.5 U_3Si	Hex	Tetr	
Si-V	1430-1900	V_3Si $\sim$2050	V_5Si_3 $\sim$2150	VSi_2 1750	Table 3.4	Cubic	Hex	Hex
Si-W	1430-3370	W_3Si_2 $\sim$2350	WSi_2 $\sim$2165		Table 3.4	Tetr	Tetr	
Si-Zr	1430-1852	Zr_5Si_3 $\sim$2200	Zr_6Si_5 2250	Others >1000	Table 3.4 for $ZrSi_2$	Hex		
Sn-Ti	232-1720	Ti_3Sn 1663	Ti_2Sn 1552*	Others >1000		Hex	Hex	
Sn-U	232-1133	U_5Sn_4? $\sim$1500	U_3Sn_5? 1375*	USn_3 1350*				Cubic
Sn-Zr	232-1830	Zr_3Sn_2? 1985	$ZrSn_2$ 1140*	Zr_4Sn 1590*			Rhomb	
Ta-Zr	2996-1830	Compounds not determined						
Te-U	453-1133	UTe_2	U_3Te_4	UTe		Tetr		Cubic

TABLE 3.1 (Continued)

System (A) (B)	M.P.°C (A) (B)	M.P.°C Compounds (1)	(2)	(3)	Resistivity References	Crystal Structures (1)	(2)	(3)
Te-W	453-3370	WTe_2						
Te-Yb	453-1800	YbTe				f.c.c.		
U-Zn	1133-419	UZn_9 ~1050				Hex		
V-Zr	1900-1860	ZrV_2 1300*			21	Hex		
W-Zr	3410-1860	ZrW_2 2150*				Cubic		
Zn-Zr	419-1860	$ZrZn_2$?						

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TABLE 3.2

RESISTIVITY AT 20°C OF SUPERCONDUCTING COMPOUNDS

Compound	P20°C - Microhm-cm	Reference - Phys. Rev 115, 90, 1953 and
TiC	125 to 156	Table 3.5 (5)
VC	150	Table 3.5 (7)
ZrC	63.4	Table 3.5 (8)
TaC	30 to 100.	Table 3.5 (4)
WC	12 to 53.	Table 3.4 (2)
Zr B_2	9.2 to 34.8	Table 3.5 (6)
Nb B_2	32.	Table 3.5 (3)
Ta B_2	68.	Table 3.5 (4)
WB	86.	Table 3.4 (6)
αMoB	45 to 50	Table 3.4 (5)
Ti B_2	15.2 to 16.2	Table 3.5 (5)
Th B_2	———	
La N	———	
Ce N	———	
Nb N	65.	Table 3.5 (3)
La $H_{2.45}$	———	———

TABLE 3.3

SELECTED METALLIC COMPOUNDS FOR ELECTRICAL CONDUCTORS AT ELEVATED TEMPERATURES HAVING RESISTIVITY DATA (COMPOSITION, M.P., RESISTIVITY AT 20°C AND T_m°C, TEMPERATURE COEFFICIENT OF RESISTIVITY, OXIDATION RESISTANCE, CRYSTAL STRUCTURE)

Compound with Composition (Nominal, Wt.%)	Melting Point (°C)	ρ, Resistivity, (Microhm-cm), at Temperature		Temperature Coefficient of Resistivity, (α) = °C^{-1}	Upper Temperature Limit for Resistance to Oxidation	Crystal Structure	Remarks	Reference
		20°C	T_n °C					
CrB2	1850	21		1.10×10^{-3} (0° to 100°C)	(1200 to 1300°C)	Hexagonal		
-29.38-B								
HfB_2	3240	10			Probably equivalent to ZrB_2;	Hexagonal	80% Theoretical Density	
-10.81-B		12				Hexagonal	---	
NiAL	1640	22			(1000 to 1095°C)	B.C.C.		
-31.43-Al								
$MoSi_2$								
-34.79-Si (actual)	1870 to 2020	22.62	215 at 1200°C	6.52×10^{-3}; (0° to 200°C)	(1650 - 1700°C)	Tetragonal		
---	Same	21.8	---	---	Same	Same		
-36.92-Si(theoretical)								
$NbSi_2$	1930	6.3			(800° to 1000°C)	Hexagonal	---	
-37.68-Si								
TaC	3540 to 3880	30	---	---	(1000 to 1100)	F.C.C. Lattice (NaCl Type)		
-6.23-C	Same	100	129. at 1307°C	2.1795×10^{-4} (20° to 1167°C)	(1000 to 1100)	Same		
$TaSi_2$	1930	6.3	---	---	(800 to 1000°C)	Hexagonal	---	
-37.68-Si								

TABLE 3.3 (Continued)

Compound with Composition- (Nominal, Wt. %)	Melting Point (°C)	ρ, Resistivity (Microhm-cm) At Temperature		Temperature Coefficient of Resistivity = °C^{-1}	Upper Temperature Limit for Resistance to Oxidation	Crystal Structure	Remarks	Reference
		20°C	Tn (C°)					
TiB_2	2920	16.23	107.8 at 1200°C	9.085 x 10^{-3}; (20° to 200°C)	(1100° to 1300°C)	Simple Hexagonal		
-31.12-B	Same	15.2	---	---	Same	Same		
TiN								
-22.62-N	2940	16.5	56.5 at 700°C	3.70 x 10^{-3}; (20° to 200°C)		F.C.C. Lattice (NaCl Type)	2 mm. dia. wire	
Same	Same	27.7	---	---	---	Same		
Same	Same	11.1	---	27 x 10^{-4} (0° to 100°C) 32 x 10^{-4} (20° to 200°C)		Same		
$TiSi_2$	1540	15.75	87.78 at 700°C	6.47 x 10^{-3} (20° to 200°C)	(900° to 1100°C)	Orthorhombic		
-53.98-Si	Same	16.7	---	---	Same	Same		
VB_2	2100.	16	---	---	(800° to 1000°C)	Hexagonal		
-29.81-B								
VSi_2	1750	10.3	---	---		Hexagonal		
-52.44-Si	Same	9.5	---	---		Same		
ZrB_2	3040	9.2	---	---	(1000° to 1100°C)	Simple Hexagonal	Without Binder	
-19.17-B	Same	13.	149.7 at 700°C 210. at 1000°C	1.5463 x 10^{-3} (20° to 1000°C)	Same	Same	2-1/2% Binder Added. (Boron)	
Same	Same	25. at 0°C	201.5 at 1200°C	7.196 x 10^{-3} (0° to 200°C)	Same	Same	Borolite Grade G; 4-1/2% Binder (Boron)	
ZrN	2980	13.5	---	---	(100° to 1200°C)	F.C.C.; (NaCl Type)		
-13.27-N		11.5	---					

TABLE 3.4

BASIC DATA - METALLIC COMPOUNDS (COMPOSITION, CRYSTAL STRUCTURE, OXIDATION RESISTANCE, M.P., RESISTIVITY (20°C) AND TEMPERATURE COEFFICIENT OF RESISTIVITY)

Metallic Compound	Nominal Composition [Wt. %]	Trade Name and/ or Designation- and Oxidation Resistance	Crystallography		Remarks		M.P. (°C)	Temperature (°C)	Resistivity (ρ) (microhm-cm)	Temperature Coefficient of Resistivity (α)	Reference, Number and Page
			System	Structure Type	Upper limit of Resistance to Oxidation in Air (°C); Ref. (14)	Others					
		Carbides									
TiC	20.05 C Bal. Ti.	Titanium	f.c.c.	Bl. (NaCl)	(1100 - 1200)	data above 20°C; per Ref. (2); p. 157	3160 to 3250	20 20 20 143 481 723	59.5 157 68 162 170 170	+ 3×10^{-4} - to 44×10^{-4}	(14); 91 (2); 157 (15); 4 (41); 170 (24); 383 (41); 170
ZrC	11.63 C Bal. Zr.	Zirconium	f.c.c.	Bl.	1100 - 1200		3175	20	63.4 60-75 63	$+12 \times 10^{-4}$ to $+30 \times 10^{-4}$	(14); 91 (15); 4 (24); 393
HfC	6.30 C Bal. Hf.	Hafnium	Cubic f.c.c.	Bl.	1100 - 1200		3890	20	109		(41); 170 (24); 365 (14); 91
VC	19.08 C Bal. V.	Vanadium	f.c.c.	NaCl- (B1); Type 4	800 - 900		2830	20 20	150 156	$+5 \times 10^{-4}$ (20°-200°C)	(41); 170 (15); 4 (14); 365
NbC	11.45 C Bal. Nb	Niobium	Cubic f.c.c.	Bl. (NaCl)	1000 - 1100		3500	20	74 74-175 74	$+1.6 \times 10^{-4}$	(41); 170 (15); 4 (14); 91
TaC	6.23 C Bal. Ta	Tantalum	Cubic f.c.c.	Bl. (NAC)	1000 - 1100		3540 to 3880	20 20	30 20-200 30	+	(41); 170 (15); 4 (14); 170
Cr_3C_2	13.34 C Bal. Zr.	Chromium	Ortho- rhombic	$D5_{10}$	1100 - 1200		1895	20	--- 564		(41); 170 (14); 91 (34); 351+
Mo_2C	5.89 C Bal. Mo	Molybdenum	Hex. c.p.	L'3	500 - 800		2400	20	97 97.5 49.0 for (MOC)		(41); 170 (14); 91 (24); 370 (15); 4

TABLE 3.4 (Continued)

W_2C	3.16 C Bal. W	Tungsten	Hex. Low Temp. from f.c.c. (High Temp. from)	L'3		2730	20	80 80-81		(41); 170 (15); 4 (24); 391+
WC	6.13 C Bal. W	Tungsten	Hex. Simple	---	500 - 800	2630	20	53 53 12-53		(41); 170 (14); 91 (24); 391+ (15); 4
(B_4C)	Reference for Oxidation Characteristics	Boron	------		800 - 1000			$4.45 \times 10^{+3}$ 3 to $8 \times 10^{+3}$	-50×10^{-4} (27 - 125 °C)	(14); 92 (15); 4 (14); 92 (15); 4
(SiC)	Reference for Oxidation Characteristics	Silicon	------		1000 - 1200			5×10^8 0.5×10^6 to $200 \times 10^{+6}$	$+15 \times 10^{-4}$ (20°-240 °C)	(14); 90 (15); 4
		Nitrides								
TiN	22.8 N Bal. Ti	Titanium	Cubic	Bl. (NaCl)	1000 - 1200	2930 to 2950	R.T. 20 20 -- --	11.1 17 10-130 --- ---	27×10^{-4} 32×10^{-4} to (20° to 200 °C)	(14); 92 (2); 303 (41);(15); 5 (24); 989, 990
ZrN	13.27 N Bal. Zr.	Zirconium	Cubic	Bl. (NaCl)	1000 - 1200	2980	20 2980 20 -195 20	160 320 13.6 3.95 11.52	$+3 \times 10^{-4}$ to 100×10^{-4} (20°-200 °C)	(41); 237 (24); 996 (14); 92 (15); 5
VN	21.45% N Bal. Zr.	Vanadium	Cubic	Bl. (NaCl)	(500 - 800) for by Moers as cited by Ref. (41), p. 243	2050	20 20 20 2050 -195	200 85.9 332.0 850 59.9	$+15 \times 10^{-4}$ (20°-200 °C)	(14); 237 (41); 243 (15); 5 (14); 92

TABLE 3.4 (Continued)

NbN	13.1% N Bal. Nb	Niobium	NbN-I NbN-II NbN-III	-Hex. -Hex. -Cubic (NaCl)	500 - 800	2050	20 2050 18 700 1200	200 450 65 101 (extrop.) 133 (extrop.)	+6 x 10^{-4} (20°-200°C)	(41); 245 (24); 983 (2); 325 (2); 325 (14); 92 (15); 5
TaN	7.19 N Bal. Ta	Tantalum	Hex.	B4 type	500 - 800	2890 to 3090		-- 135		(24); 987+ (14); 92
TaN	3.73 N Bal. Ta		Hex.	---		3090	20 1480 2840	135 103.7 116.3		(41); 247 (24); 987
Cr_2N	21.22 N Bal. Cr.	Chromium	Cubic	B1. (NaCl)	Starts to decompose at 145°C	1500				(41); (24); 539+
Cr_2N	11.87 N Bal. Cr.	Chromium	Hex. c.p.	L'3						(41); (24); 539+
Mo_2N	6.80 N Bal. Mo	Molybdenum	Cubic	L'1			5°K	Super-conducting		(41); (24); 966
NoN	12.74 N Bal. Mo.	Molybdenum	Hex.				12.0°K	Super-conducting		(41); (24); 966
$W_2N(\beta)$	3.67 N Bal. W	Tungsten	f.c.c.	L'1						(41); 254+ (24); 993
$W_2N(\gamma)$	3.67 N Bal. W	Tungsten	Cubic	---						(41); 254 (24); 993
HfN	7.27 N Bal. Hf.	Hafnium	f.c.c.	(B1.) (NaCl)		3310				(24); 813
		Borides								
TiB	18.43 B Bal. Ti	Titanium	Ortho-rhombic	B27 (FeB)	Stable below 2060	2060	20	40		(41); 312 (24); 260, 262

TABLE 3.4 (Continued)

TiB_2	31.12 B Bal. Ti	Titanium	Simple Hex.	AlB_2 (C32)	1100 - 1300	2920	20° 20 -195	15.5 15.2 3.7 9.2 26.5	2.5×10^{-3} (100-1000°C) $+150 \times 10^{-4}$ 2.9×10^{-3} $+22 \times 10^{-4}$	(17); 110 (41); 311+ (15); 7 (41); 280 (17); 110 (14); 92 (15); 7
ZrB_2	19.17 B Bal. Zr	Zirconium	Simple Hex.		1000 - 1100	3040	20 20 -195	9-N; 13-15 24-30 1.8	$+190 \times 10^{-4}$ (20-200°C) $+27 \times 20^{-4}$	(41); 311, 312 (2); 109 (15); 7 (41); 312, 311 (15); 7 (14); 92
ZrB	10.60 B Bal. Zr	Zirconium	f.c.c.		Stable 800 - 125°C	----	20	30-35	Positive	(41); 282
ZrB_{12}	58.8 B Bal. Zr	Zirconium	f.c.c.	Type UB_{12}		2680	20 20	60-80 60-100 About 58		(41); 312 (17); 110 (2); 263
HfB	5.71 Bal. Hf	Hafnium	f.c.c.	B1(NaCl)						(24); 252
HfB_2	10.81 B Bal. Hf	Hafnium	Hex.			3100 to 3250	20	10-20 12 12		(15); 7 (41); 312, 285 (17); 110 (14); 92
VB	17.52 B Bal. V	Vanadium	Ortho-rhombic				20	35-40		(41); 312
VB_2	29.81 B Bal. V	Vanadium	Hex.	C32, (AlB_2) Type	800 - 1000	2100	20 20	16 16 16	1.7×10^{-3} (800-1000°C $+170 \times 10^{-4}$ (20-200°C)	(17); 110 (41); 312, 311 (15); 7 (17); 110 (14); 92
NbB	10.43 B Bal. Nb	Niobium	Ortho-rhombic		Stable to M.P.		20	64.5		(41); 312, 290 (24); 265

TABLE 3.4 (Continued)

NbB_2	18.89 B Bal. Nb	Niobium	Hex.	C32, (AlB_2) Struct.	Stable to M.P. 1000 - 1100	2900 to 3050	20	32 28.4-65 32	$+12\times10^{-4}$	(15); 7 (41); 312, 311 (41); 290 (24); 255 (14); 92 (17); 110
TaB	5.64 B Bal. Ta	Tantalum	Ortho- rhombic		Stable from R.T. to M.P.		20	100		(41); 312 (24); 258+
TaB_2	10.69 B Bal. Ta	Tantalum	Hex.		Stable from R.T. to near M.P. 1000 - 1100	3200	20	68 68 68	$+8.5\times10^{-4}$ 1.7×10^{-3} $+80\times10^{-4}$ (20°-200°C)	(41); 312, 311 (15); 7/(17); 110 (24); 254 (15); 7 (14); 92/(17); 110
CrB	17.22 B Bal. Cr.	Chromium	Ortho- rhombic			1500	20	64 33 38 to 78	1.5×10^{-3} positive	(41); 312, 311 (41); 298+/(17);110 (15); 7
CrB_2	29.38 B Bal. Cr	Chromium	Hex.	C32, AlB_2 Type	1200 - 1300	1850	20	21 21-54 21	positive $+1.10\times10^{-3}$	(41); 312, 311 (41); 298, 299 (15); 7 (14); 92 (17); 110
Mo_2B	5.34 B Bal. Mo	Molybdenum	Tetrag.		Decomposes at 2000°C	2000	20	40 40	1.0×10^{-3} (100-1000°C)	(41); 312 (17); 110
αMoB	10.13 B Bal. Mo	Molybdenum	Tetrag. Low Temp.		Low Temp. from	2180	20	45 50	0.91×10^{-3} (100-1000°C)	(41); 312, 311 (17); 110 (41); 301
βMoB	10.13 B Bal. Mo	Molybdenum	Ortho- rhombic		Stable at high temp. only	2180	20	25		(41); 312
MoB_2	18.40 B Bal. Mo	Molybdenum	Simple Hex.	AlB_2 Type		2100	20	45		(41); 312, 311
Mo_2B_5	22.01 B Bal. Mo	Molybdenum	Hex.		1000 - 1100	2100	20	25 25 25		(41); 312 (17); 110 (14); 92 for Mo_2B_3

TABLE 3.4 (Continued)

W_2B_5	12.32 B Bal. W	Tungsten	Hex.	1000 - 1100	2200	20	21 21		(41); 312 (24); 264 (14); 92 (17); 110
WB	5.56 B Bal. W.	Tungsten	Tetragonal-low temp. Orthorombic-Hi-temp.		2860		86 for theoretical density sample		(41); 311 (24); 264 (17); 110
W_2B	2.86 B. Bal. W.	Tungsten	Tetragonal-C16, $CuAl_2$ Type		2770		56 for 85% theoretical density sample		(41); 311 (24); 264 (17); 110
		<u>Silicides</u>							
Ti_5Si_3	26.03 Si Bal. Ti	Titanium	Hexagonal		2120				(41); 324+
$TiSi_2$	53.98 Si Bal. Ti	Titanium	Orthorhombic	900 - 1100	1540	20 20	123 20.0 16.7		(41); 324+ (17); 113+ (14); 92
TiSi	36.96 Si Bal. Ti	Titanium		Stable only to 1760 °C	1760				(41); 324+
ZrSi	23.53 Si Bal. Zr	Zirconium	Hex.	Formed from Zr_6Si_5 + Melt at 24. 2% Si	2090				
$ZrSi_2$	38.09 Si Bal. Zr	Zirconium	Orthohombic	Formed from ZrSi + Melt (46% Si) 900 - 1100	1520	20	161		(15); 6 (14); 92 (41);324+
Zr_4Si	7.14 Si Bal. Zr	Zirconium		Formed peritectically from ZrSi + L at (4.5 Si)	1630				
Zr_2Si	13.33 Si Bal. Zr	Zirconium		Formed from Zr_3Si_2 + Melt (9Si)	2110				
Zr_3Si_2	17.02 Si Bal. Zr	Zirconium		Formed from Zr_4Si_3 + Melt and 14.4 Si	2210				

TABLE 3.4 (Continued)

Zr_4Si_3	18.74 Si Bal. Zr	Zirconium			Formed from Zr_6Si_5 + Melt at 18 Si	2250				
Zr_6Si_5	20.40 Si Bal. Zr	Zirconium				2250				
$HfSi_2$										
V_3Si	15.52 Si Bal. V	Vanadium	Cubic	A15		2050				(41); 348 (24); 1201, 1202
VSi_2	52.44 Si Bal. V	Vanadium	Hex.	C40	800 - 1000	1750 to 1654	20	10.3		(41); 348 (24); 1201, 1202 (14); 92
V_5Si_3	24.85 Si Bal. V	Vanadium	Hex.	$D8_8$ (Mn_5Si_3)		2150				

TABLE 3.4 (Continued)

Metallic Compound	Nominal Composition [Wt. %]	Trade Name and/or Designation-and/or Oxidation Resistance	Crystallography		Remarks		M.P. (°C)	Temperature (°C)	Resistivity (ρ) (microhm-cm)	Temperature Coefficient of Resistivity (α)	Reference Number and Page
			System	Structure Type	Upper limit of Resistance to Oxidation in Air; (°C); after Ref. (14)	Others					
		Silicides									
$NbSi_2$	37.68 Si Bal. Nb.	Niobium	Hex.	of $CrSi_2$ - Type (C40)	800 - 1000		2000 to 1950	20	6.3 24.5		(41); 330, 331 (24); 1016 (14); 92
αNb_2Si	13.13 Si Bal. Nb	Niobium									(41); 3301+ (24); 1016
βNb_2Si	13.13 Si Bal. NB	Niobium									(41); 3301+ (24); 1016
$TaSi_2$	23.70 Si Bal. Ta	Tantalum	Hex.	of $CrSi_2$ (C40) Type	900-1100		2400	20	8.5 38.2		(41); 332, 333 (24); 1194 (14); 92
Ta_5Si_2	7.21 Si Bal. Ta	Tantalum									(41); 3321+ (24); 1194
Ta_5Si	3.02 Si Bal. Ta	Tantalum									(41); 332 (24);1194
Cr_3Si	15.26 Si Bal. Cr	Excellent oxidation resistance in air to elevated temp. Ref. (38) 184+	Cubic		A-15-type						(41); 335, 336
Cr_2Si	21.27 Si Bal. Cr		Rhombic		Stable below 1000°C						(41); 335, 336

TABLE 3.4 (Continued)

CrSi	35.07 Si Bal. Cr		Cubic	B20-Type (FeSi)						(41); 335, 336
Cr_2Si_3	43.7 Si Bal. Cr									
$CrSi_2$	51.93 Si Bal. Cr		Hex.	C40-Type	1000-1200	1570		> 250 1420		(41); 335, 336 (15); 6 (14); 92
Cr_2Si_7	65.5 Si Bal. Cr									
Mo_3Si	9 Si Bal. Mo	Molybdenum	Cubic	B-W Type	Formed below 2050 °C & Solid + Liq	2050				(41); 337, 338 (41); 339
Mo_3Si_2	16.3 Si Bal. Mo	Molybdenum			Possibly Stable below 1660 °C	2080 or less				(41); 337, 338
$MoSi_2$	36.9 Si Bal. Mo	Useful in Air to 1600 °C for considerable period without serious oxidation. Ref (38), 184+		Tetrag. C11b	1650-1700	2020 to 1870	20 -80 20 20	21.5 18.9 20-25 21.8		(41); 337, 338 (41); 339 (2); 213 (14); 92
W_3Si_2	9.2 Si Bal. W	Tungsten				2250				(41); 340+
W_2Si_3	18.6 Si Bal. W	Tungsten			Stable only below 1650 °C					(41); 340+
WSi_2	23.4 Si Bal. W	Tungsten		Tetragonal, (C11b $MoSi_2$)	1500-1600	2160 to 2050	20	33.4 38.2	13×10^{-4}	(41); 340-342 (15); 6 (14); 92
HfSi	13.59 Si Bal. Hf	Hafnium	Hex.							(24); 814

TABLE 3.4 (Continued)

$HfSi_2$	29.93 Si Bal. Hf	Hafnium	Orthorhombic (C49)						(24); 814
Hf_5Si_3	8.62 Si Bal. Hf	Hafnium							(24); 814
NiA1 + 5% A1		Satisfactory Oxidation Resis. to 1100°C. Ref. (38); 185+							(38); 185
NiA1		Excellent Oxid. Resistance in Still Air to 1000-1095°C			1640	R.T	22.		42 ; 339, 358
		Note 1				100			
						250			42 ; 339, 358
						500			
						700			42 ; 339, 358
						900			
						1000			42 ; 339, 358
						1100			
NiA1 + 6% Cr						R.T	40		42 ; 339
NiA1 + 5% Nb						R.T	32		42; 339
NiA1 + 4% Ti						R.T	40		42; 339
NiA1 + 4% Zr						R.T	33		42; 339
Ni_4Zr*				"ColdWorkable with a hammer"	≈1600				42; 54
Ni_3Mn		Oxidation Resistant ?		Quenched from 600°C		R.T	72.7		42; 200
				Quenched from 460°C		R.T	42.7		42; 200
				Quenched from 400°C		R.T	26.6		42; 200
				Quenched from 20°C.		R.T	19.8		42; 200
						20	36.5		(2); 435

TABLE 3.4 (Continued)

TiAl		Fair Oxidation Resistance			1460	20°	31.669 to 34.322		(13); 234, 341
Cr_2Ti		Considered outstanding Oxidation Resistance Ref. (38) good Oxidation Resis.			1400				(38);185+ 42; 341, 234
Cr_2Zr		Considered outstanding resistance to oxidation Ref. 38							(38); 185+
Approx. PT_3Co			Curie Temp. (°C) 12 52 209	Annealed first at Quenched 1200 °C Quenched 600 °C Quenched 20 °C	1200 °C	20° 20° 20°	42.7 41.9 40.3		42 ; 203 42 ; 203 42 ; 203
$MoBe_{12}$		Req. Oxidation Resis. good to 1482 °C			About 1700				42 ; 298, 299 Also Ref. 11 ; 107
$NbBe_{12}$		good to 1482 °C			1700				42; 298, 299 11; 107
Nb_2Be_{17}		good to 1482 °C			>1700				42; 298, 299 11; 107
$TaBe_{12}$		good to 1538 °C			1850				42; 298, 299 11; 107
Ta_2Be_{17}		good to 1538 °C			1978				42 ; 298, 299 11 ; 107
$TiBe_{12}$		good to 1427 °C			>1540				42 ; 298, 299
$ZrBe_{13}$		good to 1538 °C			1927				42; 298, 299 11; 107
Zr_2Be_{17}		Expected to be good.			>1927				42; 298, 299 (11); 107

TABLE 3.4 (Continued)

		Note (1) oxidation resistance quality was based on (1) 100 hr. test (2) oxidation rate was less than 2 mils for period and temp. indicated (3) and as restricted to date for Ref. (13)							
Cr_3Ta_2		Alloys in this range have the best oxidation resistance							(13); 67
Cr_3Nb_2									(13); 67
Au_3Mn	Mn-8.50 Au-91.50	Mn-Au; (8.5-91.5)	Neel Temp. -123 °C	Order-disorder transformation @ 650 °C	960+	27	48.4	4.0×10^{-3} (below -123 °C)	(4): 220
AuMn	Mn-22.3 Au-77.7	Mn-Au; (22.3-77.7)	Neel Temp. 227 °C	Order-disorder @ 615 ref. (24); 216	1260	27	43.7	4.1×10^{-3} (below 227 °C)	(4); 220 (24); 216

TABLE 3.4 (Continued)

Alloy	Composition Wt. % (Actual); or Nominal*					Phases Present	Density $\frac{gm}{cm^3}$	Density %Theoretical	Remarks	Electrical Resistivity (ρ), Microhm-cm, @ 20°C or RT	Oxidation Resistance in Still Air @ 1000°C Wt. gain (Mg./cm^2)	Oxidation Resistance in Still Air @ 1000°C Time Hours	Reference -Number -Page
Cr-Mo-Ti	Cr	Mo	Ti	Fe	N								
	63.5	7.3	29.2			Cr_2Ti + Mo, Solid Solution	6.34	99	Sample No. 6 Heat Treated @ 1500°C- 1 hour	132	+7.30	190	(7);3,4,6,7
	54.3	15.5	25.8	0.76	0.74	(Cr, Mo, Ti) Solid Solution (b.c.c.)	6.78	98	Sample No. 1 Heat Treated @ 1500°C- 1 hour	73	+3.18	92	(7);3,4,6,7
	40.4	36.4	17.5	0.59	0.45	(Cr, Mo, Ti) Solid Solution (b.c.c.)	7.36	98	Sample No. 2 Heat Treated @ 1500°C- 1 hour	63	-78.10	190	(7);3,4,6,7
	28.9	52.8	14.8	0.69	0.44	(Cr, Mo, Ti) Solid Solution (b.c.c.)	7.40	91	Sample No. 3 Not Specified-(heat treatment	59	-218.00	190	(7);3,4,6,7
						Cr_2 Ti + 4 Mo	6.45		Sample No. 6 Heat Treatment-not specified	101			(7);9
Ni-Al-Cr	Ni	Al	Cr	O_2	N_2								
	64.2	29.3	5.4	0.55	0.02	Ni Al + Cr (b.c.c.)	5.86	96.5	Sample No. 10 Hot Pressed powders @ 1400-1480°C; or cold Pressed & Sintered in H_2 1570°C-1 hour	40.5	7.6	216	(7);14,15 16,19

TABLE 3.4 (Continued)

Ni-Al-Cr	60.3	26.9	10.5			Ni Al + Cr (b.c.c.)	6.02	98.2	Sample No. 11 Hot Pressed Powders @ 1400-1480°C; or cold Pressed & Sintered in H_2 1570°C-1 hour	38.1	18.1	216	(7);14,15, 16,19
	53.5	23.4	21.4			Ni Al + Cr (b.c.c.)	6.14	97.8	Sample No. 12 Hot Pressed powders @ 1400-1480°C; or cold Pressed & Sintered in H_2 1570°C-1 hour	48.3	25.2	216	(7);14,15, 16,19
	45.1 Nom.	20.7 Nom.	34.2 Nom.			Ni Al + Cr (b.c.c.)	6.29	98.1	Sample No. 13 Hot Pressed Powders @ 1400-1480°C; or cold Pressed & Sintered in H_2 1570°C-1 hour	53.8	8.1	192	(7);14,15, 16,19
	37.8	15.3	42.5	0.55	0.03	Ni Al + Cr	6.50	99.4	Sample No. 14 Hot Pressed Powders @ 1400-1480°C; or cold Pressed & Sintered in H_2 1570°C-1 hour	73.5	4.0	192	(7); 14,15 16,19

TABLE 3.4 (Continued)

Ni-Al-Cr	30.9	14.1	51.0	NiAl + Cr (b.c.c.)	6.54	98.3	Sample No. 15 Hot Pressed Powders @ 1400-1480°C; or cold Pressed & Sintered in H$_2$ 1570°C-1 hour	59.6	7.2	192	(7); 14, 15, 16, 19
	43.8	9.0	36.0	Ni Al + Ni$_3$ Al Cr	6.12		Sample No. 16 Hot Pressed Powders @ 1400-1480°C; or cold Pressed & Sintered in H$_2$ 1570°C-1 hour	93.0	0.5	144	(7); 14, 15 16, 19
	73.2	18.0	5.4	(Ni, Cr) Al + (Ni, Cr$_3$) Al	6.57		Sample No. 18 Same as above	121.	55.0	259	(7);14, 15, 16, 19
	Ni	Al	Ti								
Ni-Al-Ti	61.4	27.8	9.3	(Ni, Ti) Al (b.c.c.)	5.67	97.0	Sample No. 19 Same as above	50.3	8.7	200	(7); 28, 29, 30, 31
	63.5	29.3	4.1	(Ni, Ti)Al+ (b.c.c.)+	5.78	97.1	Sample No. 20 Same as above	39.5	97.0	200	(7); 28, 29 30, 31
	Ni	Al	Zr								
Ni-Al-Zr	65.1	31.1	3.5	(Ni, Zr)Al	5.83	95.9	Sample No. 22	33.4	183	200	(7); 34-37 inclusive
	62.6	28.4	9.5	(Ni, Zr)Al	6.02	97.4	Sample No. 23	20.8	231	200	(7); 34-37 inclusive

TABLE 3.4 (Continued)

Ni-Al-Nb	Ni	Al	Nb								
	64.6	29.5	4.8	(Ni, Nb)Al	5.85	97.0	Sample No. 25	31.8	23.5	200	(7);40-43 inclusive
	62.2	27.9	9.6	(Ni, Nb)Al+	5.98	95.6	Sample No. 26	33.0	256.	200	(7);40-43 inclusive
					4.69		Prepared by by powder Met. Methods. Did not melt at 1630 °C	2.37 237.	Both ρ values given by Ref (7):		(7);55, 51, 52

TABLE 3.5

BASIC DATA - METALLIC COMPOUNDS (RESISTIVITY OF METALLIC COMPOUNDS AS A FUNCTION OF TEMPERATURE FROM 0°C TO 1200°C)

Compound	Composition, (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Hf B	5.71 - B																	(24); 252	M.P.≈ 3100°C.f.c.c. structure.
Hf B_2 Hf B_2	10.81 - B			10. at 80%density 12. at 85% density														(24); 252 (41); 385	M.P.≈ 3240°C.Hex. Structure Ref. (24); 252.Ref (41); 285 of 2nd Quarter Rpt and A.I.M.E. Trans.(97); 1120
Hf C	6.30 - C			109														(14) (41); 170	M.P.≈ 3890°C Cubic Structure, of NaCl(B-1)Type (41); 170.(14)
Hf N	7.27 - N_2																	(24); 813	M.P.≈ 3310°C.f.c.c. structure. Ref. (24); 813
Hf Si	13.59 - Si																		
Hr Si_2	23.93 - Si																		
Hf_5Si_3	8.62 - Si																		

TABLE 3.5 (Continued)

Compound	Composition (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; At Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Mo Si_2	34.79 - Si 62.15 - Mo	6.52×10^{-3} (0° to 200°C)	20.	(22.62)	34	46.	58.	72.	87.	104.	122.	140.	158.	177.5	196.	(215)		(2); 213, 214	0.42% O_2 0.34% C^2
Mo Si_2	32.70 - Si 62.23 - Mo	5.50×10^{-3} (0° to 200°C)	25.	(27.75)	37.	52.5	65.	78.	95.	111.	128.	147.5	(167.)	(186.)	(205)	(224)		(2); 213, 214	1.20% - O_2 0.29% - C^2
Mo Si_2	36.92 - Si (Theoretical)	1.102×10^{-3} (20° to 538°C)		76.34					119.91 at 538°C			176.89 at 816°C			232.0 at 1093°C			(40);621	Ref.(40)
Ref. Mo	100 - Mo	3.535×10^{-3} (20° to 200°C)		5.5		9.0		13.7	16.2	18.6	21.7 at 727°C		27.2 at 927°C			35.		Table 1.8	

TABLE 3.5 (Continued)

Compound	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, microhm-cm: @ Temperature (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
NbB	10.43-B			64.5															Ref (41); 290
Nb_3B_4	13.44-B																		
NbB_2	18.89-B			32.															M.P. = 3050°C; Ref (24)
Nb_2C	6.07-C																		
NbC	11.45-C	1.6×10^{-4} (20° to 200°C)*		74.	(74.95) (estm.)	(76.13)	(77.32)	(78.50)	(79.68)	(80.87)	(82.05)	(83.24)	(84.42)	(85.60)	(86.79)	(87.97) (estm.)		(41); 170 (15);4 (14);91	M.P. = 3500°C
NbN	13.01-N_2	9.14×10^{-4} (20° to 441°C)		65				(90.) at 441°C	(93.5)	(99.45)	(105.4)	(111.3)	(117.25)	(123.2)	(129.2)	(135.1)		(2); 325	Values obtn. by extrapolation to 441°C & calc.
NbN-I	13.01-N_2 (Theoretical)	6.1575×10^{-4} (20° to 2050°C)*		200	(209.85) (estm.)	(222.17)	(234.48)	(246.79)	(259.11)	(271.42)	(283.74)	(296.05)	(308.37	(320.68)	(333.0)	(345.32) (estm.)	450 at 2050°C		M.P. = 2050°C Ref. (41); 244, 245. *; Assumed linear function of ρ vs T; for Approx. values of ρ.
NbN-II																			
NbN-III																			
$NbSi_2$	37.68-Si			6.3															M.P. = 1930°C- Ref. (41); 331.
Nb_5Si_3	15.36-Si																		M. P. = 2410°C
Nb_4Si	7.03-Si																		M.P. = 1960°C
Ref - Nb-	100- Nb	2.73×10^{-3} (20° to 200°C)		16.3	-	27.3	-	37.	41.7	46.2	51.7 at 727°C	-	(61) at 927°C			(72.)		Table 1.8	

TABLE 3.5 (Continued)

Compound	Composition, (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ta B	5.64 - B			100														(15) (41); 295	
Ta B_2	10.69 - B			68.														(41); 295	
Ta C	6.23 - C	2.1795 x 10^{-4} (20° to 1167°C)		100.	(101.74)	(103.92)	(106.10)	(108.28)	(110.46)	(112.64)	(114.82)	(117.0)	(119.18)	(121.36)	125. at 1167°C		129. at 1307°C	(25)	Samples in Inert-atm.
Ta C	6.23 - C			30.														(41); 120	
Ta N	7.19 - N_2			135													103.7 at 1480°C and 116.3 at 2840°C	(15); (41); 247	
Ta Si_2	23.70 - Si			8.5														(15); (41); 333	

TABLE 3.5 (Continued)

Compound	Composition (Wt. %) Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
Ti B	18.43 - B (Theoretical)			40.0															Ref (41); 280
Ti B_2	31.12 - B (Theoretical)	9.085×10^{-3} (20° to 200°C)	(13.28)	(18.23)	(28.04)	42.8	(53.15)	63.5	(69.40)	75.3	(80.45)	86.6	(91.55)	97.5	(102.65)	107.8	≈148 at 2000°C		Ref. (17)
Ti B_3	31.12 - B			15.2													3.7 at -192°C		Ref. (41); 280
Ti C	20.05 - C (Theoretical)	1.53×10^{-3} (20° to 200°C)	(121.20)	(125.03)	(140.35)	159.5	(178.65)	197.8	(214.05)	230.3	(245.2)	260.0	(274.)	288.	(302.)	316	≈ 360. at 1600°C		Ref. (17)
Ti C	20.05 - C (Theoretical)	4.36×10^{-4} (20° to 200°C) and: 7.07×10^{-5} (200° to 800°C)	153.	156.	160.9	162.8	163.9	166.7	170.7	169.7	169.7	(169.7)	-	(169.7)	-	(169.7)		(2); 157 158	1 mm. dia. wire.
Ti N	22.624 - N_2 (Theoretical)	3.70×10^{-3} (20° to 200°C)	15.3	16.5	21.4	27.5	33.3	39.	44.7	50.6	56.5	(62.4)	(68.3)	(74.5)	(80.3)	(86.4)	-	(2); 303 304	2 mm. dia. wire.
Ti N	22.624 - N_2 (Theoretical)	5.5132×10^{-4} (20° to 2950°C)		130.	(135.73)	(142.90)	(150.07)	(157.23)	(164.40)	(171.57)	(178.74)	(185.90)	(193.07)	(200.24)	(207.40)	(214.57)	340. at ≈2950°C	(41)	
Ti N	22.624 - N_2 (Theoretical)			21.7													8.13 at -192°C	(41)	
Ti Si_2	53.98 - Si (Theoretical)	6.47×10^{-3} (20° to 200°C)	(12.60)	(15.75)	(23.34)	(34.06)	(44.82)	(55.56)	(66.30)	(77.04)	(87.78)	(98.52)	109.26	120	130.3	133.7	100. at 1400°C & 18. at 50°C	(17)	
Ti Si_2	53.98 - Si			123.														(41); 326	
Ref. - Ti	100 - Ti	2.46×10^{-3} (20° to 200°C)		61.	-	88.	-	116.7	130.5	144.2	150. at 727°C	-	161.5 at 927°C	-		154.	166. at 882°C	Table 1.8	
Ref. (Pt-Rh) (Standard)	40 - Rh	1.327×10^{-3} (20° to 200°C)	(16.99)	17.45	(19.3)	(21.62)	(23.94)	(26.25)	(28.20) (28.57)	(30.89)	33.21	(35.52)	(37.84)	39.9 (40.164)	(42.48)	44.8		Table 1.2	

TABLE 3.5 (Continued)

Compound	Composition, Wt. % Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; At Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
U_3Si	3.8 - Si	6.234×10^{-3} (-196°C to 0°C) 2.803×10^{-3} (0° to 930°C)	52.25	(54.18)	(66.85)	(81.55)	(96.1)	(110.85)	(125.5)	(140.)	(154.8)	(169.3)	(188.6) at 930°C				23.53 at -196°C	(2); 223 224	ξ phase produced by heating at 800°C for 24 hours.
Zr B	10.60 - B			30 to 35														(41); 282	
$Zr\ B_2$	19.17 - B			9.2														(41); 282	
$Zr\ B_2$	19.17 - B. (Theoretical)	7.196×10^{-3} (0° to 200°C)	25.		43.	61.	76.	93.	106	124.	138.	152.	165.	178.	191.	201.5	229 at 1500°C	(2); 109 110	Borolite I - Grade G - 4.5% Binder.
$Zr\ B_2$	19.17 - B (Theoretical)	7.99×10^{-3} (0° to 200°C)	30.		53.	78.	100.	124.	144.	164.	182.	200.	215.	227.	240.	250.	264 at 1500°C	(2); 109 110	Borolite I - Grade S - 7.5% Binder.
$Zr\ B_2$	$2\frac{1}{2}$% Binder (Boron)	1.5463×10^{-2} (20° to 1000°C)		13.	(29.08)	(49.35)	(69.3)	(89.4)	(109.5)	(129.6)	(149.7)	(169.8)	(190)	210.				(17)	
$Zr\ B_2$	+$4\frac{1}{2}$% Binder (Boron)	1.4121×10^{-2} (20° to 1000°C)		15.5	(33.01)	(54.89)	(76.78)	(98.67)	(120.56)	(142.44)	(164.34)	(186.23)	(208.12)	230.				(17)	
$Zr\ B_2$	+7% Binder (Boron)	1.3137×10^{-2} (20° to 1000°C)		17.3	(35.48)	(58.21)	(80.93)	(103.66)	(126.39)	(149.12)	(171.84)	(194.57)	(217.20)	240.				(17)	
$Zr\ B_2$	+15% Binder (Boron)			18.5														(17)	
$Zr\ B_{12}$	58.74 - B (Theoretical)	1.55×10^{-3} (0° to 200°C)	58	59.5	(67.)	(76.)	(85)	(94)										(2); 263 264	Hot-pressed. Avg. values for samples.
Ref.-(Pt-Rh) (Standard)	40 - Rh	1.327×10^{-3} (20° to 200°C)	(16.99)	17.45	(19.3)	(21.62)	(23.94)	(26.25)	(28.20) (28.57)	(30.89)	33.21	(35.52)	(37.84)	39.9 (40.164)	(42.48)	44.8		Table 2.2	

TABLE 3.5 (Continued)

Compound	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity Microhm - cm; at Temperature, (°C)														Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
VB	17.52-B			35 to 40.														(41); 288	At 1780°C Liq. + VB_2 ⇌ VB
VB_2	29.81-B		3.5 at -192°C	16.														(24); (41); 288	M.P. ≈ 2100°C
V_2C	10.54-C																	(24)	M.P. > 1800°C
VC	19.08-C	5.1278×10^{-4} * (20° to 2230)		150.	(156.15)	(163.85)	(171.54)	(179.23)	(186.92)	(194.61)	(202.30)	(209.99)	(217.69)	(225.38)	(233.07)	(240.76)	320. at 2230°C	(24)	M.P. > 1800°C
																		(41); 106	*Assumed linearity of ρ Vs T. as an approximation.
VN	21.56-N_2	1.6010×10^{-3} (20° to 2050°C) *		200.	(225.62)	(257.64)	(289.65)	(321.68)	(353.69)	(385.72)	(417.73)	(449.76)	(481.77)	(513.78)	(545.80)	(577.82)	850. at 2050°C	(24)	M.P. ≈ 2050°C
			59.9 at -192°C	85.														(41); 243	*Assumed ρ vs T. (linear function for approximation.)
VSi_2	52.44-Si			9.5														(24) (41); 330	M.P. ≈ 1750°C
V_5Si_3	24.85-Si																	(24)	M.P. ≈ 2150°C.
V_3Si	15.52-Si																	(24)	M.P. > 1840°C
Ref-V	100-V	3.16×10^{-3} (0° to 100°C)	19.	(20.13)	25.	30.	36.										21.8 at 50.°C	(3); 310	
Ref-V	100-V	2.8×10^{-3} to 3.4×10^{-3} (0° to 100°C)		22. to 26.														Table 1.1	

TABLE 3.5 (Continued)

Compound	Composition, (Wt. %), Nominal	Temperature Coefficient of Resistivity, (α)	Resistivity, (ρ), Microhm-cm; at Temperature, (°C)															Reference -Number -Page	Remarks
			0	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	Other		
ZrC	11.63 - C			63.4														(24); (14);91	M.P. ≈ 3175°C
ZrN. (1)	13.31 - N_2	3.3783×10^{-4} (20° to 2980°C)		160.	(164.33)	(169.73)	(175.13)	(180.54)	(185.95)	(191.35)	(196.76)	(202.16)	(207.57)	(212.98)	(218.38)	(223.78)	320 at 2980°C	(24); (41); 237	M.P. ≈ 2980°C
$ZrSi_2$	38.12 - Si			161.														(24); (41); 328	M.P. = 1520°C
ZrSi	23.55 - Si																	(24)	M.P. ≈ 2225°C

Remarks. (1) Lack of Data, other than at 20°C & 2980°C; justifies the calculated values of Resistivity, ρ, ( ), as expedient and approximate.

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4. CONCLUSIONS AND RECOMMENDATIONS

Electrical conductors for high-temperature conductor applications have to satisfy three conditions up to the maximum temperature of the required application.

1. Low electrical resistivity and a smooth reproducible resistivity variation with temperature. In general, a resistivity of less than 25 microhm-cm at 20°C and 50 microhm-cm at 1200°C is required.

2. Good oxidation resistance compatable with environmental conditions and time of exposure to the high temperature environment.

3. Good mechanical properties (adequately high yield strength and low creep) up to the maximum temperature of operation.

The platinum-rhodium alloys dominate existing technology in this field. However, they exhibit conductivities approximately twenty times less than that of copper, and approximately ten times less than gold. They are quite adequate with regard to oxidation resistance and mechanical properties. One other factor should be stressed and this is the question of cost. Materials costs are generally not as important to defense contractors as they should be. Platinum-rhodium waveguide costs about $1000. per foot, which is of the order of 100 times the cost of the same item made out of copper. A similar ratio of cost is encountered for antennas, power cables and hook-up wire. The costs of the most relevant metals to high-temperature conductor research are (see table 1.15 - 1953 prices).

Element:	Cu	Ni	Cr	Mo	Ag	W	Pb	Au	Ru	Pt	Rh	Ir
Cost: ($/lb)	0.3	0.6	1.2	7.2	12.4	15.	350.	510.	1165.	1355.	1820.	2480.

The principal objective for research in the field of high-temperature high-conductivity materials is to find a substitute for Pt-Rh alloys which provides an overall weight, cost and reliability advantage over these alloys as materials for high-temperature conductors.

In general, this study has considered three classes of conductor materials for high-temperature electrical conductor applications, which may provide, on further development, alternatives to the Pt-Rh alloys.

1. Pure Metals: Pure metals or mechanically-supported pure metals of high oxidation resistance and pure metals or mechanically-supported pure metals protected by oxidation resistant coatings.

2. Metallic alloys: Alloys in which the overall mechanical, thermal, and, if necessary, the oxidation-resistance over the component pure metals are improved without an unacceptable decrease in electrical conductivity and electrical stability.

3. Metallic compounds: Binary compounds which exhibit metallic conductivity.

It is the principle purpose of this section of the report to summarize those areas where further work on pure metals, alloys and compounds should lead to significant improvements in the state of the art. Interim summaries and conclusions have already been given in this report. If all the recommendations presented were to be followed, it would cost many millions of dollars and hundreds of man-years of research funding. In this conclusion we try to arrive at a practical list of research suggestions, designed to give the maximum results for a moderate expenditure of effort.

Before a selection of the most profitable areas for further research can be decided, three general specifications have to be made.

1. Specification of the temperature range of application.

2. Specification of the cost of component materials.

3. Specification of the funds to be expended on research and development.

For applications up to 1200°C, the evidence suggests that the best approach to the development of electrical conductors, superior and less costly than the Pt-Rh alloys, is development of internal oxidation-hardened and dispersion-hardened noble metals, especially Pt, Rh and Pd, in order of preference. Of these metals, Pd has a significant cost advantage which is offset by its greater susceptibility to oxidation. It should be noted that Pt might be hardened by dispersion or oxidation-hardening methods with only a few percent increase in electrical conductivity. This is to be compared with the increase in excess of 100 percent for the hardening of Pt by additions of rhodium. For applications at temperatures less than 900°C, internally oxidization-hardened or dispersion-hardened gold represents the most favorable prospects as far as electrical conductivity, oxidation resistance, and cost are concerned. The details of a suggested program of research on internal oxidation and dispersion hardening of Pt, Ir, Rh, Pd and Au is given in table 4.1. Here the volume percent additions of the order of 7.5% refers to the after treatment condition. For the internal oxidation-hardening (I.O.H.) method, the metallic element addition (Al, Be, Ce, Hf, La, Mg, Nd, Si, Sm, Th, Ti or Y) is made, and the binary alloy is internally oxidized in a work-hardened state. The resulting dispersed oxide should then represent approximately 7.5% of the volume, the balance being made up of the noble metal. For the dispersion-hardening (D.H.) method, the oxide additions are dispersed, using powder metallurgical techniques. These methods have been described in section 2.2.4 and examples of their application given in section 2.4.2 and tables 2.10 to 2.18. In either method of hardening (I.O.H.) or D.H.), the desirable characteristics of the dispersed oxide are as follows:

a. 7.5 volume % of oxide (approximately);

b. oxide particle diameter of the order of 0.02 microns;

c. uniform distribution or interparticle spacing of dispersed oxide.

The results given in section 2.4.2 for internal oxidation and dispersion-hardened alloy of Cu and Ag were very favorable. Several-fold improvements in strength were obtained at resistivities less than 2.5 microhm-cm. If similar results can be obtained for Pt, Au and other noble metals, a significant technological and cost advance will have been made in the field of high-temperature conductors.

For applications at maximum temperatures up to 500°C, the internal oxidation-hardened or dispersion-hardened alloys of copper ($Cu-Al_2O_3$ or SiO_2) or silver ($Ag-Al_2O_3$ or SiO_2) can be used at very considerable savings in materials costs. The performance of alloys of this type have been discussed in tables 2.10 to 2.18, and section 2.4.2, in considerable detail. In addition, many of the I.O.H. and D.H. hardeners suggested in table 4.1 are suitable for Cu and Ag. For prolonged exposure to high temperatures at 500°C, the copper alloy will require oxidation protection by means of an oxidation-resistant coating.

An alternative to the dispersion and oxidation-hardening methods is the supported pure metal structures discussed in section 1.4.2. The most useful of these are pure Pt or Au mechanically supported on a compatible insulating or conductive substrate. For applications in which exposure to high temperature is transitory, Pt or Au plated, nichrome or steel may be adequate for use up to 600°C and for use up to 1000°, Mo or W may be satisfactory. For extended use at high temperatures, the Pt or Au must be separated from the metallic base material by a diffusion-inhibiting layer and an agent to aid adhesion at high temperatures. An evaporated layer of silicon oxide is a possible solution to both of these problems.

For higher temperature application, a flexible substrate of quartz-fibreglass could prove an adequate supporting substrate for electrical hook-up wire and power cables. The pure platinum or gold wires could be co-entwined with the quartz nonfilament fibres and the whole bundle wrapped with quartz-fibre insulation. Such techniques have been used for gold-cobalt alloy wires at lower temperatures using borosilicate glass fibres.

Further work is also recommended on developing suitable oxidation protection methods for Mo, W and Ru and dilute alloys of these metals. These materials have low resistivity and relatively good mechanical properties at elevated temperatures.

Additional systems of scientific interest consist of noble transition metals doped with polyvalent impurities such as As, Sb, Bi, S, Se, Te and U. These additions may be more efficient at filling in the d-band of the noble transition metal elements (see section 1.4.1) than the monovalent addition, Au, Ag, Cu, with which most of the previous work has been attempted.

Finally, some work is recommended on a number of substitutionally-ordened noble metal alloys. Extensive lists of these alloy systems have been given in section 2.4.2. The most promising of these alloys were indicated by an asterisk. (Additional systems of interest are Pt-Re, Pd-Re, Pt-Ru, and Pd-Ru.)

The research programs, suggested in section 3 on metallic compounds, are also worthy of consideration after the approaches suggested above have been further explored. Although the long-range prospects for metallic compounds and their alloys may seem favorable for the development of useful high temperature conductors, significant results may not be as easily achieved as with metallic alloys or supported pure metals.

Finally, it is hoped that the extensive tabulation of data and properties of metals, alloys and compounds will be of use in the selection of the best available electrical conductor material for specific use in the temperature range from 0°C up to 1200°C.

TABLE 4.1

RECOMMENDED DISPERSION OR INTERNAL OXIDATION-HARDENED TYPES OF ALLOYS FOR HIGH-TEMPERATURE ELECTRICAL CONDUCTORS

Alloy Composition (vol. %) (after preparation)	Preferred Method for Preparation of Alloy	Preferable Temperature Limits of Alloy in Oxidizing Atmosphere	Reference to Constitutional Diagram for Alloy prior to Oxidation
X - Bal. Ag.			M. Hansen & K. Anderko; <u>Constitution of Binary Alloys</u>; McGraw Hill; 1958
7.5 Al_2O_3 -	I.O.H.	> 300°C ≲800°C	p.1
7.5 BeO -	I.O.H; or D.H.		p.2
7.5 CeO_2 -	N.D.		p.16
7.5 HfO_2	D.H.		——
7.5 La_2O_3 -	N.D.		p.28
7.5 MgO -	N.D.		p.30
7.5 Nd_2O_3 -	D.H.		——
7.5 Sc_2O_3 -	D.H.		——
7.5 SiO_2 -	N.D.		p.51
7.5 Sm_2O_3 -	D.H.		——
7.5 ThO_2 -	N.D.		p.57
7.5 TiO_2 -	N.D.		p.58
7.5 Y_2O_3 -	D.H.	> 300°C ≳800°C	——
X - Bal. Cu.			
7.5 Al_2O_3 -	N.D.	R.T. to 875°C	p.84
7.5 BeO -	N.D.		p.281
7.5 CeO_2 -	N.D.		p.450
7.5 HfO_2 -	N.D.		p.586
7.5 La_2O_3 -	N.D.		p.592
7.5 MgO -	N.D.		p.596
7.5 Nd_2O_3 -	N.D.	Protection from oxidation required	p.601
7.5 Sc_2O_3 -	D.H.		——
7.5 SiO_2 -	N.D.		p.629
7.5 Sm_2O_3 -	D.H.		——
7.5 ThO_2 -	D.H.		——
7.5 TiO_2 -	N.D.		p.642
7.5 Y_2O_3 -	D.H.	R.T. to 875°C	——

Key:
I.O.H. = Internal Oxidation Hardening-Method
D.H.* = Dispersion Hardening (Powder Metallurgy)-Method
N.D.* = Not Decided

* Absence of sufficient information such as incomplete constitutional diagrams required to formulate thermal treatment for internal oxidation hardening often favors the selection of dispersion hardening.

TABLE 4.1 (Continued)

Alloy Composition (vol. %) (after preparation)	Preferred Method for Preparation of Alloy	Preferable Temperature Limits of Alloy in Oxidizing Atmosphere	Reference to Constitutional Diagram for Alloy prior to Oxidation
X - Pd			p.124
7.5 Al_2O_3 -	N.D.	> 875°C to ≈1300°C	p.293
7.5 BeO -	N.D.		——
7.5 CeO_2 -	D.H.		——
7.5 HfO_2 -	D.H.		——
7.5 La_2O_3 -	D.H.		——
7.5 MgO -	N.D.		p.913
7.5 Nd_2O_3 -	D.H.		——
7.5 Sc_2O_3 -	D.H.		——
7.5 SiO_2 -	N.D.		p.1125
7.5 Sm_2O_3 -	D.H.		——
7.5 ThO_2 -	D.H.		——
7.5 TiO_2 -	N.D.		p.1128
7.5 Y_2O_3 -	D.H.	> 875°C to ≈1300°C	——
X - Bal. Pt.			
7.5 Al_2O_3 -	N.D.	R.T. to ≈1500°C	p.127
7.5 BeO -	N.D.		p.294
7.5 CeO_2 -	N.D.		p.460
7.5 HfO_2 -	D.H.		——
7.5 La_2O_3 -	D.H.		——
7.5 MgO -	N.D.		p.914
7.5 Nd_2O_3 -	N.D.		p.1014
7.5 Sc_2O_3 -	D.H.		——
7.5 SiO_2 -	N.D.		p.1140
7.5 Sm_2O_3 -	D.H.		——
7.5 ThO_2 -	D.H.		——
7.5 TiO_2 -	N.D.		p.1143
7.5 Y_2O_3 -	D.H.	R.T. to ≈1500°C	——

TABLE 4.1 (Continued)

Alloy Composition (vol. %) (after preparation)	Preferred Method for Preparation of Alloy	Preferable Temperature Limits of Alloy in Oxidizing Atmosphere	Reference to Constitutional Diagram for Alloy prior to Oxidation
X - Bal. Ir.			
7.5 Al_2O_3 -	D.H.	≯1140°C to ≈ 2100°C	—
7.5 BeO -	N.D.	↑	p.287
7.5 CeO -	D.H.		—
7.5 HfO_2 -	D.H.		—
7.5 La_2O_3 -	D.H.		—
7.5 MgO -	N.D.		p.868
7.5 Nd_2O_3 -	N.D.		p.870
7.5 Sc_2O_3 -	D.H.		—
7.5 SiO_2 -	N.D.		p.874
7.5 Sm_2O_3 -	D.H.		—
7.5 ThO_2 -	D.H.		—
7.5 TiO_2 -	N.D.	↓	p.875
7.5 Y_2O_3 -	D.H.	≯1140°C to ≈ 2100°C	—
X - Bal. Rh.			
7.5 Al_2O_3 -	N.D.	≯1100°C to ≈ 1700°C	—
7.5 BeO -	N.D.	↑	p.295
7.5 CeO_2 -	D.H.		—
7.5 HfO_2 -	D.H.		—
7.5 La_2O_3	D.H.		—
7.5 MgO -	N.D.		p.915
7.5 Nd_2O_3 -	D.H.		—
7.5 Sc_2O_3 -	D.H.		—
7.5 SiO_2 -	N.D.		p.1155
7.5 Sm_2O_3 -	D.H.		—
7.5 ThO_2 -	D.H.		
7.5 TiO_2 -	N.D.	↓	p.1157
7.5 Y_2O_3 -	D.H.	≯1100°C to ≈ 1700°C	

TABLE 4.1 (Continued)

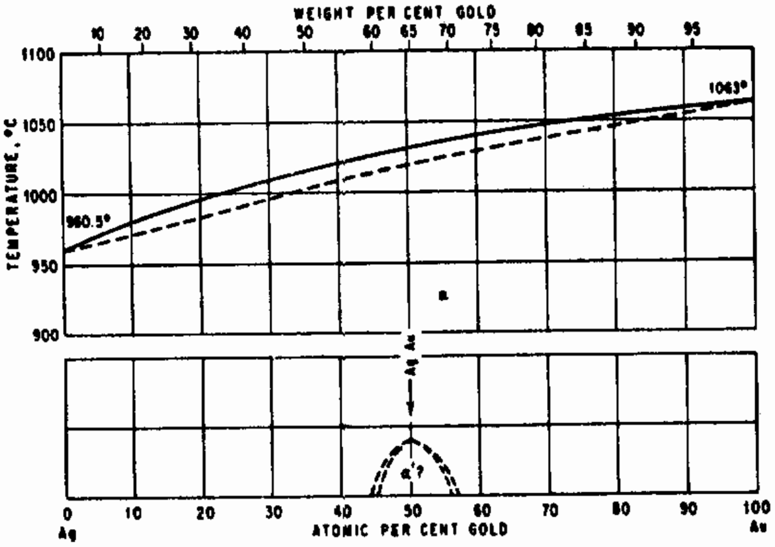
Alloy Composition (vol. %) (after preparation)	Preferred Method for Preparation of Alloy	Preferable Temperature Limits of Alloy in Oxidizing Atmosphere	Reference to Constitutional Diagram for Alloy prior to Oxidation
X - Bal. Au.			
7.5 Al_2O_3 -	D.H. or I.O.H.	R.T. TO ⩽ 800°C	p.68
7.5 BeO -	N.D.	↑	p.187
7.5 CeO_2 -	N.D.		p.198
7.5 HfO_2 -	D.H.		—
7.5 La_2O_3 -	N.D.		p.212
7.5 MgO -	N.D.		p.213
7.5 Nd_2O_3 -	D.H.		—
7.5 Sc_2O_3 -	D.H.		—
7.5 SiO_2 -	N.D. or I.O.H.		p.232
7.5 Sm_2O_3 -	D.H.		—
7.5 ThO_2 -	N.D.		p.236
7.5 TiO_2 -	N.D.	↓	p.237
7.5 Y_2O_3 -	D.H.	R.T. to ⩽ 800°C	—
X - Bal. 92.5 Vol. % Wt % of Alloy, 20 Rh, 80 Pt.			
7.5 Al_2O_3 -	N.D.	R.T. to 1575°C	—
7.5 BeO -	N.D.	↑	—
7.5 CeO_2 -	N.D.		—
7.5 HfO_2 -	N.D.		—
7.5 La_2O_3 -	N.D.		—
7.5 MgO -	N.D.		—
7.5 Nd_2O_3 -	N.D.		—
7.5 Sc_2O_3 -	N.D.		—
7.5 SiO_2 -	N.D.		—
7.5 Sm_2O_3 -	N.D.		—
7.5 ThO_2 -	N.D.		—
7.5 TiO_2 -	N.D.	↓	—
7.5 Y_2O_3 -	N.D.	R.T. to 1575°C	—

APPENDIX

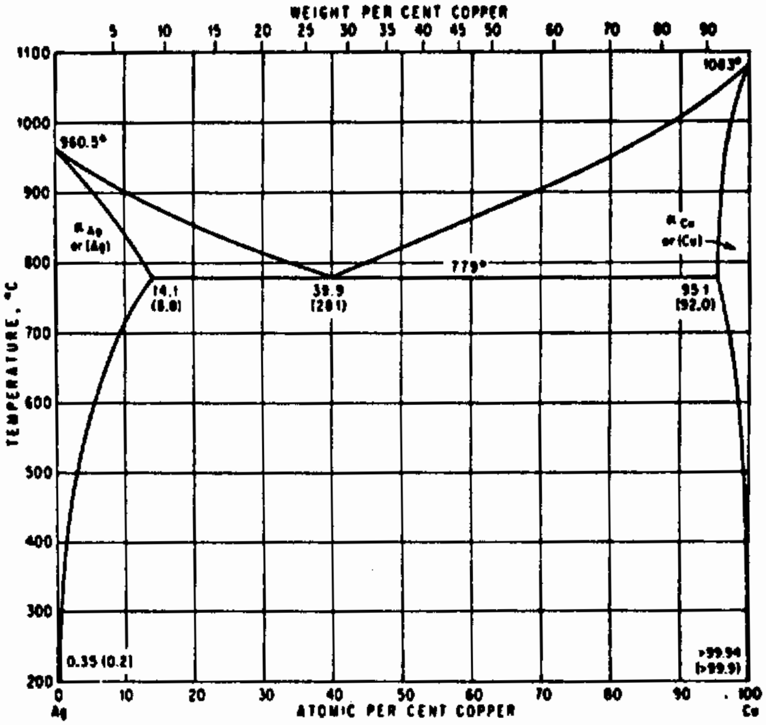
Compilation of Phase Diagrams

Phase diagrams selected from "CONSTITUTION OF BINARY ALLOYS" by Max Hansen, 2nd Ed., Copyright, 1958. McGraw-Hill Book Company; used by permission.

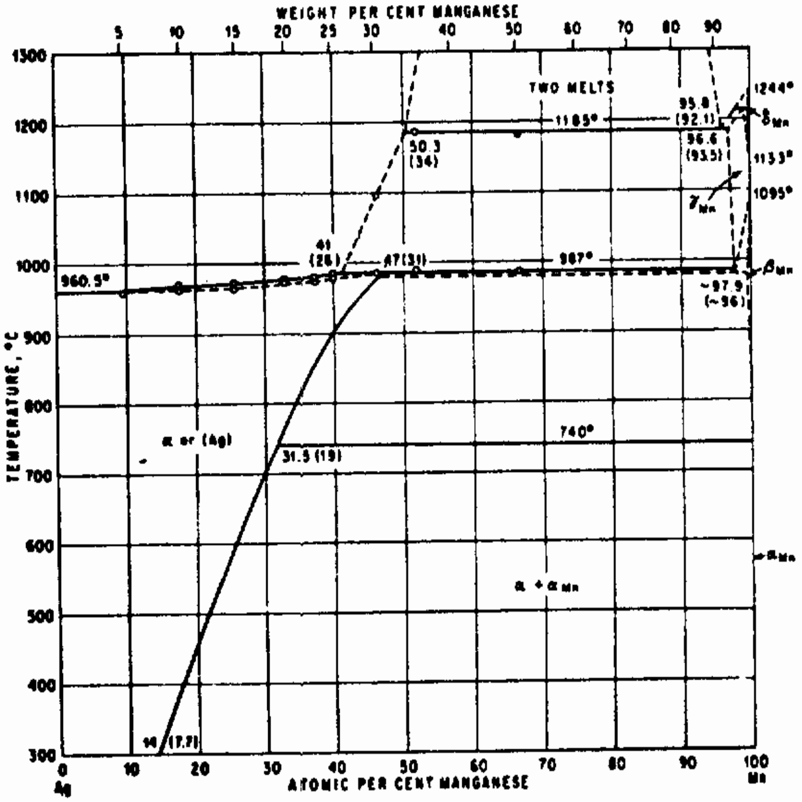
(Ag-Au, Ag-Cu, Ag-Mn, Ag-Pd, Ag-Pt, Al-Cu, Al-Cu, Al-Fe, Al-Ni, Al-Ti, Au-Cu, Au-Fe, Au-Mn, Au-Pd, Au-Pt, B-Ti, B-Zr, Be-Cu, C-Nb, C-Ta, C-Ti, C-V, Co-Fe, Co-Ni, Co-Ta, Cr-Cu, Cr-Fe, Cr-Ni, Cu-Mn, Cu-Ni, Cu-Pd, Cu-Pt, Cu-Si, Cu-Sn, Cu-Zn, Fe-Pt, Fe-Si, Ir-Pt, Mn-Ni, Mo-Si, N-Nb, N-Ti, N-Zr, Nb-Si, Ni-Pd, Ni-Pt, Ni-Si, Pt-Rh, Si-Ta, Si-Ti, Si-U, Si-V, Si-Zr, Sn-Ti)


WEIGHT PER CENT GOLD
10
20
30
40
50
60
65
70
75
80
85
90
95
1100
1050
1000
950
900
TEMPERATURE, °C
1063°
960.5°
α
Ag Au
α'?
0
Ag
10
20
30
40
50
60
70
80
90
100
Au
ATOMIC PER CENT GOLD

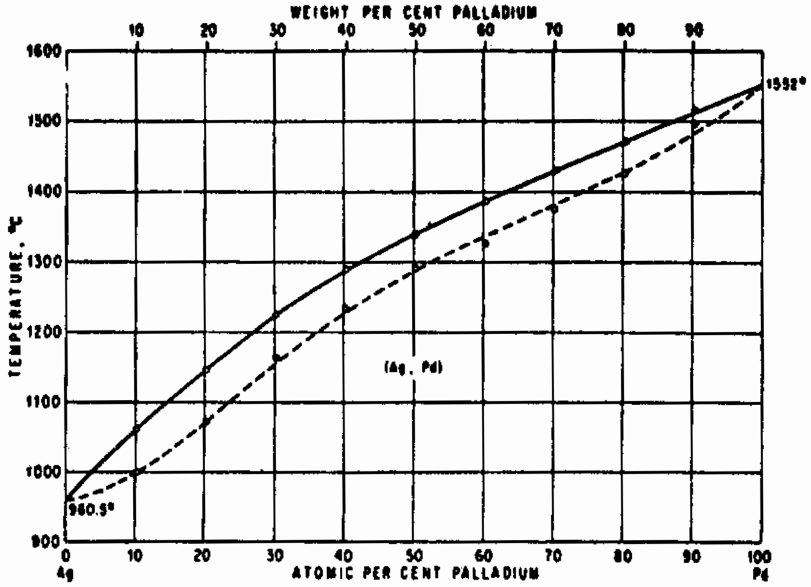
Ag-Au


WEIGHT PER CENT COPPER
5
10
15
20
25
30
35
40
45
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE, °C
960.5°
1083°
α Ag or (Ag)
α Cu or (Cu)
779°
14.1 (8.8)
39.9 (28.1)
95.1 (92.0)
0.35 (0.2)
>99.94 (>99.9)
0
Ag
10
20
30
40
50
60
70
80
90
100
Cu
ATOMIC PER CENT COPPER

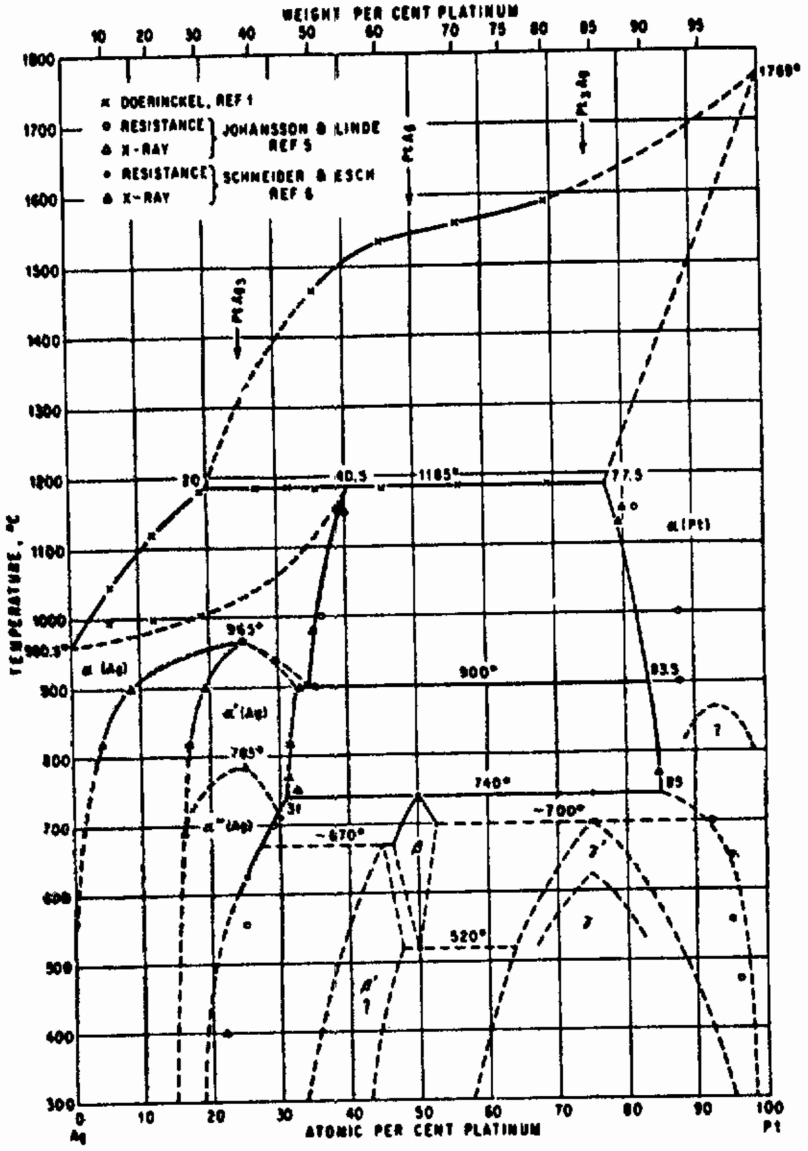
Ag- Cu


WEIGHT PER CENT MANGANESE
5
10
15
20
25
30
40
50
60
70
80
90
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
TWO MELTS
1244°
95.8
(92.1)
δMn
1185°
50.3
(34)
96.6
(93.5)
1133°
1095°
γMn
41
(26)
47(31)
987°
βMn
960.5°
~97.9
(~96)
α or (Ag)
740°
31.5 (19)
αMn
α + αMn
14 (7.7)
0
Ag
10
20
30
40
50
60
70
80
90
100
Mn
ATOMIC PER CENT MANGANESE

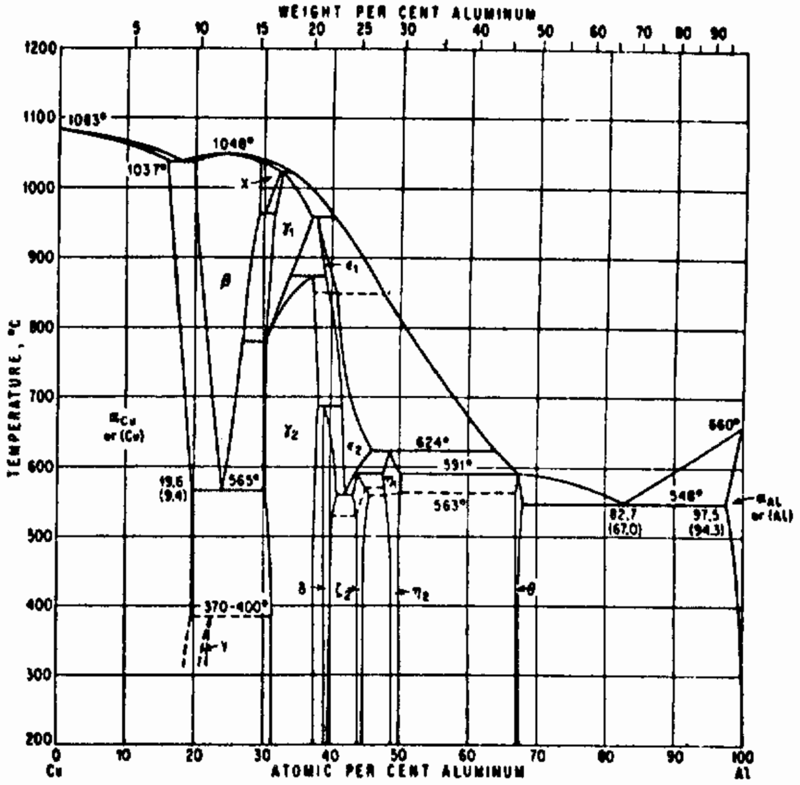
Ag-Mn


WEIGHT PER CENT PALLADIUM
10
20
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
1100
1000
900
TEMPERATURE, °C
1552°
(Ag, Pd)
960.5°
0
Ag
10
20
30
40
50
60
70
80
90
100
Pd
ATOMIC PER CENT PALLADIUM

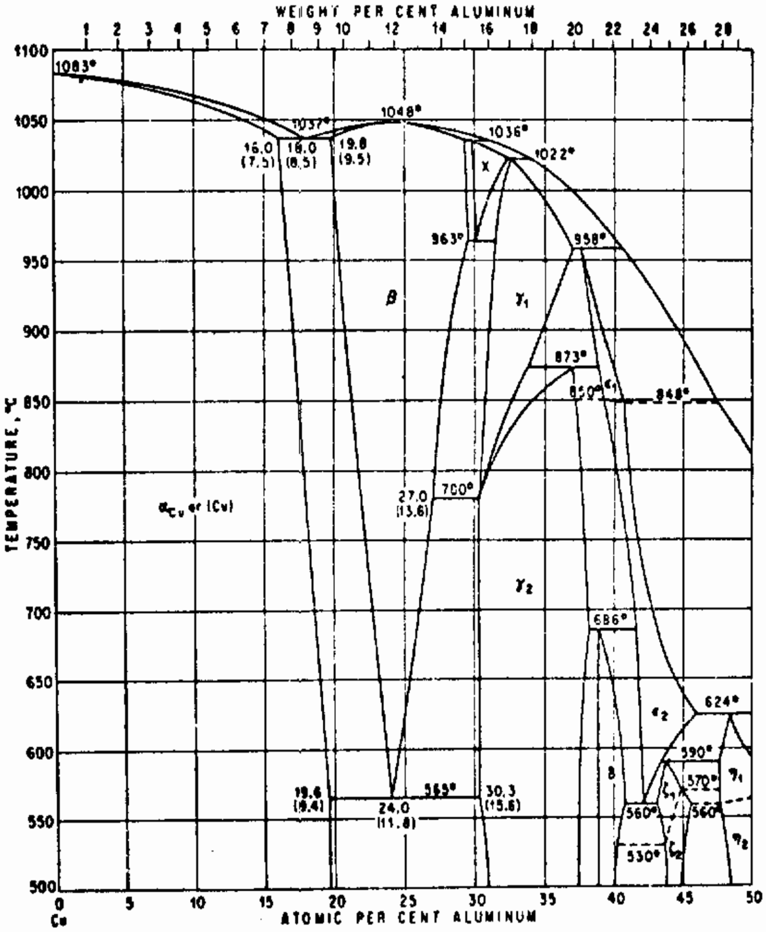
Ag-Pd


WEIGHT PER CENT PLATINUM
10
20
30
40
50
60
70
75
80
85
90
95
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
× DOERINCKEL, REF 1
○ RESISTANCE
△ X-RAY
JOHANSSON & LINDE REF 5
● RESISTANCE
▲ X-RAY
SCHNEIDER & ESCH REF 6
PtAg
Pt₃Ag
PtAg₃
1769°
20
40.5
1185°
77.5
α (Pt)
960.5°
α (Ag)
965°
900°
83.5
α' (Ag)
785°
740°
85
31
~700°
α'' (Ag)
~670°
β
γ
?
520°
β'
?
0
Ag
10
20
30
40
50
60
70
80
90
100
Pt
ATOMIC PER CENT PLATINUM

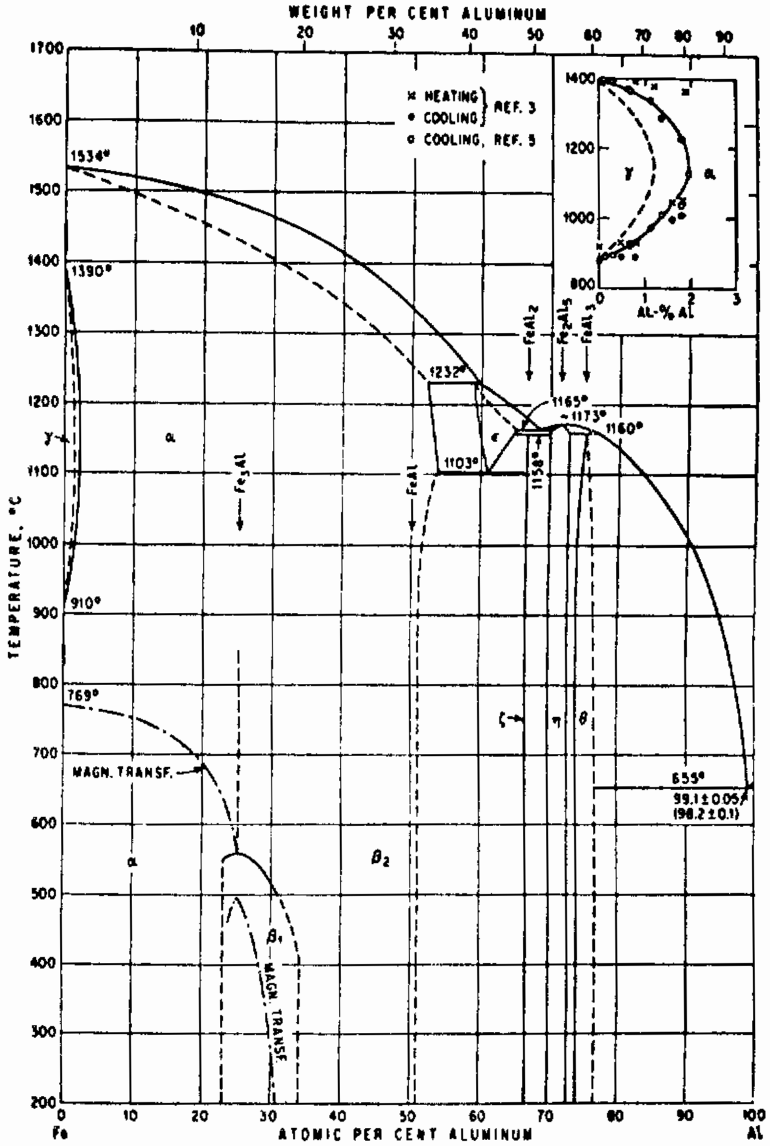
Ag-Pt


WEIGHT PER CENT ALUMINUM
5
10
15
20
25
30
40
50
60
70
80
90
TEMPERATURE, °C
1200
1100
1000
900
800
700
600
500
400
300
200
1083°
1037°
1048°
X
γ_1
β
ϵ_1
α_{Cu} or (Cu)
γ_2
ϵ_2
624°
591°
660°
19.6 (9.4)
565°
563°
η_1
548°
82.7 (67.0)
97.5 (94.3)
α_{Al} or (Al)
370-400°
δ
ζ_2
η_2
θ
β
γ
0 Cu
10
20
30
40
50
60
70
80
90
100 Al
ATOMIC PER CENT ALUMINUM

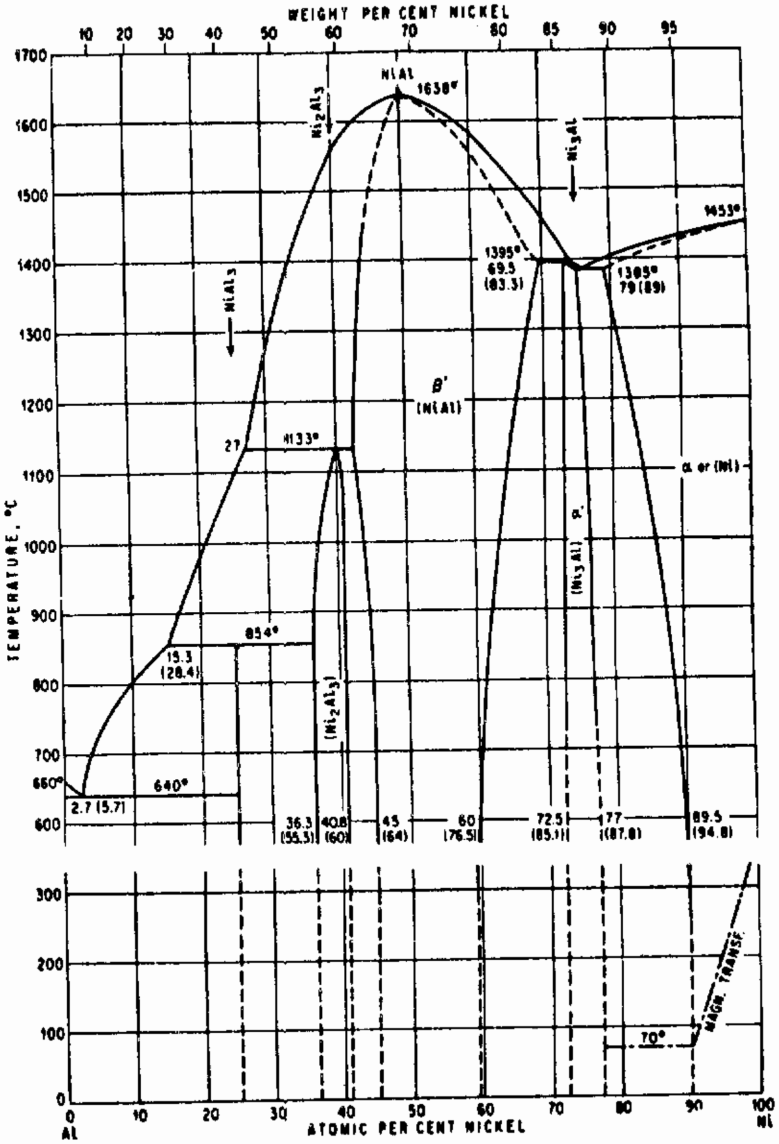
Al-Cu


WEIGHT PER CENT ALUMINUM
1
2
3
4
5
6
7
8
9
10
12
14
16
18
20
22
24
26
28
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
TEMPERATURE, °C
0
Cu
5
10
15
20
25
30
35
40
45
50
ATOMIC PER CENT ALUMINUM
1083°
1037°
1048°
1036°
1022°
16.0
(7.5)
18.0
(8.5)
19.8
(9.5)
X
963°
958°
β
γ1
873°
850°
ε1
848°
αCu or (Cu)
27.0
(13.6)
780°
γ2
686°
ε2
624°
590°
δ
570°
η1
ζ1
19.6
(9.4)
565°
30.3
(15.6)
24.0
(11.8)
560°
560°
530°
ζ2
η2

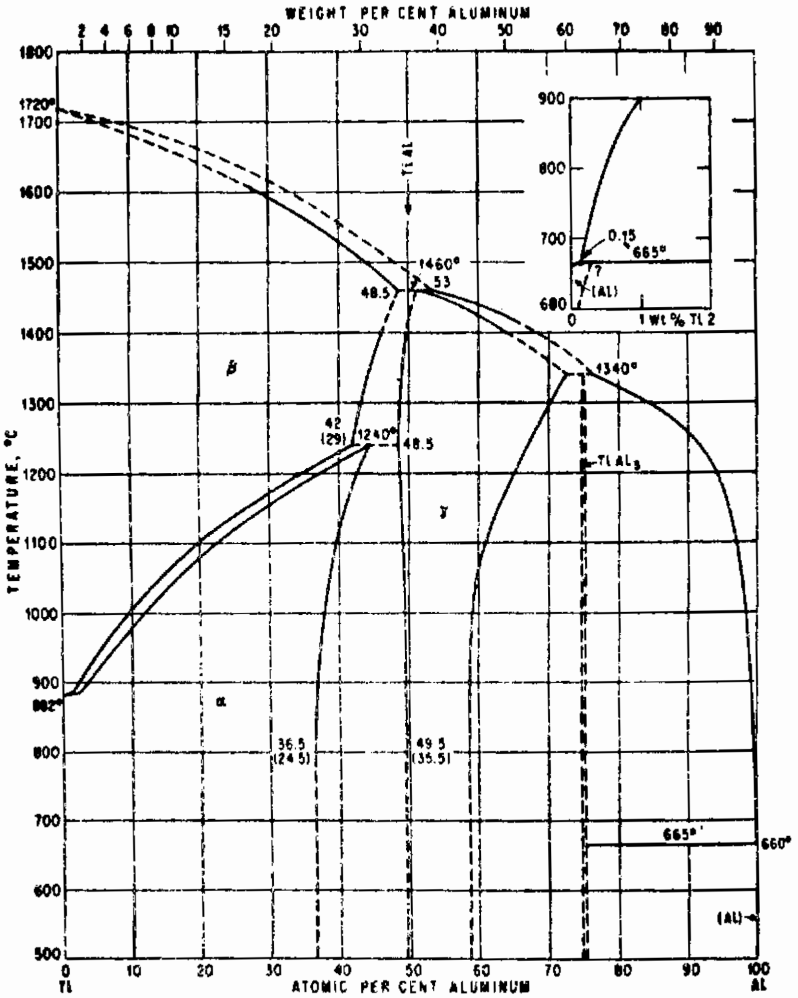
Al-Cu


WEIGHT PER CENT ALUMINUM
10
20
30
40
50
60
70
80
90
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE, °C
× HEATING
• COOLING
REF. 3
○ COOLING, REF. 5
1534°
1390°
910°
769°
γ
α
Fe3Al
FeAl
FeAl2
Fe2Al5
FeAl3
1232°
1103°
ε
1158°
1165°
~1173°
1160°
ζ
η
θ
MAGN. TRANSF.
655°
99.1±0.05
(98.2±0.1)
α
β2
β1
MAGN. TRANSF.
1400
1200
1000
800
0
1
2
3
AL-% AL
γ
α
0
10
20
30
40
50
60
70
80
90
100
Fe
Al
ATOMIC PER CENT ALUMINUM

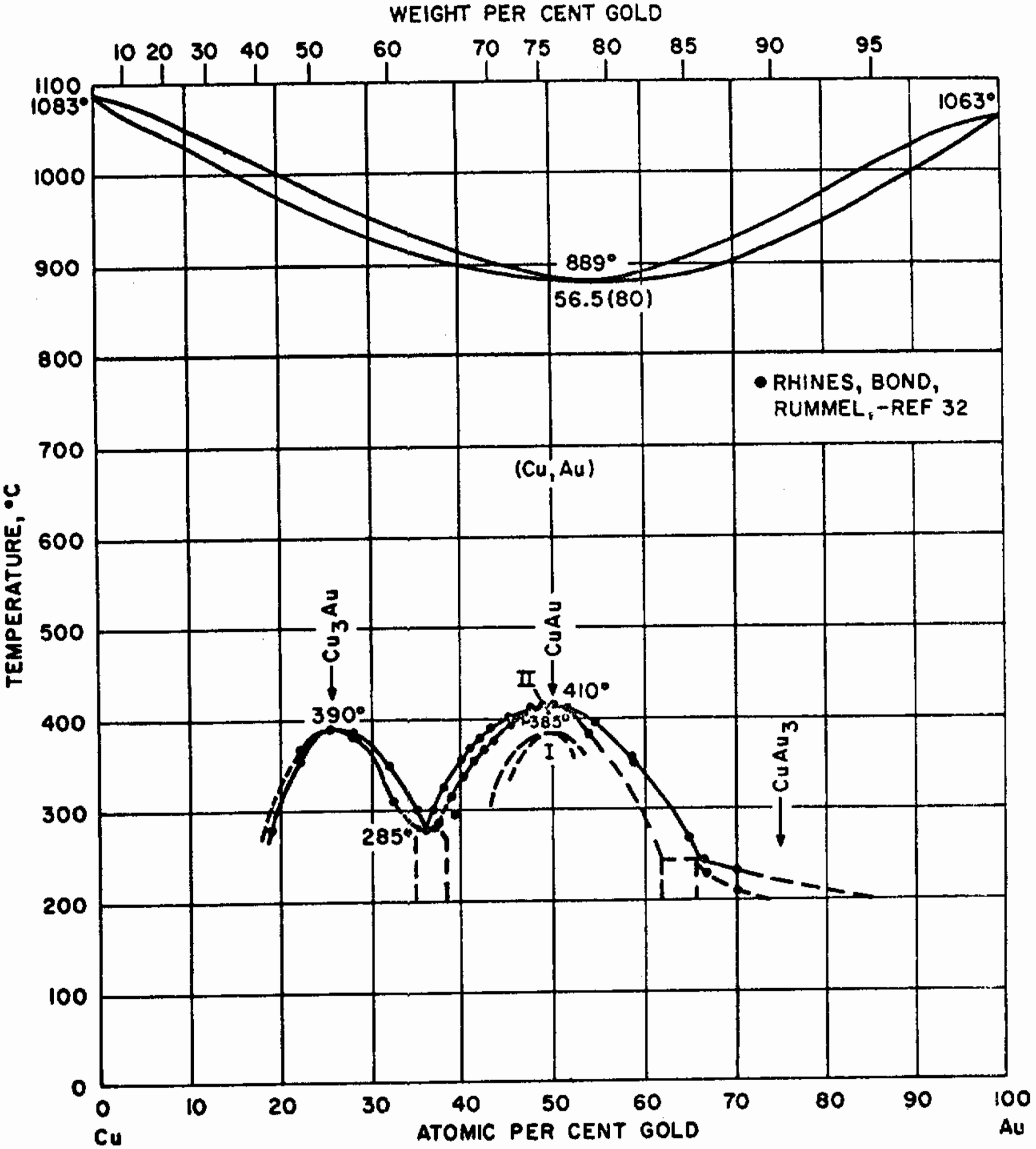
Al-Fe


WEIGHT PER CENT NICKEL
10
20
30
40
50
60
70
80
85
90
95
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
300
200
100
0
TEMPERATURE, °C
NiAl
1638°
Ni2Al3
Ni3Al
NiAl3
1453°
1395°
69.5
(83.3)
1385°
79 (89)
β'
(NiAl)
27
1133°
α or (Ni)
α'
(Ni3Al)
854°
15.3
(28.4)
(Ni2Al3)
640°
2.7 (5.7)
36.3
(55.3)
40.8
(60)
45
(64)
60
(76.5)
72.5
(85.1)
77
(87.8)
89.5
(94.8)
70°
MAGN. TRANSF.
0
Al
10
20
30
40
50
60
70
80
90
100
Ni
ATOMIC PER CENT NICKEL

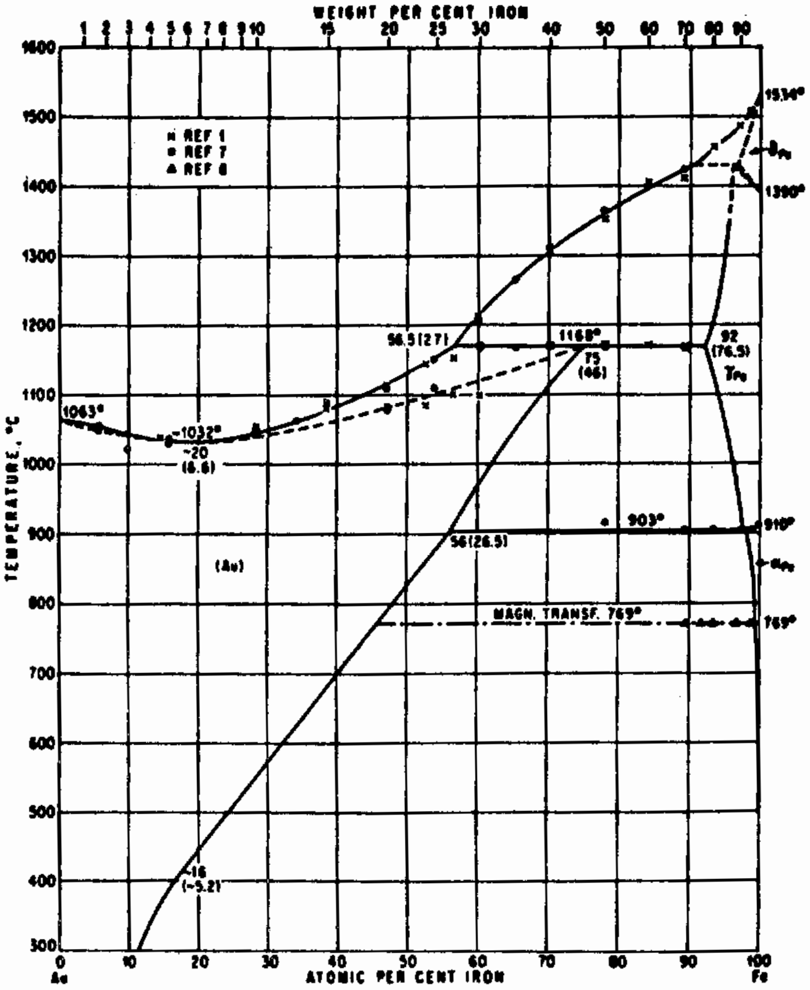
Al-Ni


WEIGHT PER CENT ALUMINUM
2 4 6 8 10 15 20 30 40 50 60 70 80 90
1800
1720°
1700
1600
1500
1400
1300
1200
1100
1000
900
882°
800
700
600
500
TEMPERATURE, °C
TiAl
1460°
53
48.5
β
1340°
42
(29)
1240°
48.5
TiAl3
γ
α
36.5
(24.5)
49.5
(35.5)
665°
660°
(Al)
900
800
700
600
0.15
665°
?
(Al)
0 1 Wt % Ti 2
0 10 20 30 40 50 60 70 80 90 100
Ti
Al
ATOMIC PER CENT ALUMINUM

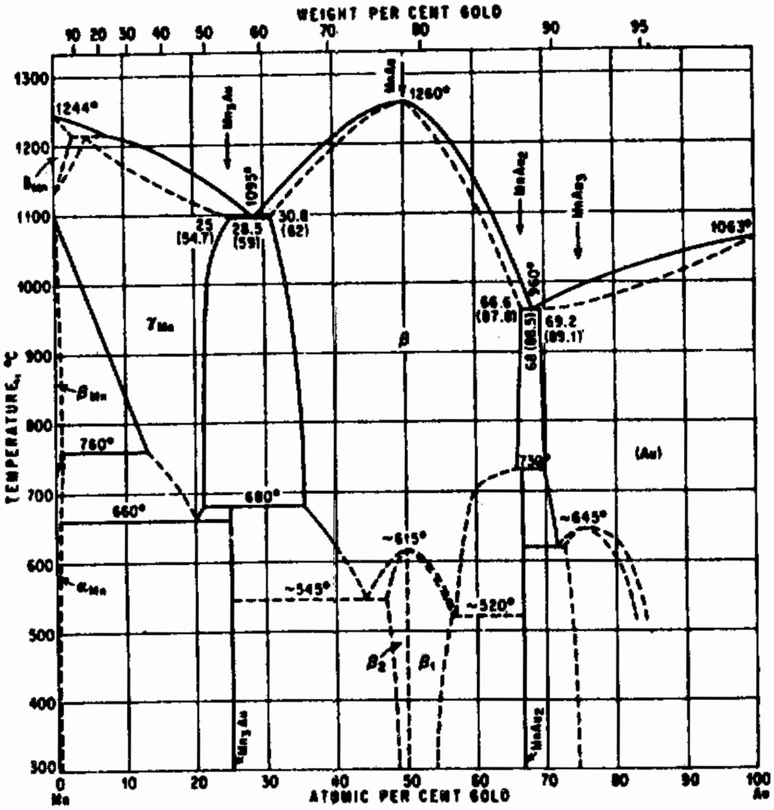
Al-Ti


WEIGHT PER CENT GOLD
10 20 30 40 50 60 70 75 80 85 90 95
1100
1083°
1063°
1000
900
889°
56.5(80)
800
● RHINES, BOND, RUMMEL, -REF 32
700
(Cu, Au)
600
500
Cu3Au
CuAu
II
410°
400
390°
385°
I
CuAu3
300
285°
200
100
0
TEMPERATURE, °C
0 Cu
10 20 30 40 50 60 70 80 90
100 Au
ATOMIC PER CENT GOLD

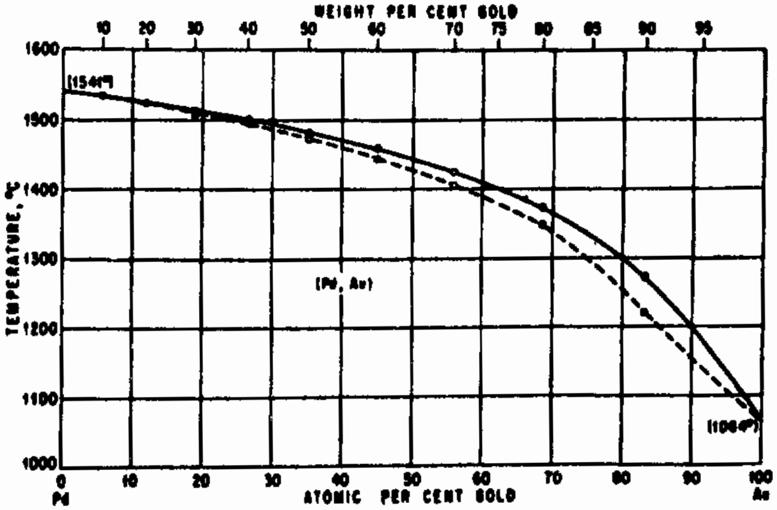
Au-Cu


WEIGHT PER CENT IRON
1 2 3 4 5 6 7 8 9 10 15 20 25 30 40 50 60 70 80 90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
× REF 1
● REF 7
▲ REF 8
1534°
δ_{Fe}
1390°
56.5(27)
1168°
75
(46)
92
(76.5)
γ_{Fe}
1063°
~1032°
~20
(6.6)
903°
910°
56(26.5)
α_{Fe}
(Au)
MAGN. TRANSF. 769°
769°
~16
(~5.2)
0
Au
10 20 30 40 50 60 70 80 90 100
Fe
ATOMIC PER CENT IRON

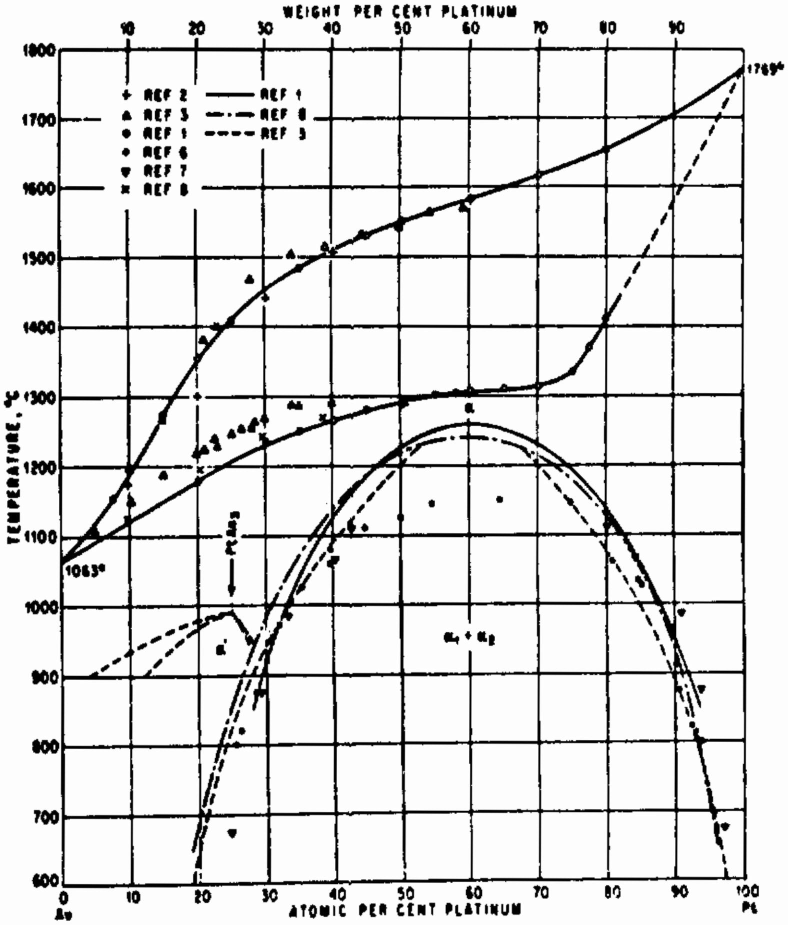
Au-Fe


WEIGHT PER CENT GOLD
10
20
30
40
50
60
70
80
90
95
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
1244°
β_{Mn}
Mn_3Au
1095°
25
(54.7)
28.5
(59)
30.8
(62)
MnAu
1260°
$MnAu_2$
$MnAu_3$
1063°
960°
66.6
(87.8)
68 (88.5)
69.2
(89.1)
γ_{Mn}
β
β_{Mn}
760°
(Au)
730°
680°
660°
~645°
~615°
~545°
~520°
α_{Mn}
β_2
β_1
Mn_3Au
$MnAu_2$
0
Mn
10
20
30
40
50
60
70
80
90
100
Au
ATOMIC PER CENT GOLD

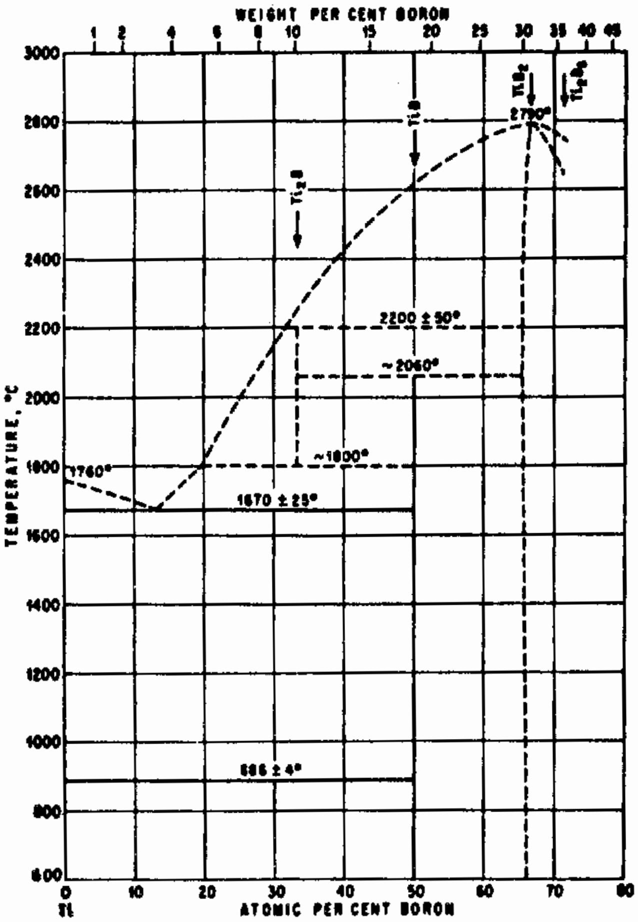
Au-Mn


WEIGHT PER CENT GOLD
10
20
30
40
50
60
70
75
80
85
90
95
1600
1500
1400
1300
1200
1100
1000
TEMPERATURE, °C
(1541°)
(Pd, Au)
(1064°)
0
Pd
10
20
30
40
50
60
70
80
90
100
Au
ATOMIC PER CENT GOLD

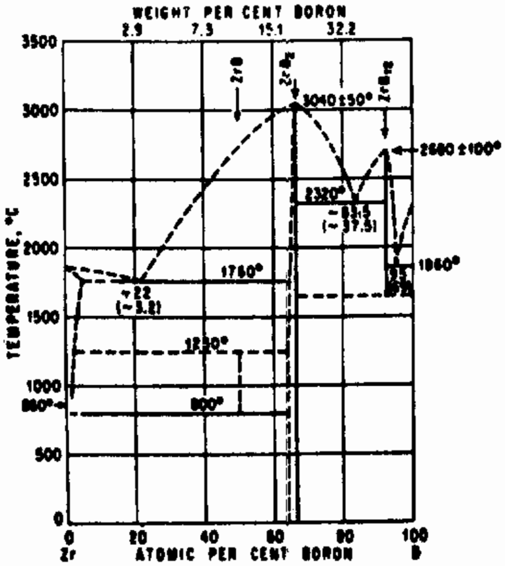
Au-Pd


WEIGHT PER CENT PLATINUM
10
20
30
40
50
60
70
80
90
+ REF 2
▲ REF 3
● REF 1
• REF 6
▼ REF 7
× REF 8
REF 1
REF 8
REF 3
1769°
1063°
Pt Au3
α'
α
α1 + α2
TEMPERATURE, °C
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
0
Au
10
20
30
40
50
60
70
80
90
100
Pt
ATOMIC PER CENT PLATINUM

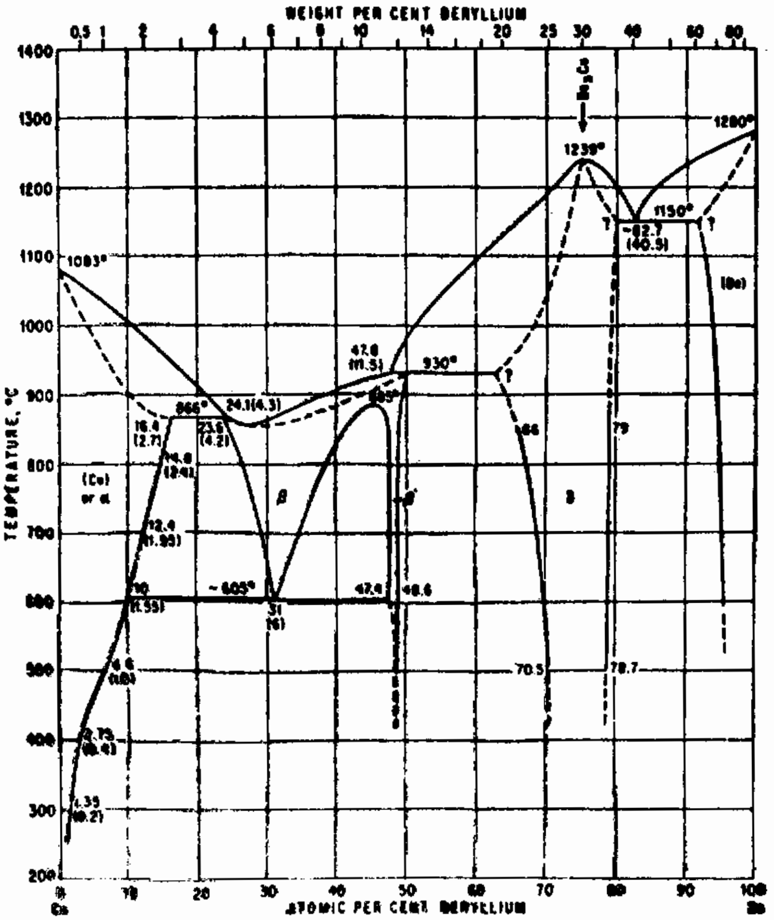
Au-Pt


WEIGHT PER CENT BORON
1
2
4
6
8
10
15
20
25
30
35
40
45
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
TEMPERATURE, °C
Ti_2B
TiB
TiB_2
Ti_2B_5
2790°
2200 ± 50°
~2060°
~1800°
1760°
1670 ± 25°
886 ± 4°
0
Ti
10
20
30
40
50
60
70
80
ATOMIC PER CENT BORON

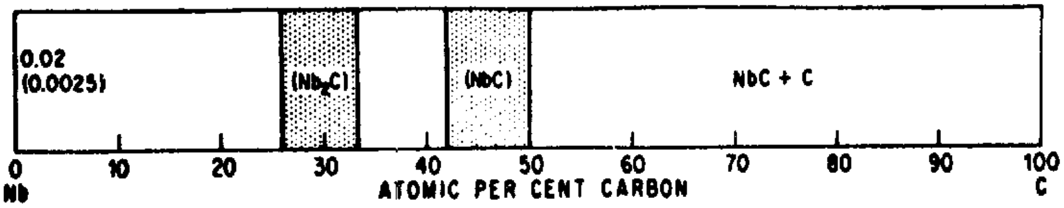
B-Ti


WEIGHT PER CENT BORON
2.9
7.3
15.1
32.2
3500
3000
2500
2000
1500
1000
500
0
TEMPERATURE, °C
ZrB
ZrB_2
ZrB_{12}
3040±50°
2680±100°
2320°
~83.5
(~37.5)
1760°
~22
(~3.2)
1860°
1230°
800°
860°
0
Zr
20
40
60
80
100
B
ATOMIC PER CENT BORON

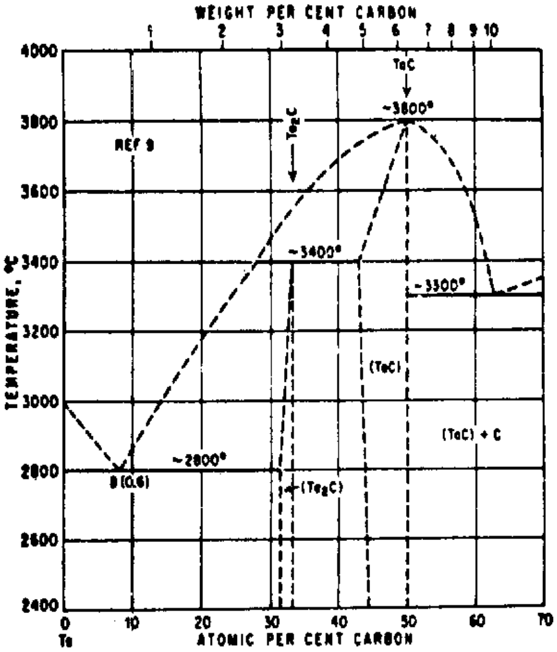
B-Zr


WEIGHT PER CENT BERYLLIUM
0.5
1
2
4
6
8
10
14
20
25
30
40
60
80
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE, °C
Be₂Cu
1280°
1239°
1150°
~82.7
(40.5)
?
1083°
(Be)
47.8
(11.5)
930°
?
866°
24.1(4.3)
16.4
(2.7)
23.6
(4.2)
885°
86
79
(Cu)
or α
14.8
(2.4)
β
+β'
δ
12.4
(1.95)
10
(1.55)
~605°
47.4
48.6
31
(6)
6.6
(1.0)
70.5
78.7
2.75
(0.4)
1.35
(0.2)
0
Cu
10
20
30
40
50
60
70
80
90
100
Be
ATOMIC PER CENT BERYLLIUM

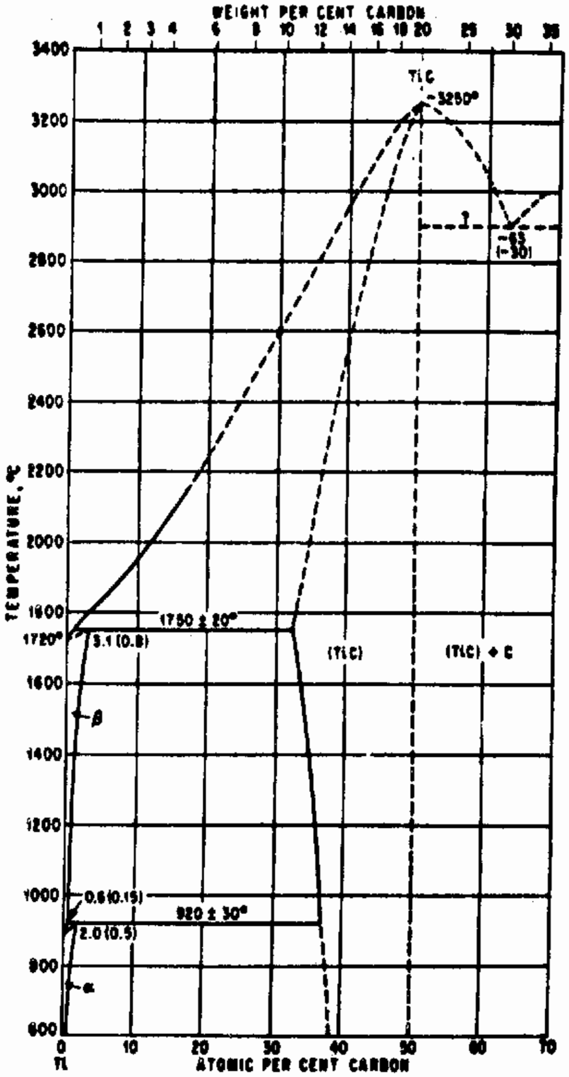
Be-Cu


0.02
(0.0025)
(Nb_2C)
(NbC)
NbC + C
0
Nb
10
20
30
40
50
60
70
80
90
100
C
ATOMIC PER CENT CARBON

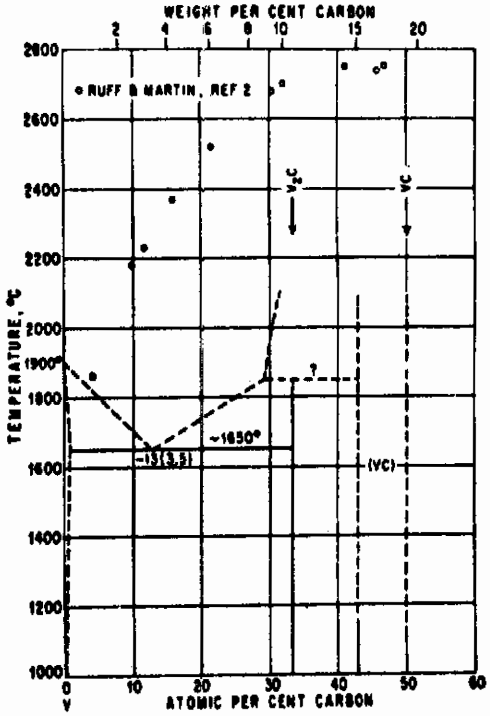
C-Nb


WEIGHT PER CENT CARBON
1
2
3
4
5
6
7
8
9
10
4000
3800
3600
3400
3200
3000
2800
2600
2400
TEMPERATURE, °C
REF 9
Ta_2C
TaC
~3800°
~3400°
~3300°
(TaC)
(TaC) + C
~2800°
8 (0.6)
(Ta_2C)
0
Ta
10
20
30
40
50
60
70
ATOMIC PER CENT CARBON

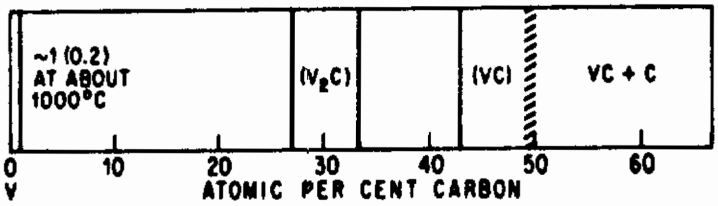
C-Ta


WEIGHT PER CENT CARBON
1
2
3
4
6
8
10
12
14
16
18
20
25
30
35
3400
3200
3000
2800
2600
2400
2200
2000
1800
1720°
1600
1400
1200
1000
800
600
TEMPERATURE, °C
TiC
~3250°
?
~63
(~30)
1750 ± 20°
3.1 (0.8)
(TiC)
(TiC) + C
β
0.6 (0.15)
920 ± 30°
2.0 (0.5)
α
0
Ti
10
20
30
40
50
60
70
ATOMIC PER CENT CARBON

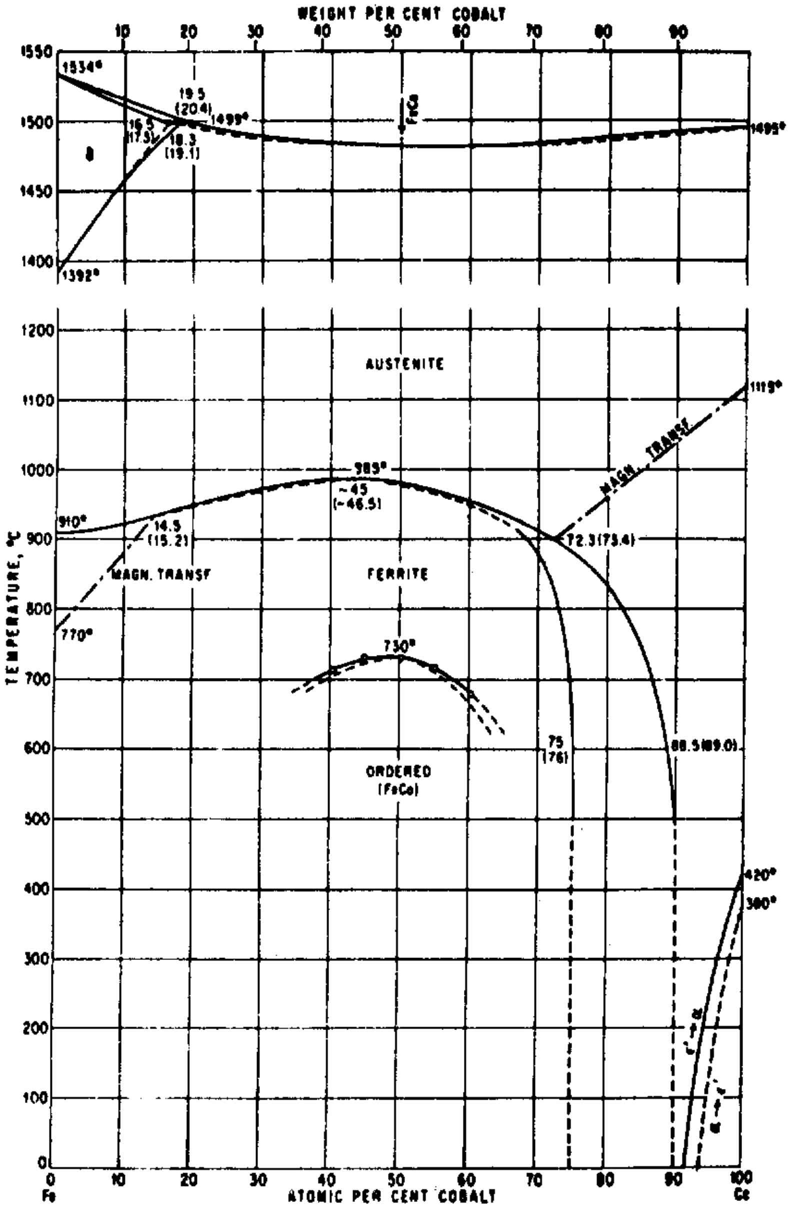
C-Ti


WEIGHT PER CENT CARBON
2
4
6
8
10
15
20
2800
2600
2400
2200
2000
1900°
1800
1600
1400
1200
1000
TEMPERATURE, °C
• RUFF & MARTIN, REF 2
V_2C
VC
?
~1650°
~13(3.5)
(VC)
0
V
10
20
30
40
50
60
ATOMIC PER CENT CARBON

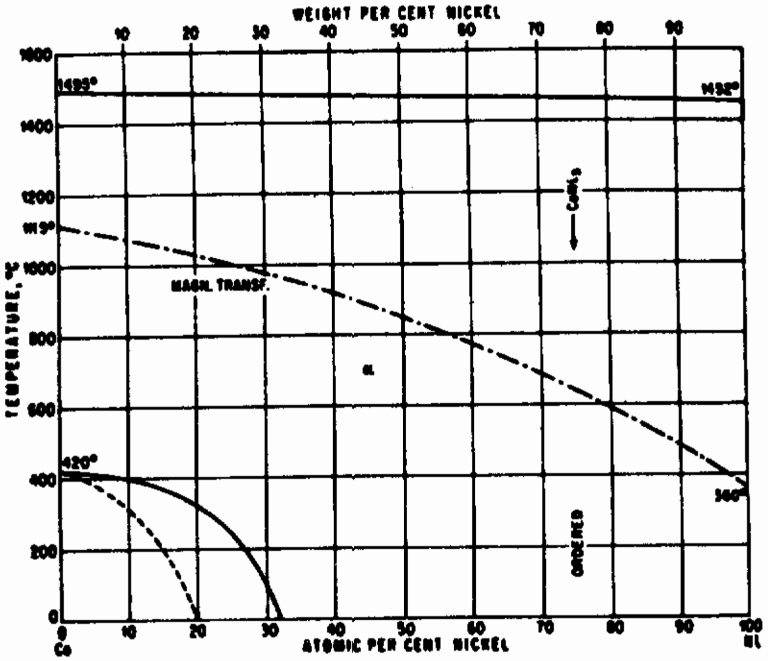
C-V


~1 (0.2)
AT ABOUT
1000°C
(V_2C)
(VC)
VC + C
0
V
10
20
30
40
50
60
ATOMIC PER CENT CARBON

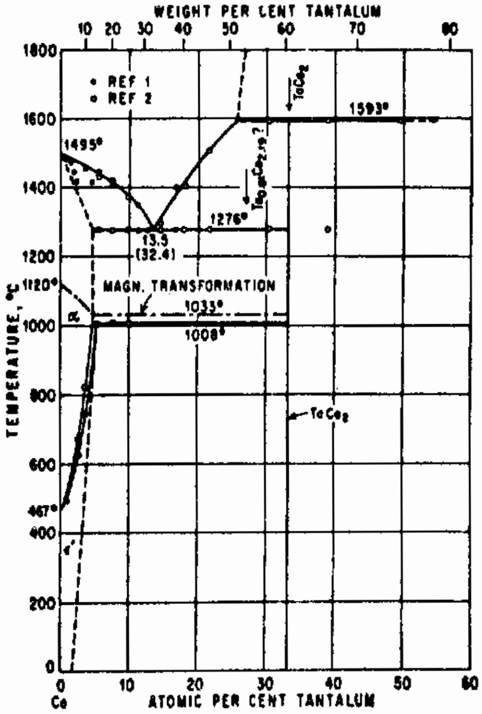
C-V


WEIGHT PER CENT COBALT
10
20
30
40
50
60
70
80
90
1550
1500
1450
1400
1534°
19.5
(20.4)
1499°
16.5
(17.5)
18.3
(19.1)
δ
FeCo
1495°
1392°
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE, °C
AUSTENITE
1119°
MAGN. TRANSF
989°
~45
(~46.5)
910°
14.5
(15.2)
72.3(73.4)
MAGN. TRANSF
FERRITE
770°
730°
75
(76)
88.5(89.0)
ORDERED
(FeCo)
420°
380°
ε→α
α→ε
0
Fe
10
20
30
40
50
60
70
80
90
100
Co
ATOMIC PER CENT COBALT

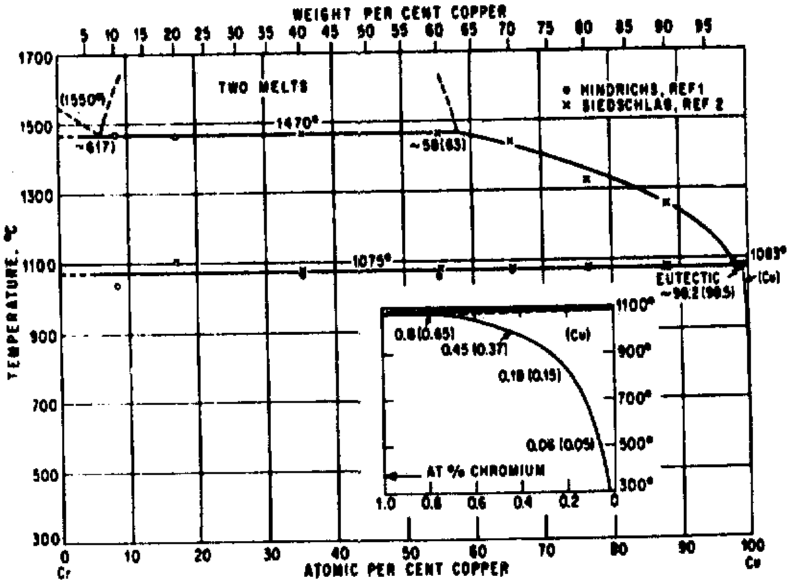
Co-Fe


WEIGHT PER CENT NICKEL
10
20
30
40
50
60
70
80
90
1600
1495°
1452°
1400
1200
1115°
$\longleftarrow CoNi_3$
1000
MAGN. TRANSF.
800
α
600
420°
400
360°
ORDERED
200
0
TEMPERATURE, °C
0
Co
10
20
30
40
50
60
70
80
90
100
Ni
ATOMIC PER CENT NICKEL

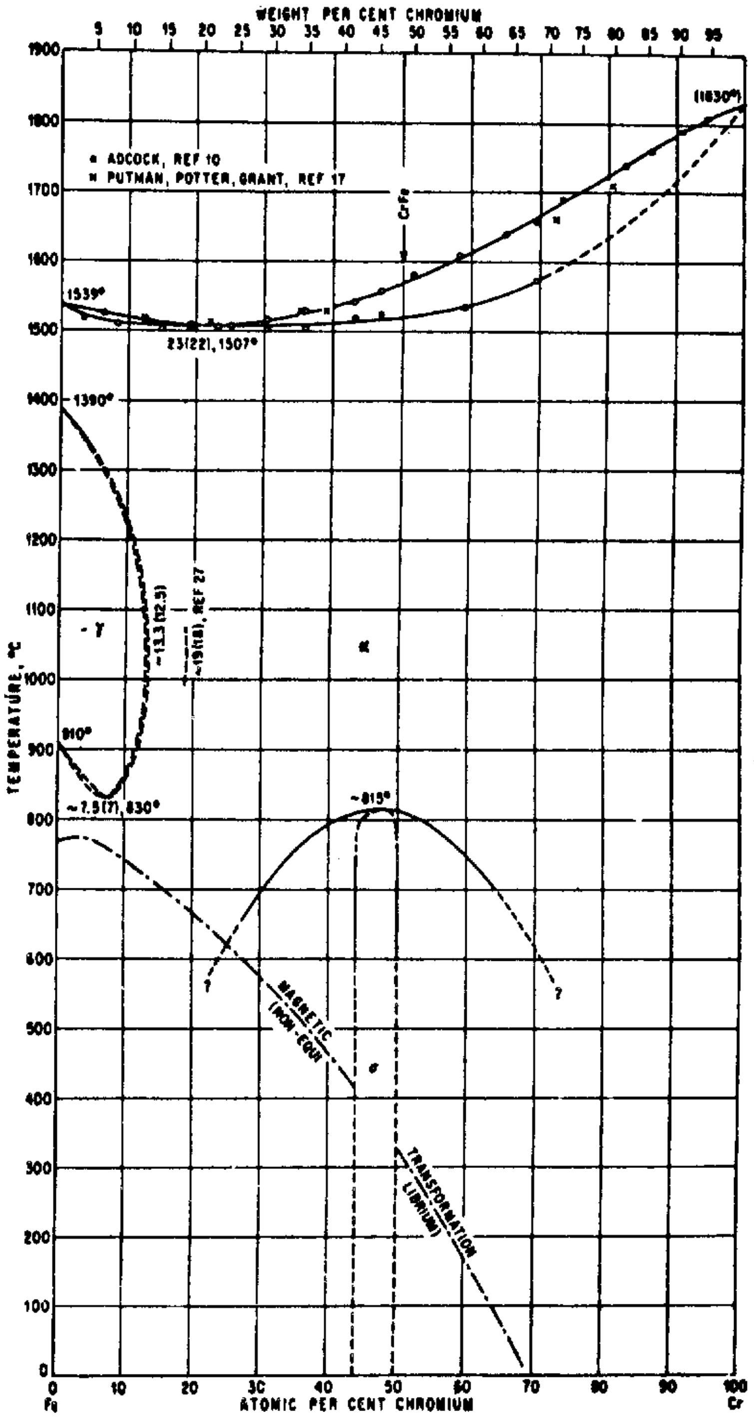
Co-Ni


WEIGHT PER CENT TANTALUM
10
20
30
40
50
60
70
80
• REF 1
○ REF 2
TaCo₂
1593°
1495°
Ta0.81Co2.19 ?
1276°
13.5
(32.4)
1120°
MAGN. TRANSFORMATION
1033°
α
1008°
TaCo₂
467°
α'
TEMPERATURE, °C
1800
1600
1400
1200
1000
800
600
400
200
0
0
Co
10
20
30
40
50
60
ATOMIC PER CENT TANTALUM

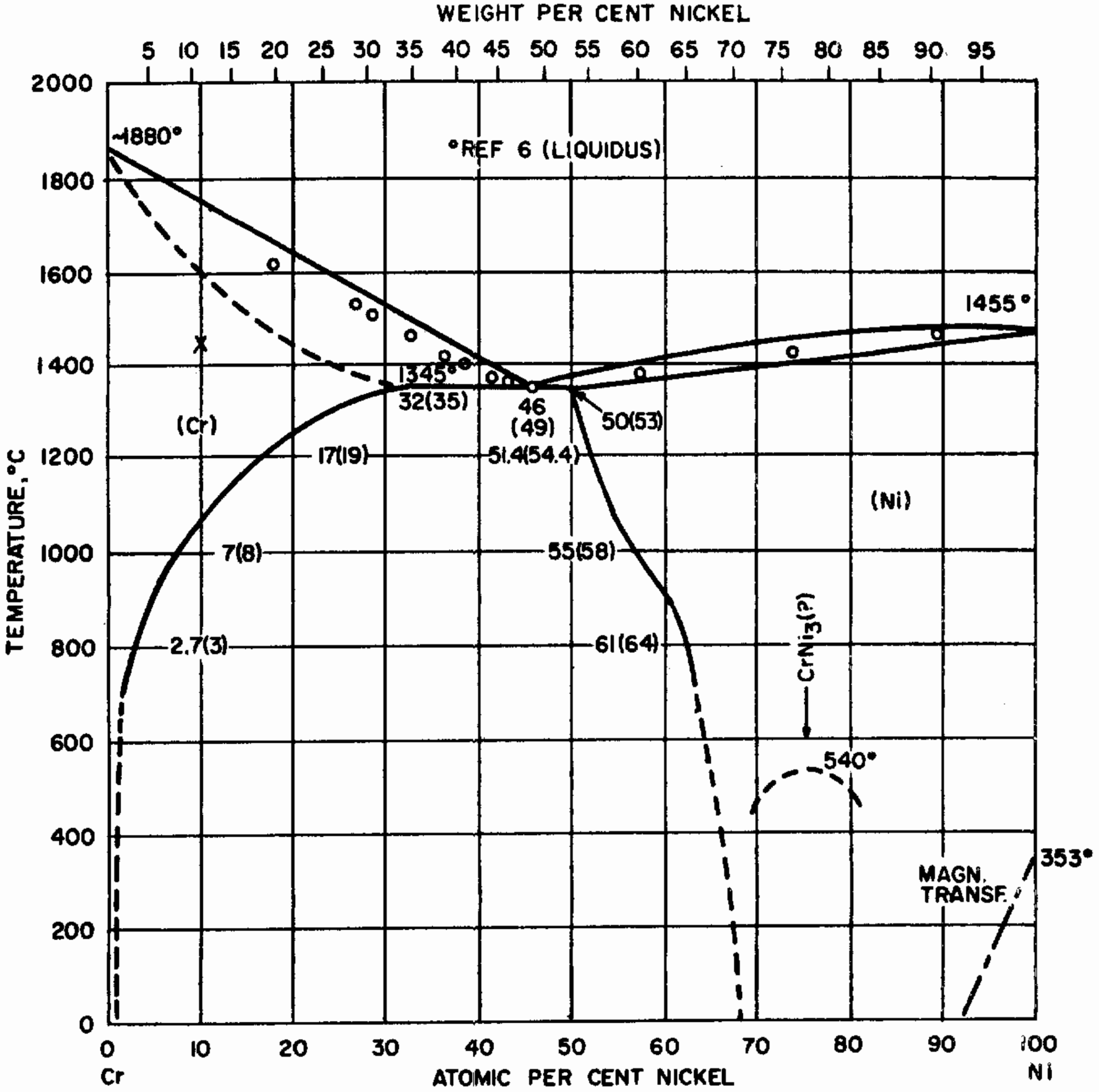
Co-Ta


WEIGHT PER CENT COPPER
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95
TWO MELTS
● HINDRICHS, REF 1
× SIEDSCHLAG, REF 2
(1550°)
~6(7)
1470°
~58(63)
1075°
1083°
EUTECTIC ~98.2 (98.5)
(Cu)
TEMPERATURE, °C
1700
1500
1300
1100
900
700
500
300
0.8 (0.65)
0.45 (0.37)
0.18 (0.15)
0.06 (0.05)
1100°
900°
700°
500°
300°
AT % CHROMIUM
1.0 0.8 0.6 0.4 0.2 0
0 Cr
10 20 30 40 50 60 70 80 90
100 Cu
ATOMIC PER CENT COPPER

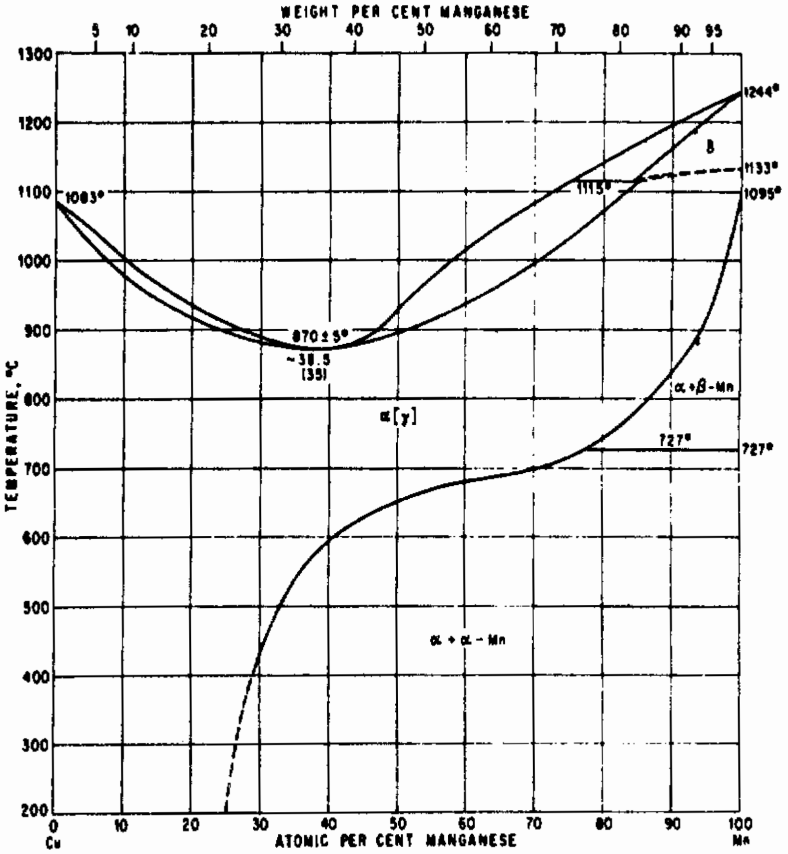
Cr-Cu


WEIGHT PER CENT CHROMIUM
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
● ADCOCK, REF 10
× PUTMAN, POTTER, GRANT, REF 17
(1830°)
CrFe
1539°
23(22), 1507°
1390°
γ
~13.3(12.5)
~19(18), REF 27
α
910°
~7.5(7), 830°
~815°
?
?
MAGNETIC
(NON-EQUI
σ
TRANSFORMATION
LIBRIUM)
TEMPERATURE, °C
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
Fe
10
20
30
40
50
60
70
80
90
100
Cr
ATOMIC PER CENT CHROMIUM

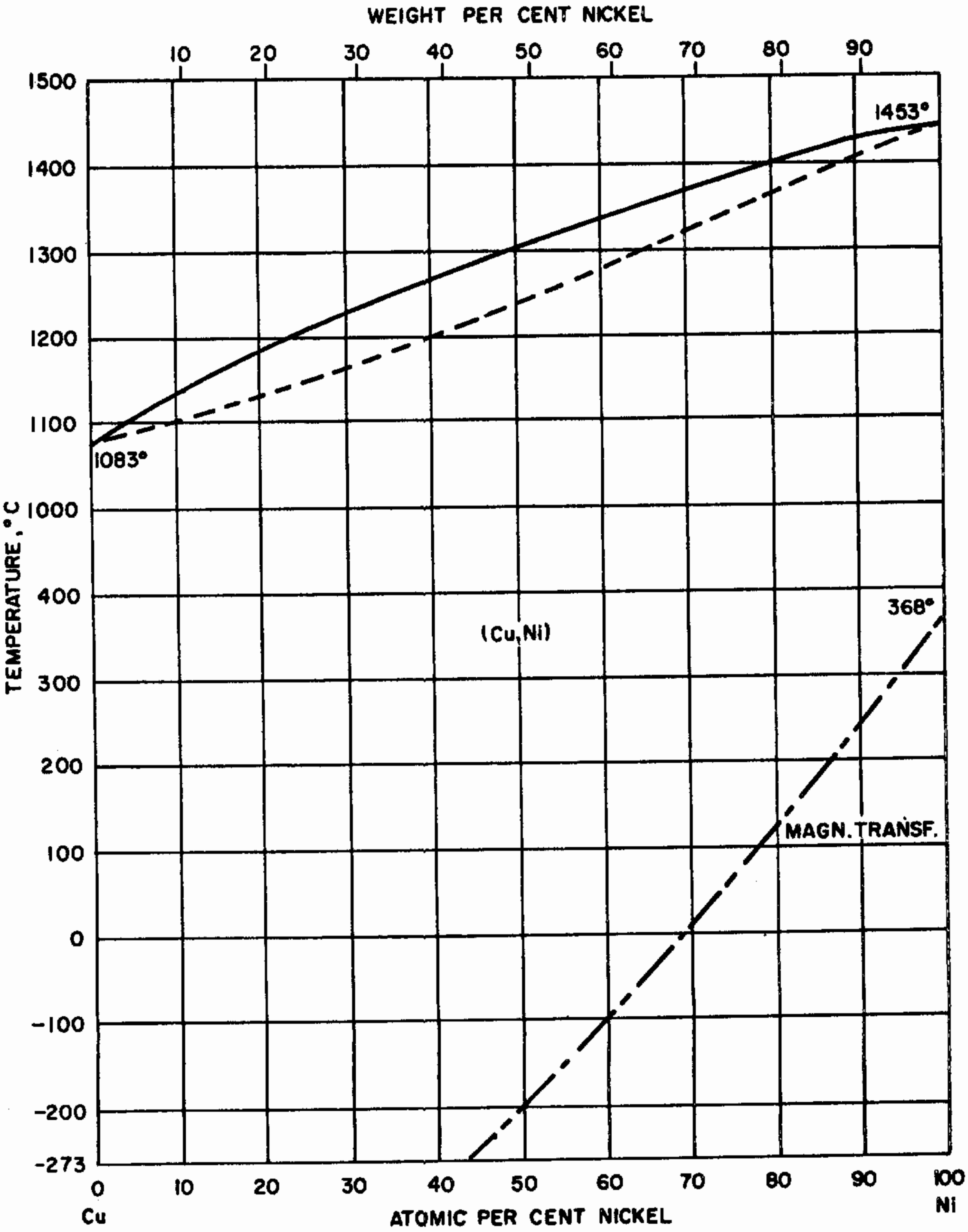
Cr-Fe


WEIGHT PER CENT NICKEL
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
2000
1800
1600
1400
1200
1000
800
600
400
200
0
TEMPERATURE, °C
~1880°
°REF 6 (LIQUIDUS)
1455°
X
1345°
32(35)
46
(49)
50(53)
(Cr)
17(19)
51.4(54.4)
(Ni)
7(8)
55(58)
2.7(3)
61(64)
CrNi3(?)
540°
353°
MAGN.
TRANSF.
0
Cr
10
20
30
40
50
60
70
80
90
100
Ni
ATOMIC PER CENT NICKEL

Cr-Ni

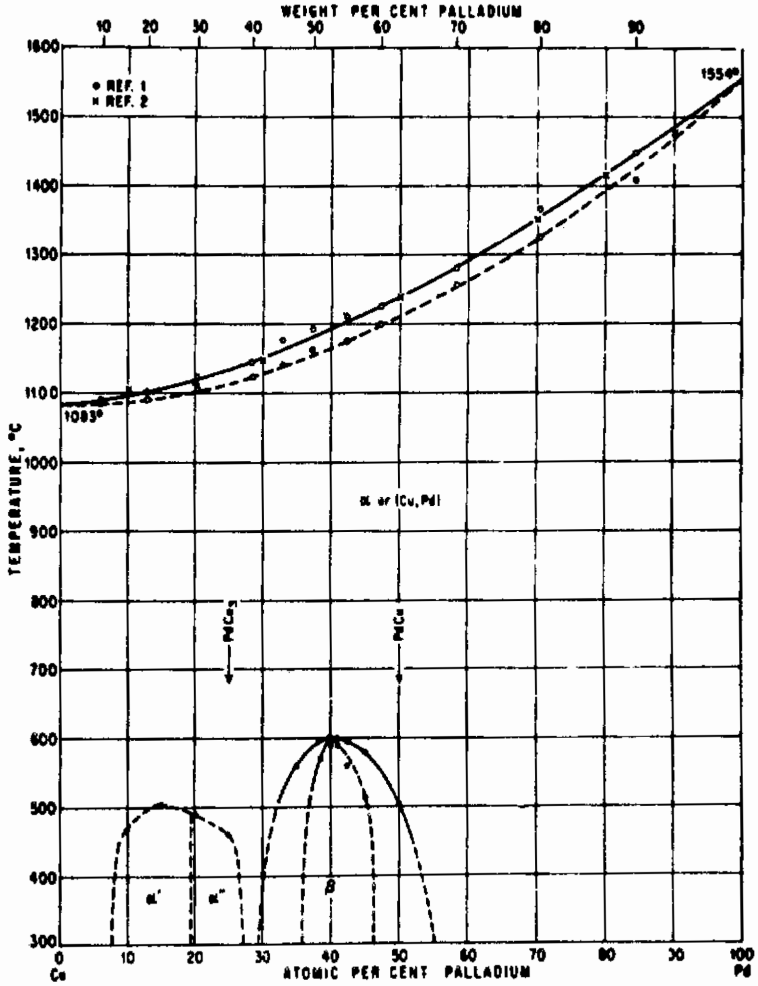

WEIGHT PER CENT MANGANESE
5
10
20
30
40
50
60
70
80
90
95
1300
1200
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE, °C
1244°
β
1133°
1115°
1095°
1083°
870 ± 5°
~36.5
(35)
α + β - Mn
α [γ]
727°
727°
α + α - Mn
0
Cu
10
20
30
40
50
60
70
80
90
100
Mn
ATOMIC PER CENT MANGANESE

Cu-Mn

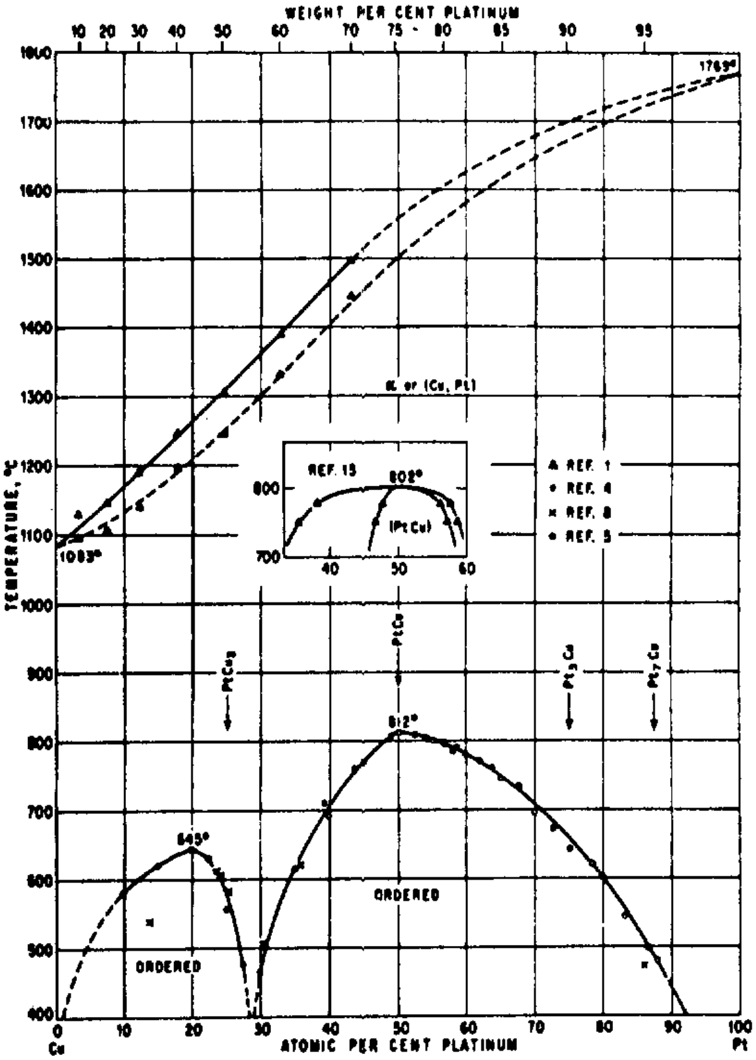


WEIGHT PER CENT NICKEL
10
20
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
400
300
200
100
0
-100
-200
-273
TEMPERATURE, °C
1453°
1083°
(Cu,Ni)
368°
MAGN. TRANSF.
0
Cu
10
20
30
40
50
60
70
80
90
100
Ni
ATOMIC PER CENT NICKEL

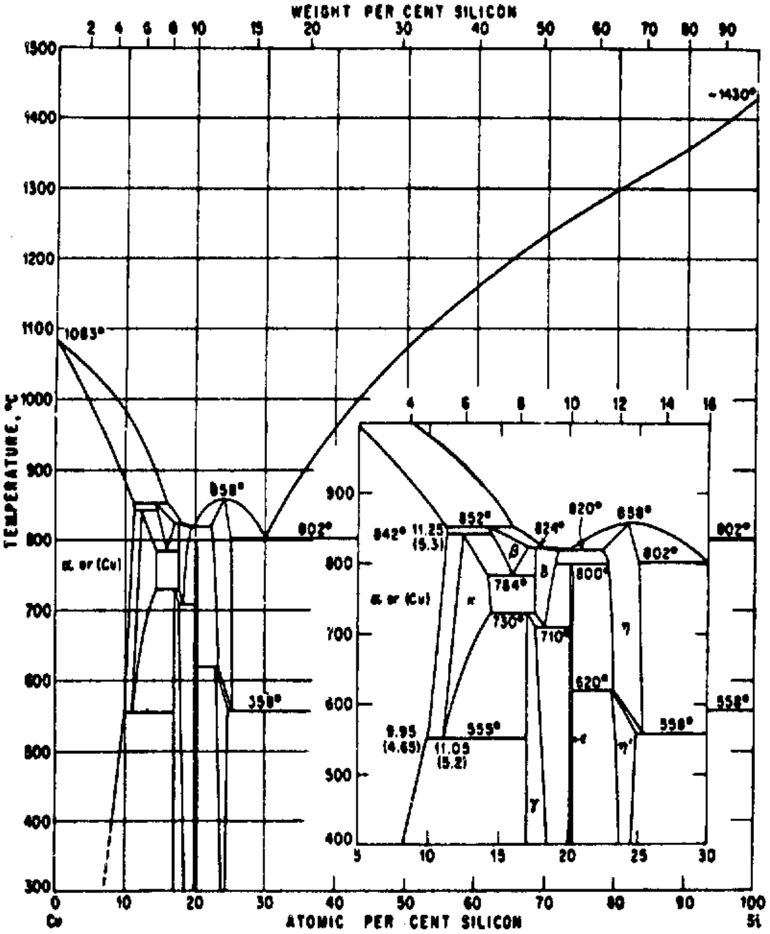
Cu-Ni


WEIGHT PER CENT PALLADIUM
10
20
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
• REF. 1
× REF. 2
1554°
1083°
TEMPERATURE, °C
α or (Cu, Pd)
PdCu3
PdCu
α'
α''
β
0
Cu
10
20
30
40
50
60
70
80
30
100
Pd
ATOMIC PER CENT PALLADIUM

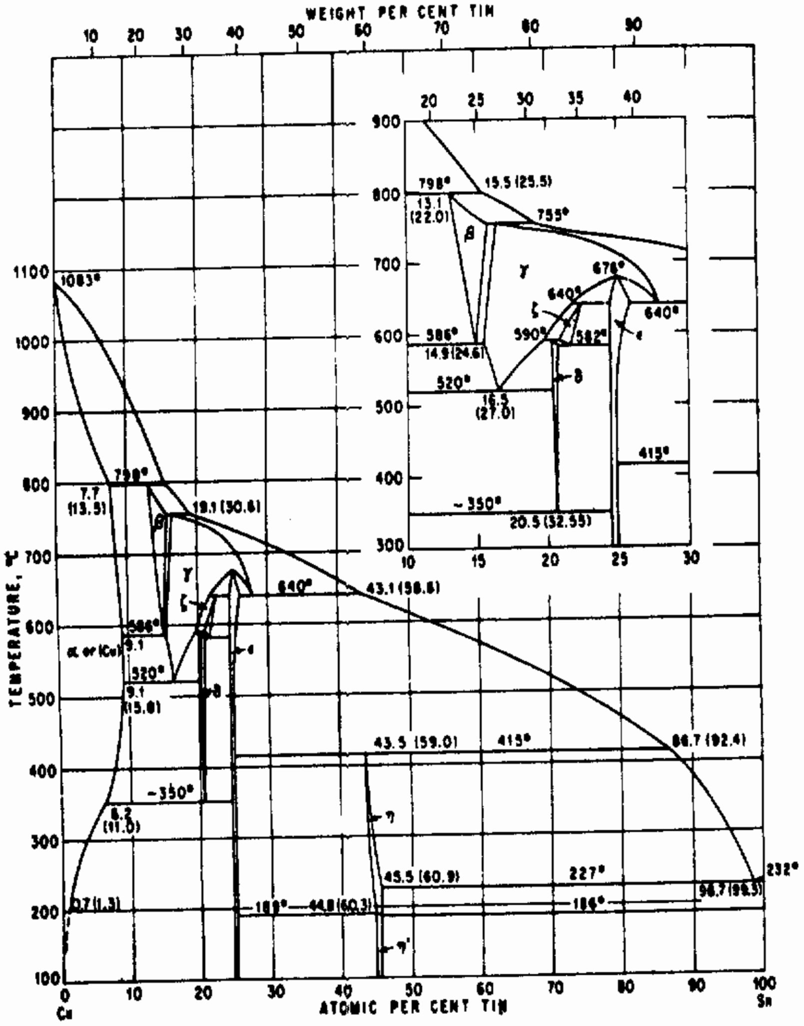
Cu-Pd


WEIGHT PER CENT PLATINUM
10
20
30
40
50
60
70
75
80
85
90
95
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
TEMPERATURE, °C
1769°
1083°
α or (Cu, Pt)
REF. 13
802°
800
700
(PtCu)
40
50
60
▲ REF. 1
● REF. 4
× REF. 8
● REF. 5
PtCu₃
PtCu
Pt₃Cu
Pt₇Cu
812°
645°
ORDERED
ORDERED
0
Cu
10
20
30
40
50
60
70
80
90
100
Pt
ATOMIC PER CENT PLATINUM

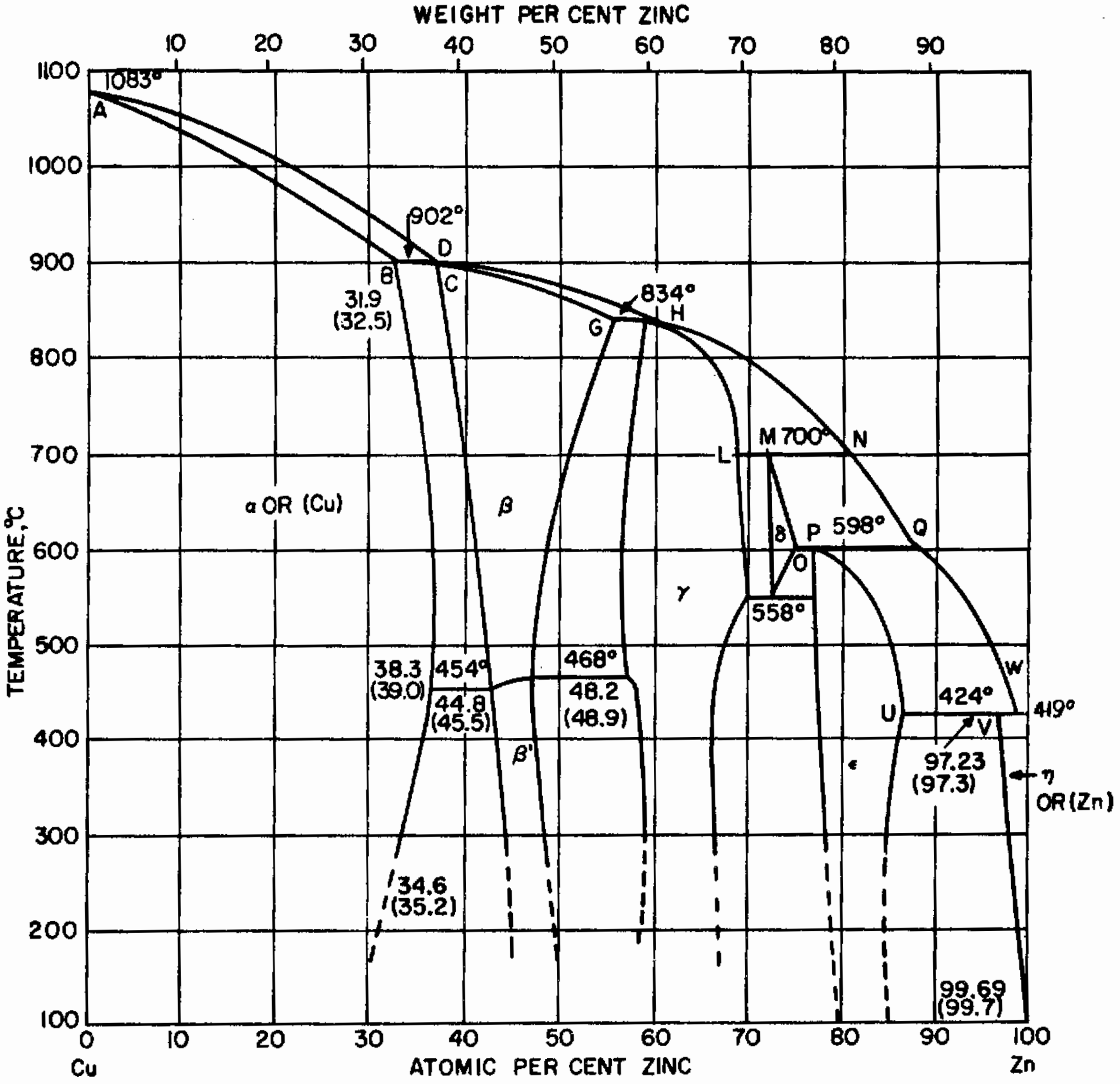
Cu-Pt


WEIGHT PER CENT SILICON
2
4
6
8
10
15
20
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
~1430°
1083°
858°
802°
558°
α or (Cu)
0
Cu
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON
4
6
8
10
12
14
16
842°
11.25
(5.3)
852°
824°
820°
858°
802°
β
δ
784°
730°
710°
800°
κ
η
620°
9.95
(4.65)
11.05
(5.2)
555°
558°
ε
η'
γ
5
10
15
20
25
30

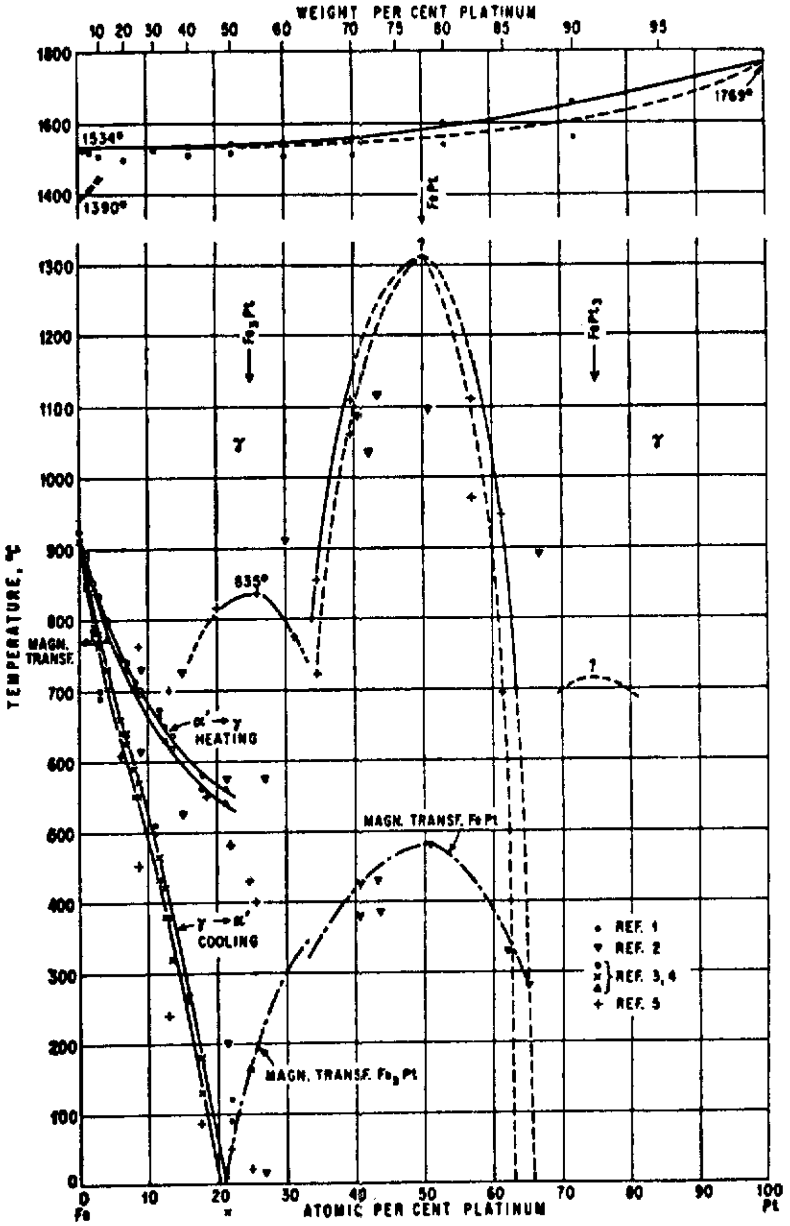
Cu-Si


WEIGHT PER CENT TIN
10
20
30
40
50
60
70
80
90
TEMPERATURE, °C
1100
1000
900
800
700
600
500
400
300
200
100
1083°
798°
7.7
(13.5)
19.1 (30.6)
β
γ
ζ
640°
43.1 (58.6)
586°
9.1
α or (Cu)
520°
9.1
(15.8)
δ
ε
43.5 (59.0)
415°
86.7 (92.4)
~350°
8.2
(11.0)
η
45.5 (60.9)
227°
232°
98.7 (99.3)
0.7 (1.3)
189°
44.8 (60.3)
186°
η'
0
Cu
ATOMIC PER CENT TIN
100
Sn
20
25
30
35
40
900
800
700
600
500
400
300
798°
15.5 (25.5)
13.1
(22.0)
755°
β
γ
676°
640°
ζ
640°
586°
590°
582°
14.9 (24.6)
ε
520°
δ
16.5
(27.0)
415°
~350°
20.5 (32.55)
10
15
20
25
30

Cu-Sn

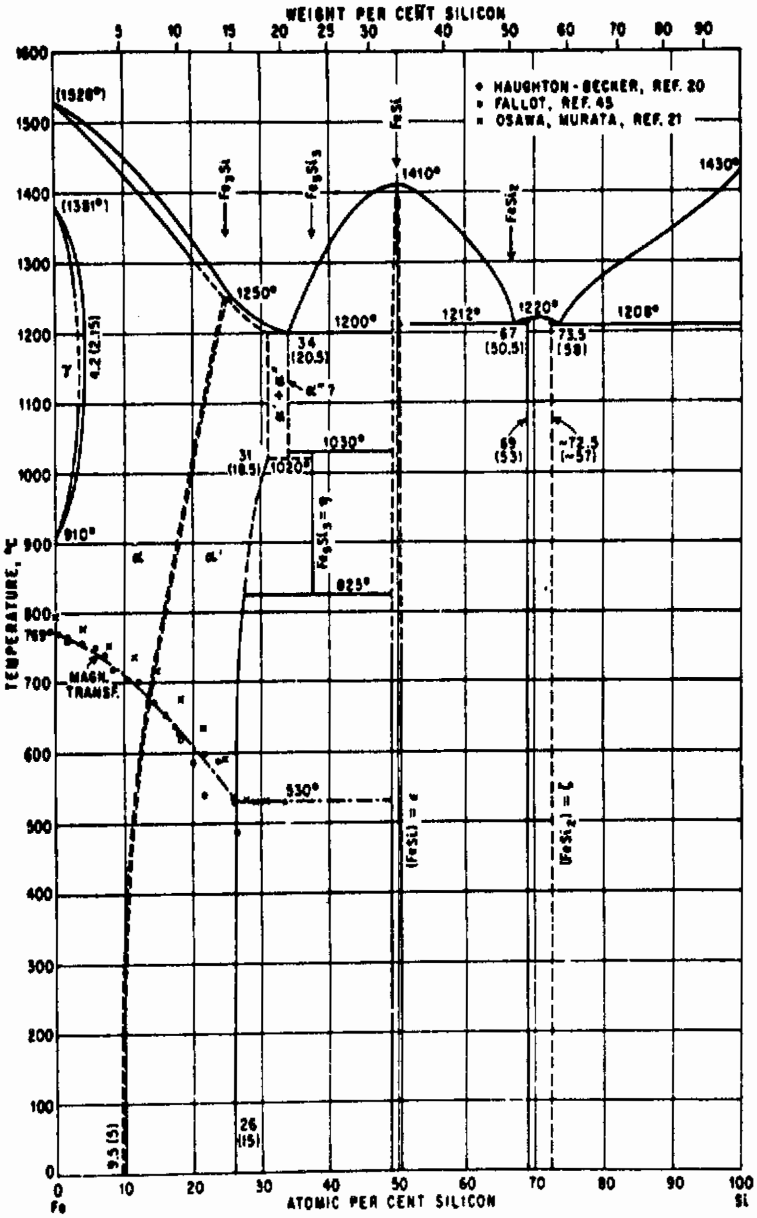

WEIGHT PER CENT ZINC
10
20
30
40
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
100
TEMPERATURE, °C
1083°
A
902°
D
B
C
31.9
(32.5)
834°
H
G
α OR (Cu)
β
L
M 700°
N
δ
P
598°
Q
O
γ
558°
38.3
(39.0)
454°
44.8
(45.5)
468°
48.2
(48.9)
β'
W
U
424°
V
419°
97.23
(97.3)
ε
η
OR (Zn)
34.6
(35.2)
99.69
(99.7)
0
10
20
30
40
50
60
70
80
90
100
Cu
ATOMIC PER CENT ZINC
Zn

Cu-Zn

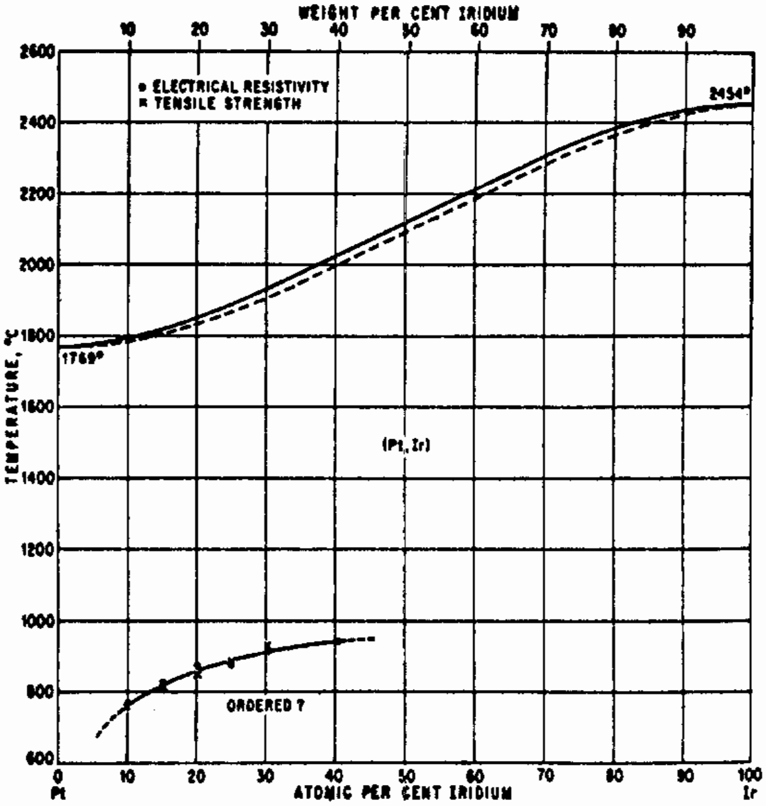


WEIGHT PER CENT PLATINUM
10
20
30
40
50
60
70
75
80
85
90
95
1800
1600
1400
1534°
1390°
1769°
FePt
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE, °C
Fe3Pt
FePt3
γ
γ
835°
?
?
MAGN. TRANSF.
α' → γ HEATING
γ → α' COOLING
MAGN. TRANSF. FePt
MAGN. TRANSF. Fe3Pt
• REF. 1
▼ REF. 2
REF. 3, 4
+ REF. 5
0 Fe
10
20
30
40
50
60
70
80
90
100 Pt
ATOMIC PER CENT PLATINUM

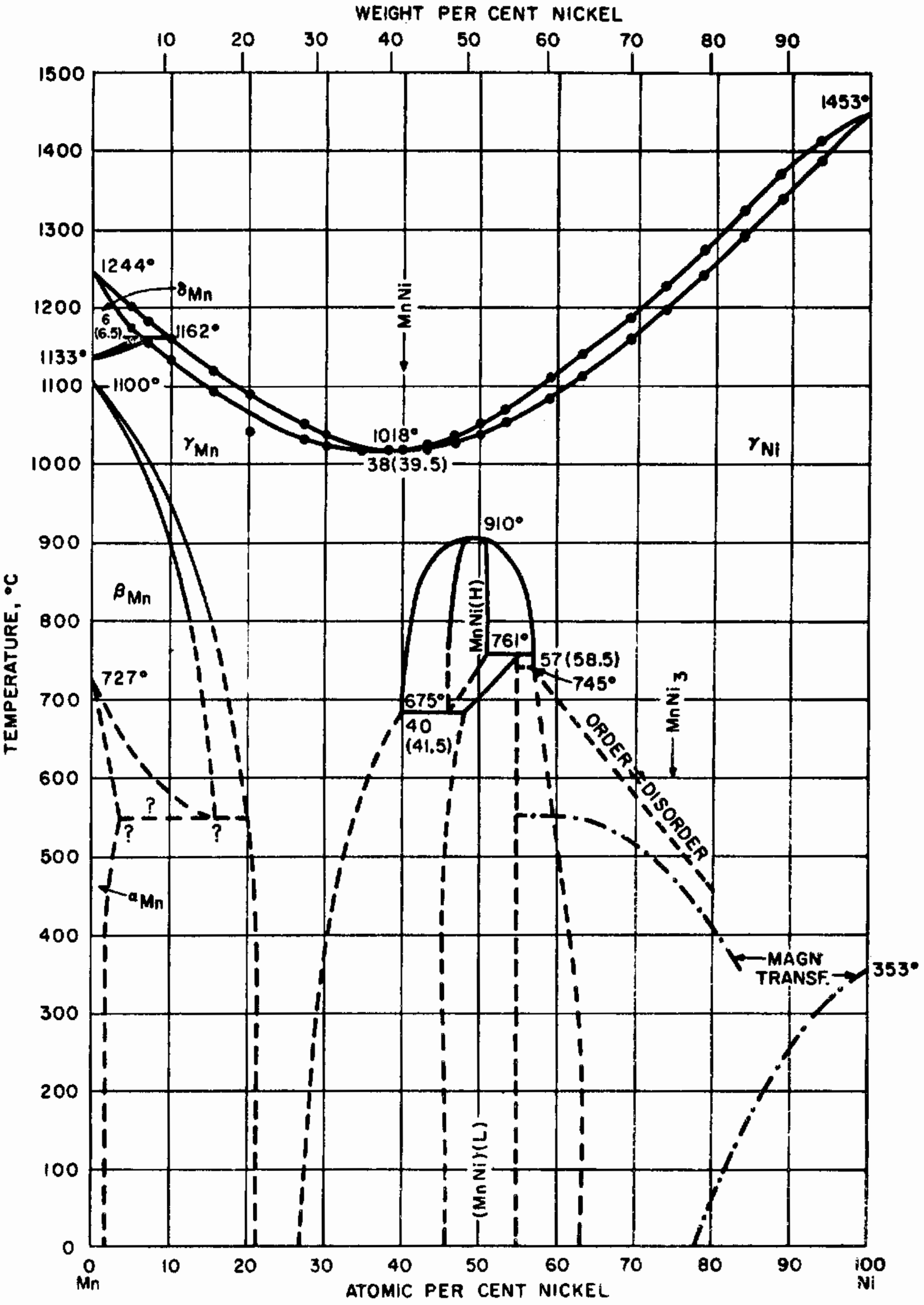
Fe-Pt


WEIGHT PER CENT SILICON
5
10
15
20
25
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE, °C
• HAUGHTON - BECKER, REF. 20
▪ FALLOT, REF. 45
× OSAWA, MURATA, REF. 21
(1528°)
(1381°)
Fe3Si
Fe5Si3
FeSi
FeSi2
1410°
1430°
1250°
1200°
1212°
1220°
1208°
34
(20.5)
67
(50.5)
73.5
(58)
γ
4.2 (2.15)
α'+α"
α"?
69
(53)
~72.5
(~57)
31
(18.5)
1020°
1030°
910°
α
α'
Fe5Si3 = η
825°
769°
MAGN. TRANSF.
530°
(FeSi) = ε
(FeSi2) = ζ
9.5 (5)
26
(15)
0
Fe
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON

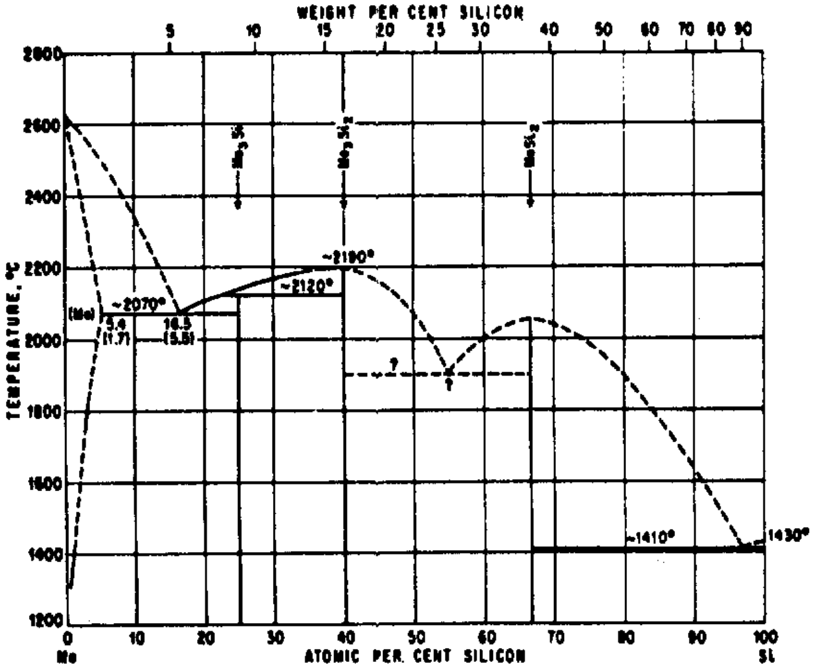
Fe-Si


WEIGHT PER CENT IRIDIUM
10
20
30
40
50
60
70
80
90
● ELECTRICAL RESISTIVITY
× TENSILE STRENGTH
2454°
1769°
(Pt, Ir)
ORDERED ?
TEMPERATURE, °C
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
0
Pt
10
20
30
40
50
60
70
80
90
100
Ir
ATOMIC PER CENT IRIDIUM

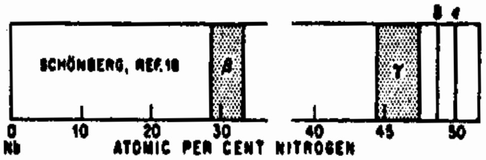
Ir-Pt


WEIGHT PER CENT NICKEL
10
20
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE, °C
1453°
1244°
δMn
6
(6.5)
1162°
1133°
1100°
MnNi
γMn
1018°
38(39.5)
γNi
910°
βMn
MnNi(H)
761°
57(58.5)
727°
745°
MnNi3
675°
40
(41.5)
ORDER ⇄ DISORDER
?
?
?
αMn
MAGN. TRANSF.
353°
(MnNi)(L)
0
Mn
10
20
30
40
50
60
70
80
90
100
Ni
ATOMIC PER CENT NICKEL

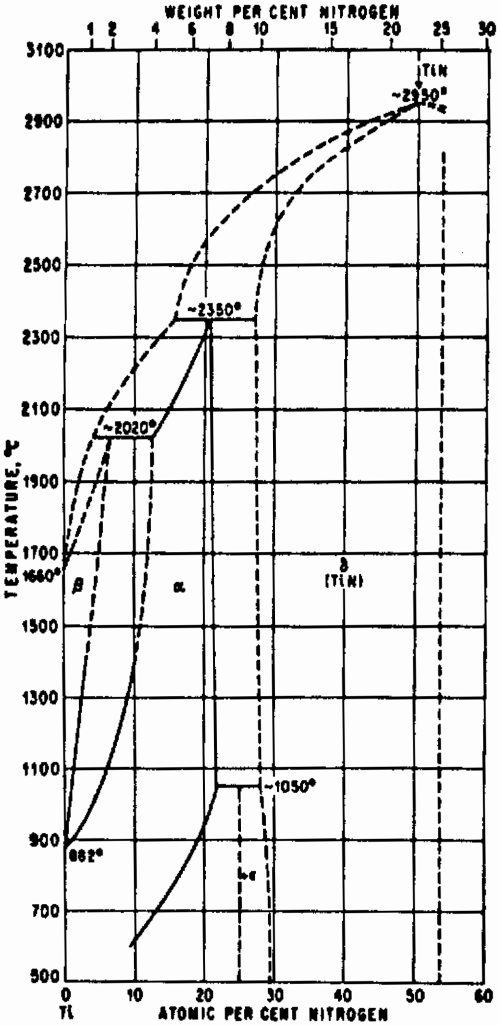
Mr-Ni


WEIGHT PER CENT SILICON
5
10
15
20
25
30
40
50
60
70
80
90
2800
2600
2400
2200
2000
1800
1600
1400
1200
TEMPERATURE, °C
Mo_3Si
Mo_5Si_3
$MoSi_2$
~2190°
~2120°
~2070°
(Mo)
5.4
(1.7)
16.5
(5.5)
?
?
~1410°
1430°
0
10
20
30
40
50
60
70
80
90
100
Mo
Si
ATOMIC PER CENT SILICON

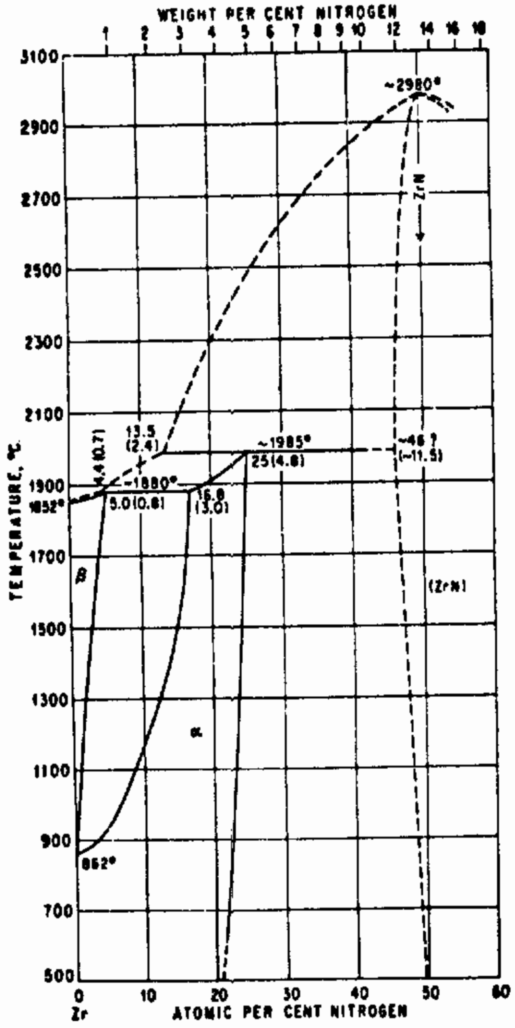
Mo-Si


SCHÖNBERG, REF.18
β
γ
δ
ε
0
Nb
10
20
30
40
45
50
ATOMIC PER CENT NITROGEN

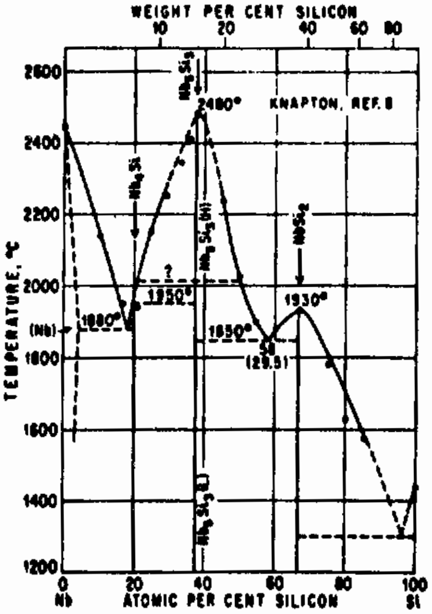
N-Nb


WEIGHT PER CENT NITROGEN
1
2
4
6
8
10
15
20
25
30
TEMPERATURE, °C
3100
2900
2700
2500
2300
2100
1900
1700
1660°
1500
1300
1100
900
700
500
TiN
~2950°
~2350°
~2020°
β
α
δ
(TiN)
~1050°
882°
ε
0
Ti
10
20
30
40
50
60
ATOMIC PER CENT NITROGEN

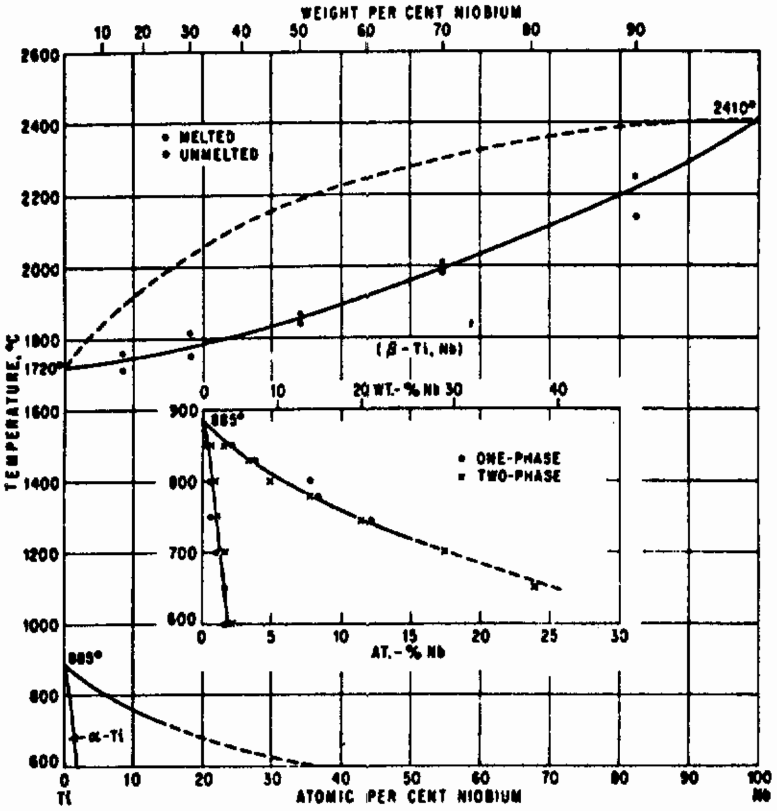
N-Ti


WEIGHT PER CENT NITROGEN
1
2
3
4
5
6
7
8
9
10
12
14
16
18
3100
2900
2700
2500
2300
2100
1900
1852°
1700
1500
1300
1100
900
700
500
TEMPERATURE, °C.
~2980°
ZrN
13.5
(2.4)
4.4(0.7)
~1880°
5.0(0.8)
16.8
(3.0)
~1985°
25(4.8)
~46 ?
(~11.5)
β
(ZrN)
α
862°
0
Zr
10
20
30
40
50
60
ATOMIC PER CENT NITROGEN

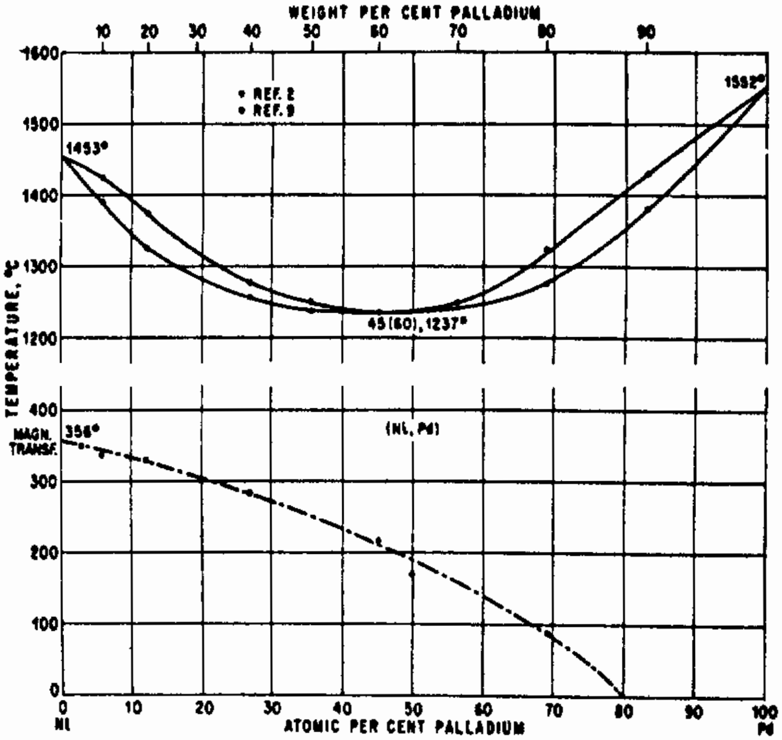
N-Zr


WEIGHT PER CENT SILICON
10
20
40
60
80
2600
2400
2200
2000
1800
1600
1400
1200
TEMPERATURE, °C
Nb_5Si_3
2480°
KNAPTON, REF. 8
Nb_4Si
Nb_5Si_3 (H)
$NbSi_2$
?
1950°
1880°
(Nb)
1850°
1930°
58
(29.5)
Nb_5Si_3 (L)
0
Nb
20
40
60
80
100
Si
ATOMIC PER CENT SILICON

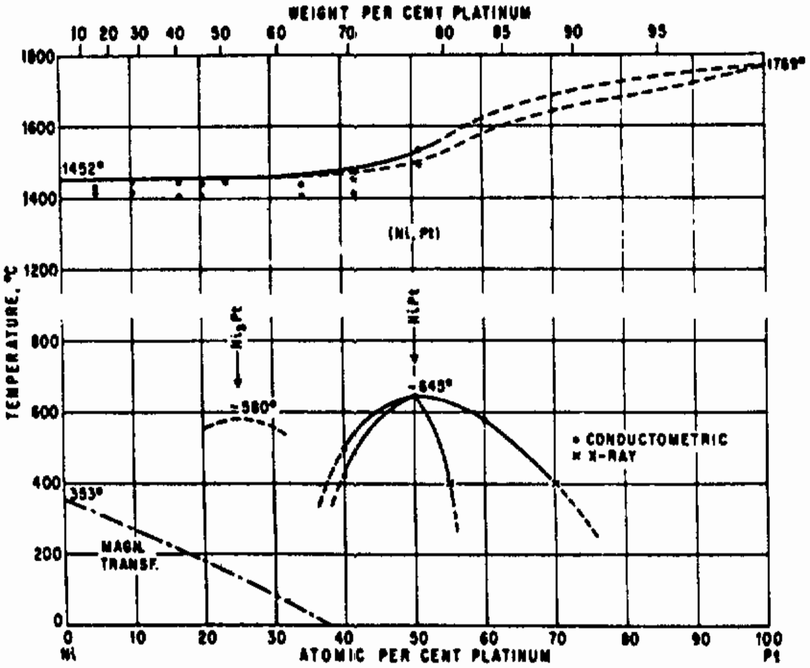
Nb-Si


WEIGHT PER CENT NIOBIUM
10
20
30
40
50
60
70
80
90
2600
2400
2200
2000
1800
1720°
1600
1400
1200
1000
800
600
TEMPERATURE, °C
2410°
• MELTED
• UNMELTED
(β - Ti, Nb)
0
10
20 WT.- % Nb 30
40
900
885°
800
700
600
• ONE-PHASE
× TWO-PHASE
0
5
10
15
20
25
30
AT.- % Nb
885°
α-Ti
0
Ti
10
20
30
40
50
60
70
80
90
100
Nb
ATOMIC PER CENT NIOBIUM

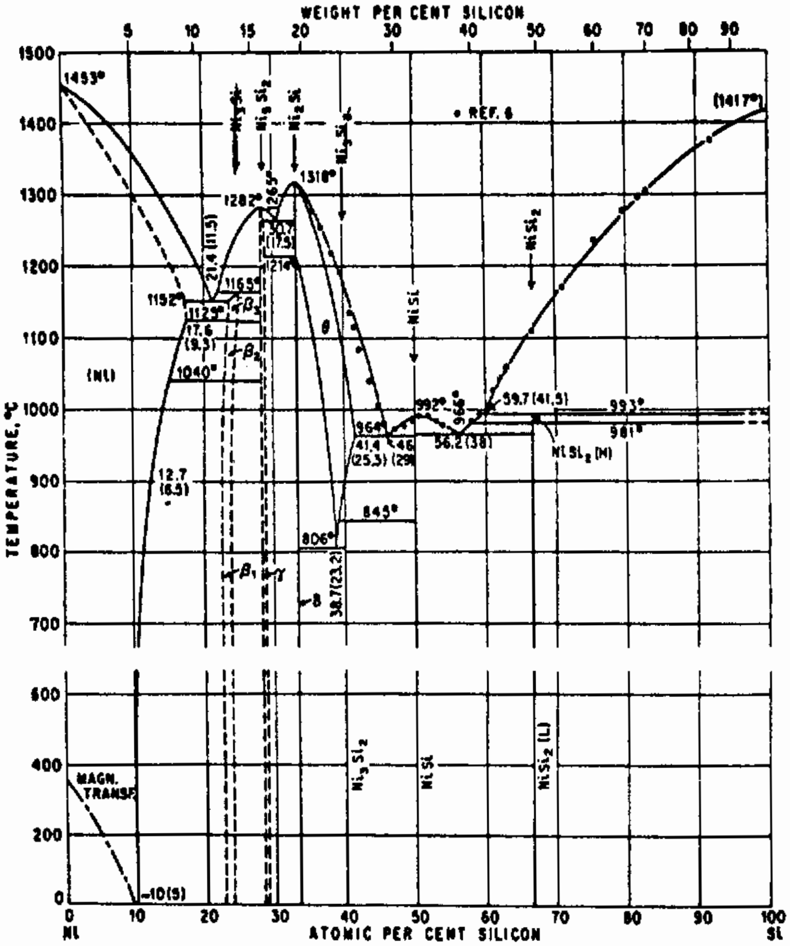
Nb-Ti


WEIGHT PER CENT PALLADIUM
10
20
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
400
300
200
100
0
• REF. 2
• REF. 9
1453°
1552°
45(60), 1237°
TEMPERATURE, °C
MAGN. TRANSF.
358°
(Ni, Pd)
0
Ni
10
20
30
40
50
60
70
80
90
100
Pd
ATOMIC PER CENT PALLADIUM

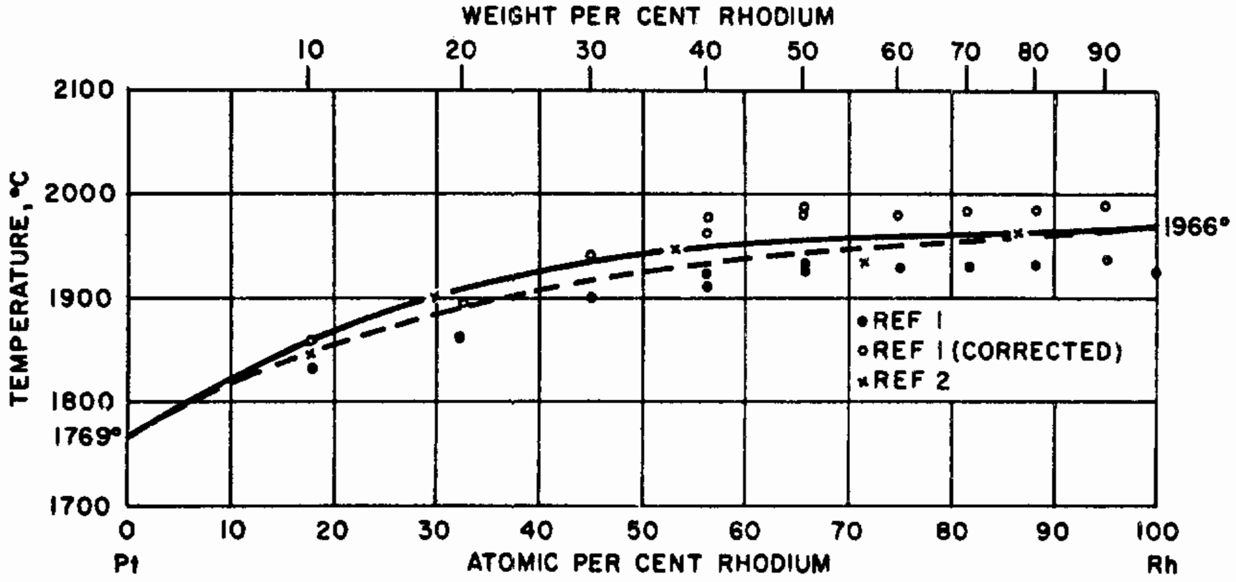
Ni-Pd


WEIGHT PER CENT PLATINUM
10
20
30
40
50
60
70
80
85
90
95
1800
1600
1400
1200
800
600
400
200
0
TEMPERATURE, °C
1452°
1769°
(Ni, Pt)
Ni3Pt
NiPt
≈580°
645°
353°
MAGN.
TRANSF.
• CONDUCTOMETRIC
× X-RAY
0
Ni
10
20
30
40
50
60
70
80
90
100
Pt
ATOMIC PER CENT PLATINUM

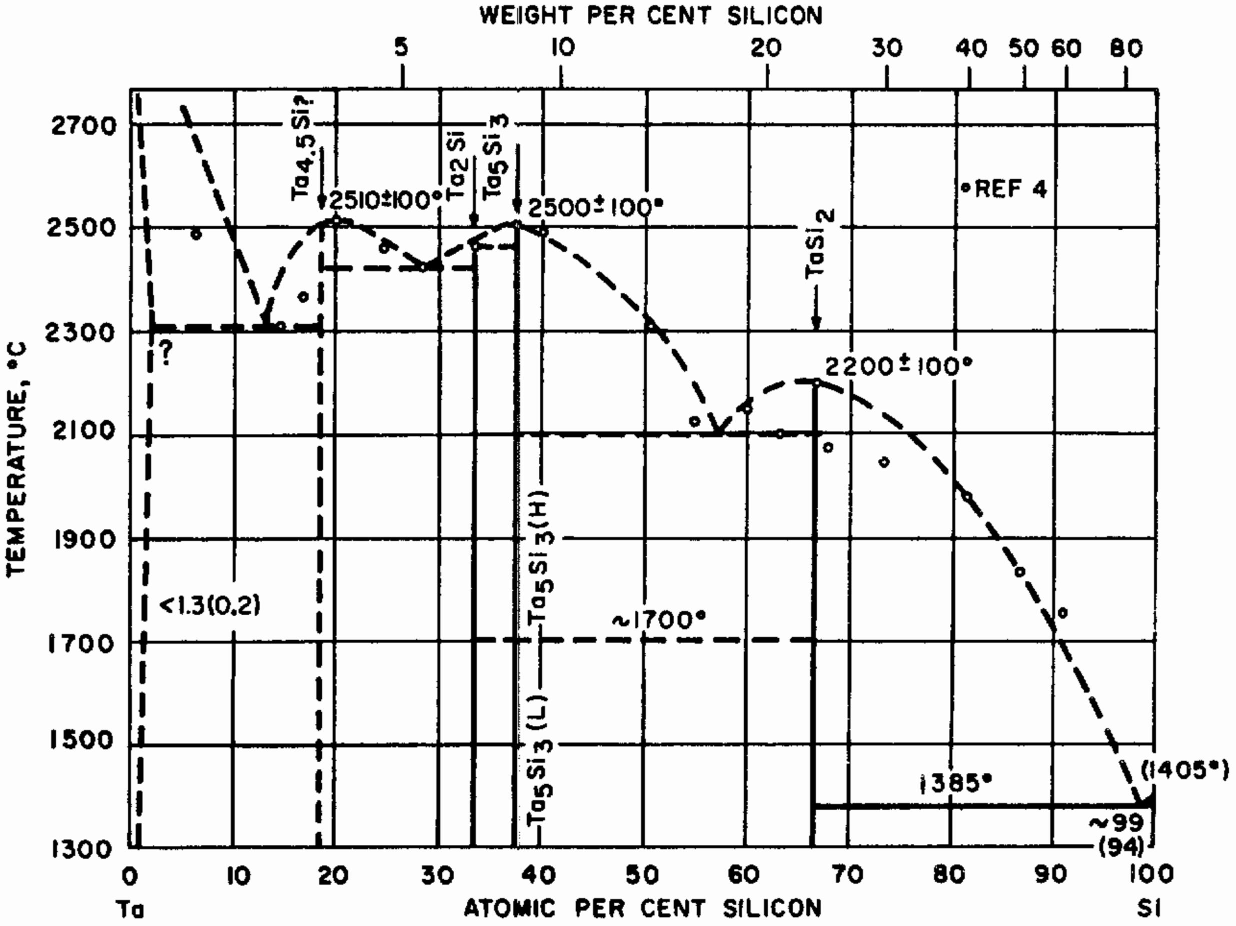
Ni-Pt


WEIGHT PER CENT SILICON
5
10
15
20
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
900
800
700
600
400
200
0
TEMPERATURE, °C
1453°
(1417°)
• REF. 6
Ni3Si
Ni5Si2
Ni2Si
Ni3Si2
NiSi2
NiSi
1318°
1282°
1265°
30.7
(17.5)
1214°
21.4 (11.5)
1165°
1152°
1129°
β3
17.6
(9.3)
β2
1040°
(Ni)
θ
992°
966°
59.7 (41.5)
993°
981°
964°
41.4
(25.3)
46
(29)
56.2 (38)
NiSi2 (H)
12.7
(6.5)
845°
806°
β1
γ
δ
38.7 (23.2)
Ni3Si2
NiSi
NiSi2 (L)
MAGN.
TRANSF.
~10(9)
0
Ni
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON

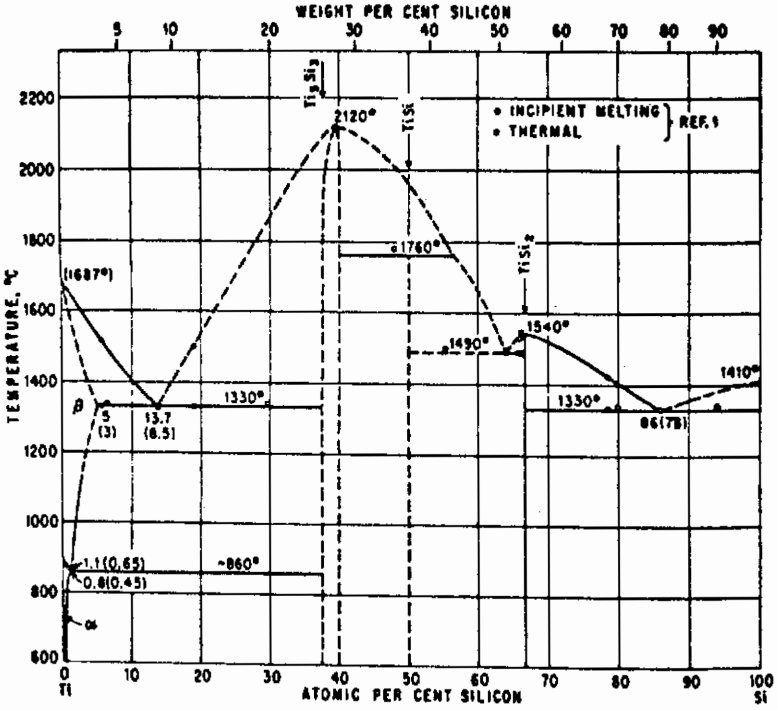
Ni-Si


WEIGHT PER CENT RHODIUM
10
20
30
40
50
60
70
80
90
2100
2000
1900
1800
1769°
1700
TEMPERATURE, °C
1966°
•REF 1
◦REF 1 (CORRECTED)
×REF 2
0
10
20
30
40
50
60
70
80
90
100
Pt
ATOMIC PER CENT RHODIUM
Rh

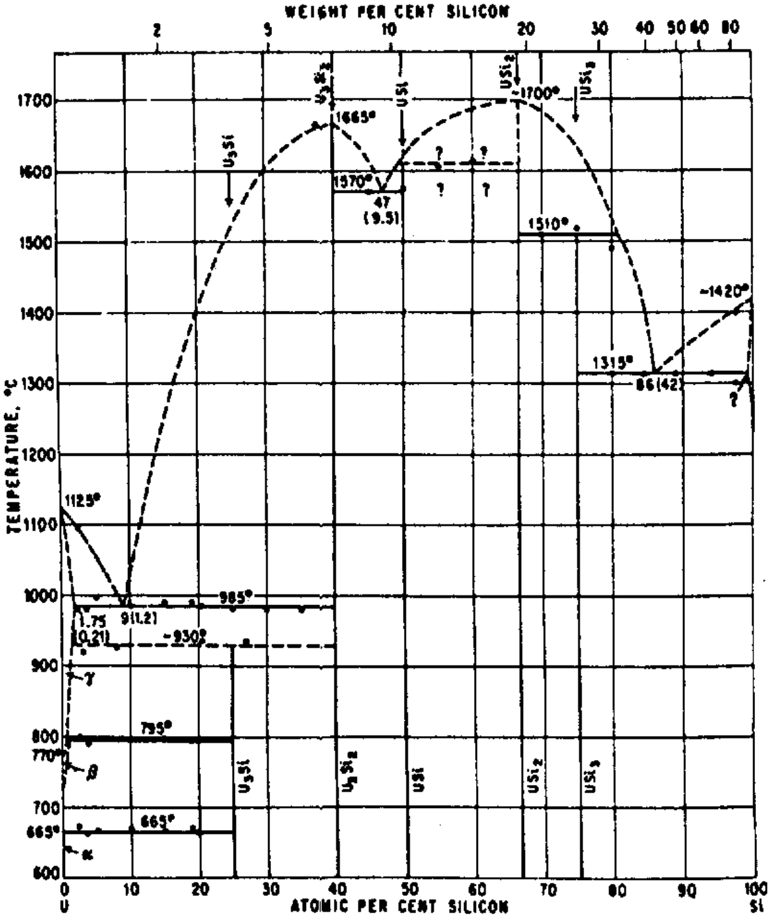
Pt-Rh


WEIGHT PER CENT SILICON
5
10
20
30
40
50
60
80
2700
2500
2300
2100
1900
1700
1500
1300
TEMPERATURE, °C
Ta4.5Si?
2510±100°
Ta2Si
Ta5Si3
2500±100°
•REF 4
TaSi2
2200±100°
?
<1.3(0.2)
Ta5Si3(H)
~1700°
Ta5Si3(L)
1385°
(1405°)
~99
(94)
0
10
20
30
40
50
60
70
80
90
100
Ta
ATOMIC PER CENT SILICON
Si

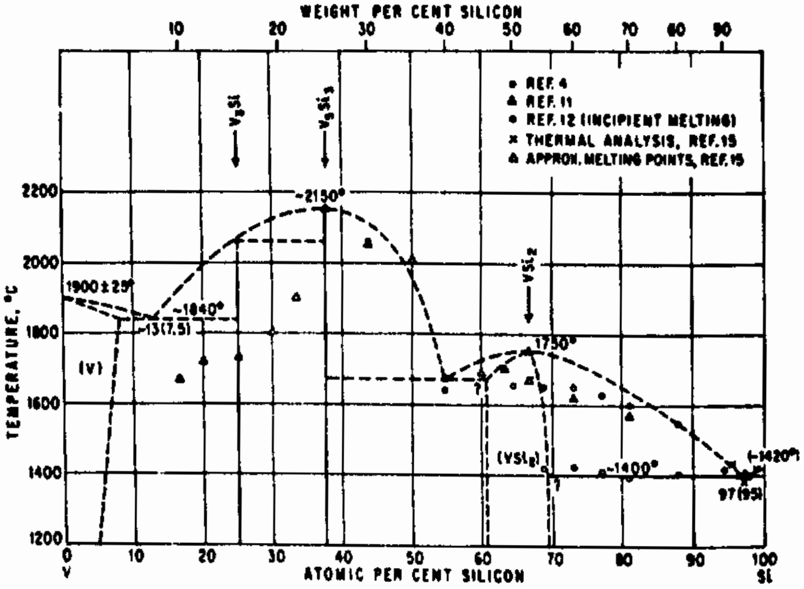
Si-Ta


WEIGHT PER CENT SILICON
5
10
20
30
40
50
60
70
80
90
Ti_5Si_3
TiSi
$TiSi_2$
• INCIPIENT MELTING
• THERMAL
REF. 1
2120°
(1687°)
1760°
1490°
1540°
1410°
1330°
1330°
β
5
(3)
13.7
(6.5)
86(78)
1.1(0.65)
0.8(0.45)
~860°
α
TEMPERATURE, °C
2200
2000
1800
1600
1400
1200
1000
800
600
0
Ti
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON

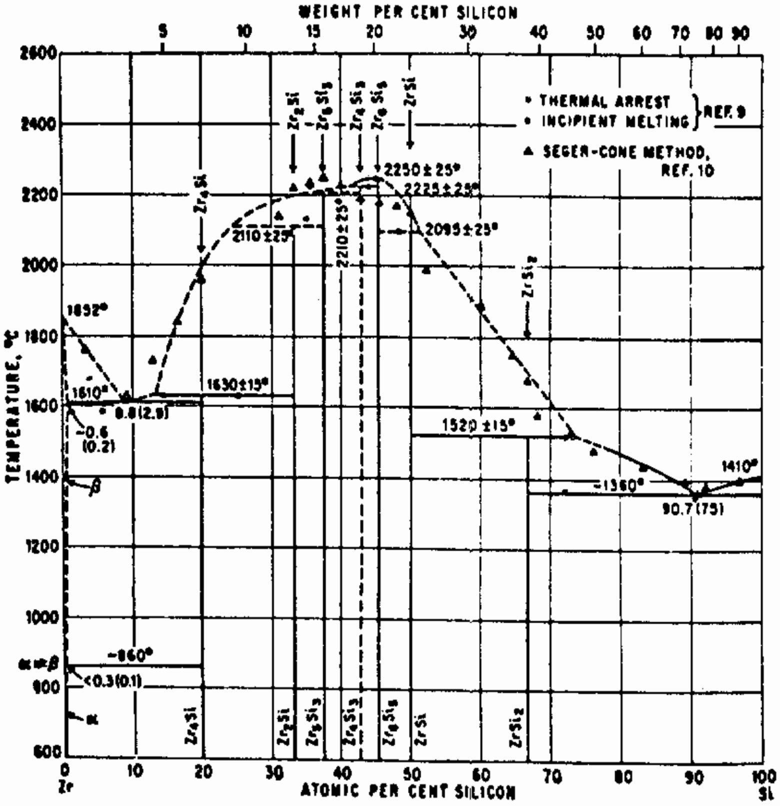
Si-Ti


WEIGHT PER CENT SILICON
2
5
10
20
30
40
50
60
80
TEMPERATURE, °C
1700
1600
1500
1400
1300
1200
1100
1000
900
800
770°
700
665°
600
U3Si
U3Si2
USi
USi2
USi3
1665°
1570°
47
(9.5)
?
~1700°
1510°
~1420°
1315°
86(42)
1125°
985°
1.75
(0.21)
9(1.2)
~930°
γ
795°
β
665°
α
0
U
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON

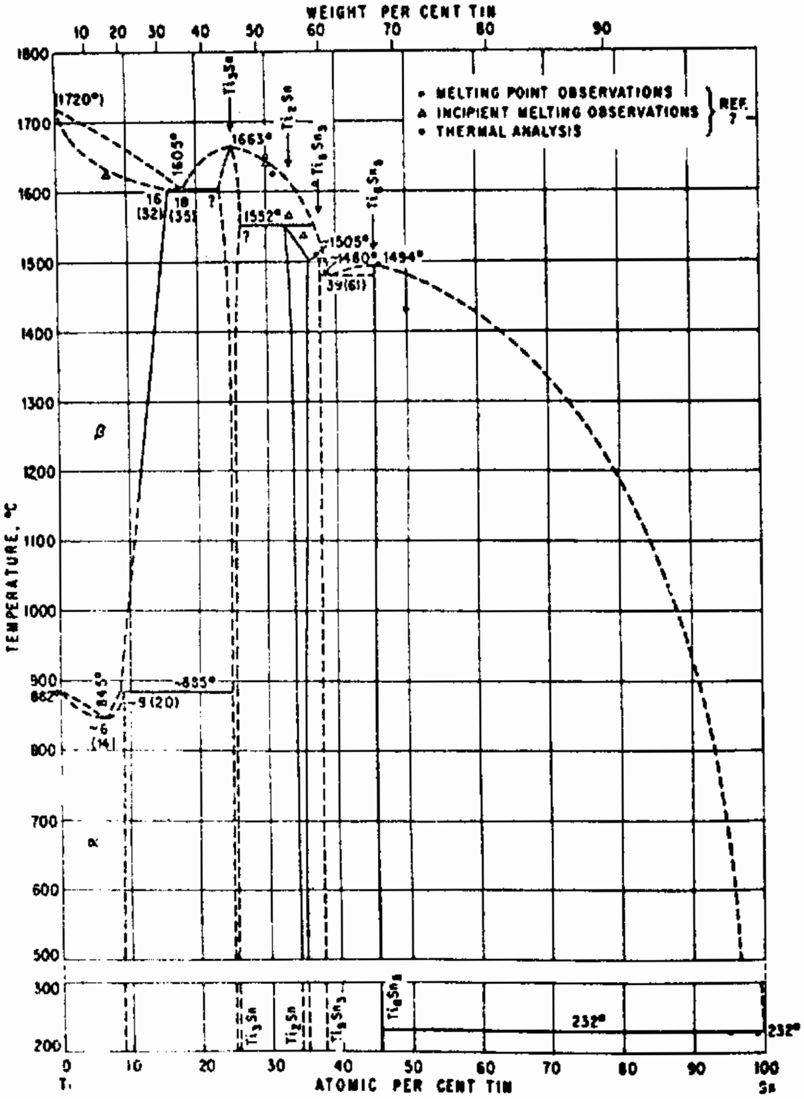
Si-U


WEIGHT PER CENT SILICON
10
20
30
40
50
60
70
80
90
● REF. 4
▲ REF. 11
● REF. 12 (INCIPIENT MELTING)
× THERMAL ANALYSIS, REF. 15
△ APPROX. MELTING POINTS, REF. 15
V_3Si
V_5Si_3
VSi_2
~2150°
1900 ± 25°
~1840°
~13(7.5)
(V)
1750°
(VSi_2)
?
?
?
~1400°
(~1420°)
97(95)
TEMPERATURE, °C
2200
2000
1800
1600
1400
1200
0
V
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON

Si-V


WEIGHT PER CENT SILICON
5
10
15
20
30
40
50
60
70
80
90
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
TEMPERATURE, °C
• THERMAL ARREST
• INCIPIENT MELTING
REF. 9
▲ SEGER-CONE METHOD, REF. 10
Zr_4Si
Zr_2Si
Zr_6Si_5
Zr_4Si_3
Zr_6Si_5
ZrSi
$ZrSi_2$
2250 ± 25°
2225 ± 25°
2110 ± 25°
2210 ± 25°
2095 ± 25°
1852°
1610°
1630±15°
8.8 (2.9)
~0.6 (0.2)
β
1520 ±15°
1410°
~1360°
90.7 (75)
~860°
α ⇌ β
<0.3 (0.1)
α
0
Zr
10
20
30
40
50
60
70
80
90
100
Si
ATOMIC PER CENT SILICON

Si-Zr


WEIGHT PER CENT TIN
10
20
30
40
50
60
70
80
90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
862°
800
700
600
500
300
200
TEMPERATURE, °C
(1720°)
1605°
16
(32)
18
(35)
?
Ti3Sn
1663°
Ti2Sn
Ti5Sn3
Ti6Sn5
1552°
?
~1505°
~1480°
1494°
39(61)
• MELTING POINT OBSERVATIONS
△ INCIPIENT MELTING OBSERVATIONS
• THERMAL ANALYSIS
REF. 7
β
α
~885°
~9(20)
845°
~6
(14)
232°
232°
0
Ti
10
20
30
40
50
60
70
80
90
100
Sn
ATOMIC PER CENT TIN

Sn-Ti