NIST Technical Note 1531

DC Conductivity Measurements of Metals

Michael D. Janezic
Raian F. Kaiser
James Baker-Jarvis
George Free

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Electromagnetics Division
Electronics and Electrical Engineering Laboratory

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DC Conductivity Measurements of Metals

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We examine a measurement method for characterizing the dc conductivity of metal alloys commonly used in the manufacture of weapons. From accurate measurements of the voltage and current across a cylindrical metal sample, we calculate the metal's dc conductivity. Equations for the dc conductivity are derived from first principles, including a detailed uncertainty analysis. In a measurement comparison with a National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) for conductivity, we verified the performance of our measurement system. Using this system, we measured the dc conductivity of ten metal alloys over a temperature range of 15 to 40 °C.

Key words: dc conductivity; metal; resistivity; temperature; weapons.

1. Introduction

In this paper we summarize a technique for measuring the dc conductivity of metals commonly used in weapons, and present electrical conductivity results for several metal alloys as a function of temperature. Although the conductivity of many metals can be found in the literature, the values are often for only a particular alloy or at a specific temperature. As new metal alloys are developed the conductivity of some metals remains unknown or unpublished, which is a problem for designers and manufacturers who require accurate conductivity data. As a result, we constructed a system for measurement of dc conductivity that can accurately measure the conductivity of a wide range of metals using easily machined cylindrical metal rod samples.

We begin this Tech Note with a brief introduction to the classical and quantum-mechanical theories for describing electrical conduction in metals. This chapter provides some description of the phenomenon of electrical conductivity and gives the reader some insight into the temperature dependence of metal conductivity.

Following this introductory chapter, we overview a technique for measuring the dc conductivity of metals. We begin by describing our measurement system and follow with a section that derives the necessary equations used to calculate the conductivity of a metal rod. Also covered in this chapter are a description of the measurement procedure and a detailed uncertainty analysis.

In the final chapter, we present the measurement results for 10 different metal alloys that cover a wide range of conductivities. We first verified the conductivity measurement system using a National Institute of Standard and Technology (NIST) Standard Reference Material (SRM). After the verification process, we characterized the selected metal alloys and calculated dc conductivity results at ambient temperature. Since the conductivity of metals is temperature-dependent, in this Tech Note we also describe how we employed an environmental chamber to broaden our temperature range from 15 to 40 °C. From results from this system, we present temperature-dependent dc conductivity for 10 metal alloys.

2. Theory of Electrical Conductivity

2.1 Classical Model of Electrical Conductivity

For over a hundred years, physicists have attempted to describe the phenomena of electrical conduction in metals. At the beginning of the 1900's, Drude developed his classical theory based on the concept of a gas of free electrons. Although this theory has limitations because it ignores the quantum behavior of the electron, the classical model does present some useful insight into electrical conduction and the calculation of electrical conductivity.

As outlined in Reference [1], the classical model assumes that the metal consists of immobile positive ions and freely moving negative electrons that are randomly distributed in the metal. Some of these electrons remain bound to the positive ions while the remaining valence electrons are free to move far from the positive ions to which they were orginally bound. The movement of these valence electrons is modeled using the classical kinetic theory of gases, under the following assumptions.

First, the model assumes that the valence electrons experience collisions with the immobile positive ions. However, the precise details regarding how the electron is scattered is unspecified. The average interval between collisions for a single electron is assumed to be τ. This time constant τ has several names: relaxation time, collision time, or mean free time. Through each collision, the electron's velocity and direction are changed. Between collisions, the model assumes that the electron does not interact with either the positive ions (free-electron approximation) or the other valence electrons (independent-electron approximation). With these assumptions in place, the classical free-electron model is used to model the dc electrical conductivity of a metal.

A valence electron with charge $-e$ collides with one of the immobile positive metal ions at time t, giving the electron a velocity $\vec{v}_0$. When electron is affected by an applied external electric field E, its resulting acceleration is $-eE/m$. The electron's velocity is now a sum of the velocity after the collision plus the velocity due to the electron's interaction with the electric field:

$$\vec{v}_{total} = \vec{v}_0 + \frac{-e\vec{E}t}{m}. \tag{1}$$

If instead of one electron, we consider n free electrons having collisions at time $t = 0$, then each electron will have a velocity of the form (1). Note however that for each electron, $\vec{v}_0$ is random and will average to zero over all n electrons. Thus the average velocity $\vec{v}_{avg}$ of the n electrons is given by

$$\vec{v}_{avg} = \frac{-eEt}{m}. \tag{2}$$

If no other collisions occur, the electrons would continue to accelerate. However, other collisions do occur and the classical model assumes that the average interval between collisions is τ, resulting in an average electron velocity of

$$\vec{v}_{avg} = \frac{-eE\tau}{m}. \tag{3}$$

Since there are n electrons moving with an average velocity $\vec{v}_{avg}$, we define a current density $\vec{J}$ by

$$\vec{J} = -ne\vec{v}_{avg} = \frac{ne^2E\tau}{m}. \tag{4}$$

From Ohm's law we also know that

$$\vec{J} = \sigma\vec{E}, \tag{5}$$

where σ is the electrical conductivity of the metal. Using these two expressions for J, we find that σ can be expressed as

$$\sigma = \frac{ne^2\tau}{m}. \tag{6}$$

In Drude's time, the electrical conductivity σ of metals was known to be inversely proportional to temperature. There is nothing explicit in Eq. (6) about how the conductivity varies with temperature. Drude tried to argue that τ might also have a T^{-1} dependence, but this assumption was found to contradict experimental results found for the thermal conductivity [2]. Although Lorentz tried to modify the Drude model by assuming that the electron velocities were governed by the Maxwell-Boltzmann distribution function, it was not until quantum theory was developed that the conductivity of metals could be adequately described [3].

2.2 Quantum Model of Electrical Conductivity

In the previous section, we summarized the classical free-electron model theory for metal conductivity. Because it ignored the quantum behavior of the electron it had several limitations, including the inability to predict the temperature dependence of a metal's conductivity. In this section we discuss how quantum mechanics was employed to improve the theory of electrical conductivity in metals, including the effect of temperature on conductivity.

In trying to improve on the classical free-electron theory of conductivity, Sommerfeld (1928) began with some of the same assumptions used in the classical model. Included in his model was the assumption that between collisions the electrons would have no interactions with either the fixed positive ions or the other electrons. Sommerfeld's improvement in the theoretical model came when he understood that the electron velocities were governed not by the classical Maxwell-Boltzmann distribution function, but by the quantum-mechanical Fermi-Dirac distribution function. The development of Fermi-Dirac statistics (1926) followed from the Heisenberg uncertainty principle (1925) and the Pauli exclusion principle (1925), both important new ideas in quantum mechanics. With this modification, the allowed electron energy levels become discrete rather than continuous, and the number of electrons with the same energy is restricted.

Although Sommerfeld's use of Fermi-Dirac statistics was an improvement when describing electrical conduction in metals, his model was still inadequate because it did not adequately describe the effect of positive ions in the metal [1]. Specifically, the model assumed that the ions were fixed and randomly distributed throughout the metal, and did not take into account the effect of the positive ions on the dynamics of the moving electrons. As a result, the model could not explain why the mean free path, the distance an electron travels between collisions, was experimentally found to be several hundred angstroms greater than expected at room temperatures for good conductors, and significantly higher at lower temperatures. In addition to the problem of the large mean free path, this model did not correctly predict the temperature dependence of electrical conductivity.

A major advance in the understanding of electrical conductivity was made when new discoveries showed that the positive ions were not randomly distributed throughout the metal. Using X-ray diffraction experiments, the ions were found to be actually arranged in a periodic array or lattice. With this knowledge, Bloch (1928) developed a theory for electrons in a metal by solving Schrödinger's equation for a periodic potential array. Bloch showed that an electron moving at a constant velocity through a perfect array of fixed ions would continue to move at that velocity. Surprisingly, the electrons do not scatter due to the expected collisions with the fixed positive ions. For this ideal situation involving a perfect array of positive ions, the electrons would still create a current even if there is no impressed electric field, resulting in infinite conductivity. However, due to the small thermal vibrations of the ions about their equilibrium positions, the ion array is not perfectly periodic. These lattice vibrations are interpreted as quanta called phonons, and the moving electrons are, in fact, scattered by electron-phonon scattering. As the temperature increases, the number of phonons created is proportional to temperature and more electrons are scattered by an increased populations of phonons. Theory predicts that this increased scattering leads to a T^{-1} temperature dependence of the electrical conductivity. At very low temperatures, where the population of phonons is nearly zero, defects and voids in the periodic array can still scatter electrons [4], so real metals cannot have an infinite conductivity even at absolute zero. The model of an electron traveling in a periodic array of thermally agitated positive ions has been able to correctly explain the electron's large mean-free-paths and the temperature dependence of the metal's electrical conductivity.

We have very briefly described how quantum mechanics was able to adequately describe the process of electrical conduction in metals, although we have necessarily left out many details. The quantum theory of electronic transport that describes the phenomena of electrical conduction in metals is complicated, and the reader who wants a greater understanding of the quantum-mechanical model of electrical conduction should consult one of the many solid-state physics books that cover this topic, including those we reference in this paper.

3. Measurement of DC Conductivity

3.1 Measurement System

In order to measure the dc conductivity of various metal alloys, we constructed the measurement system shown in Figure 1. This system is described in [5] and is similar to the standard test method described in ASTM B193-02 [6]. It is designed to measure the dc conductivity of the metal under test from the geometrical dimensions of a cylindrical metal rod and the dc current and voltage difference along some length L of the metal specimen. The equipment necessary for the measurement system includes two digital nanovoltmeters, a dc power supply, a four-terminal standard resistor, and a two-terminal knife-edge probe. The dc power supply is connected in series with the metal rod under test and the standard resistor.

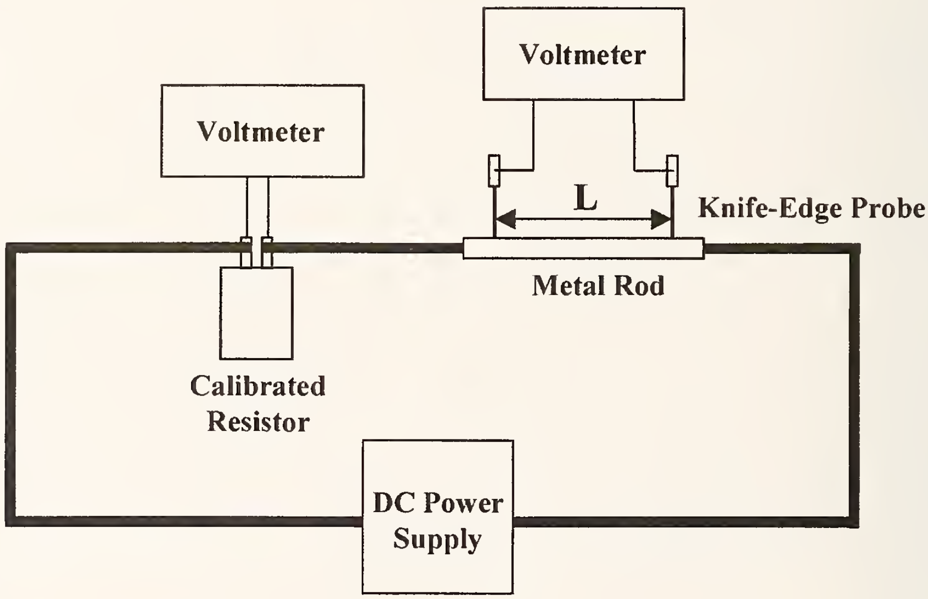

Figure 1: System for measurement of dc conductivity.

3.2 Measurement Theory

In this section we outline the measurement theory used to calculate the dc conductivity of the metal rod using the measurement system summarized in Section 3.1. We begin by defining the electrical resistance of a metal rod of uniform cross-section, a value that is a function of the conductivity of the metal and the geometrical dimensions of the metal rod.

In particular, the electrical resistance R across the terminals of the knife-edge probe, whose contacts with the rod are separated by a distance L is

$$R = \frac{L}{\sigma A}, \tag{7}$$

where A is the cross-sectional area of the metal rod and σ is the dc conductivity of the metal rod. Solving for σ, we obtain

$$\sigma = \frac{L}{RA}. \tag{8}$$

Using the definition of resistance R, $V = IR$, we can rewrite Eq. (8) in terms of the measured voltage V_m and current I_m seen at the terminals of the knife-edge probe:

$$\sigma = \frac{L}{A}\frac{I_m}{V_m}. \tag{9}$$

Assuming that the current through the metal rod I_m is the same as the current through the calibrated resistor I_r we obtain for the conductivity

$$\sigma = \frac{L}{A}\frac{1}{R_r}\frac{V_r}{V_m}. \tag{10}$$

Note that Eq. (10) is general for any metal specimen that has a uniform cross-section A. In our case, we chose circular-cylindrical metal rods. Therefore, for a circular-cylindrical rod of diameter d, Eq. (10) reduces to

$$\sigma = \frac{4L}{\pi d^2}\frac{1}{R_r}\frac{V_r}{V_m} \quad [\mathrm{S/m}]. \tag{11}$$

The dc electrical resistivity ρ of the metal rod is the inverse of the conductivity:

$$\rho = \frac{\pi d^2}{4L} R_r \frac{V_m}{V_r} \quad [\Omega \cdot \mathrm{m}]. \tag{12}$$

3.3 Measurement Procedure

Before assembling the measurement system, as shown in Figure 1, we allowed the two nanovolt meters and the dc power supply to warm up sufficiently to minimize possible measurement drift. Prior to making the conductivity measurement, we cleaned the metal rod and measured its diameter d, taking many points along the length of the specimen to ensure that the cross-section is uniform. We then placed the metal sample in the measurement system and connected the knife-edge probe, making sure that the probe contacts were clean and set firmly against the metal surface. With the dc power supply providing zero current, we

Table 1: Measured variables and calculated dc conductivity of a stainless steel T17-4P4 alloy at temperature T = 24.8 °C.

Variable	Value
L	53.053 mm
d	2.9997 mm
R_r	10 mΩ
V_r	1 mV
V_m	0.7622 mV
σ	0.985 MS/m

zeroed both the nanovoltmeter connected to the standard resistor and the nanovoltmeter connected to the knife-edge probe.

With the measurement system now calibrated, we increased the current supplied by the dc power supply and read the resulting voltages across both the standard resistor V_r and the knife-edge probe V_m. It is important to collect the voltage data as quickly as possible as the temperature in the rod begins to increase as soon as the current begins to flow through the metal rod, ohmically heating it. As the conductivity is a function of temperature, this is an important issue.

Given the diameter d of the metal rod, the length L between the contacts of the knife-edge probe, resistance R_r of the standard resistor, and the voltage differences across the standard resistor V_r and knife-edge probe V_m, we can calculate the conductivity σ of the metal rod using expression (11).

In Table 1, we show an example of a typical conductivity measurement for a sample of stainless steel T17-4P4 alloy at a temperature of 24.8 °C.

3.4 Uncertainty Analysis

In this section we identify the major sources of uncertainty and perform an uncertainty analysis for the calculation of the dc conductivity of a metal rod. The uncertainties in dc conductivity include the uncertainties Δd in the measured diameter of the metal rod, ΔL in the length of the voltage probe, ΔR in the resistance of the calibrated resistor, ΔV_r in the voltage difference across the calibrated resistor, and ΔV_m in the voltage difference across the probe connected to the metal rod. Assuming that each of these sources of uncertainty

Table 2: Uncertainty budget for the measured dc conductivity of T17-4P4 stainless steel

Source of uncertainty		Source uncertainty	Standard uncertainty in σ [S/m]
Probe length L	53.053 mm	0.024 mm	446 (A)
Metal rod diameter d	2.9997 mm	0.002 mm	1313 (A)
Resistor resistance R_r	10 mΩ	0.5 mΩ	49245 (B)
Resistor voltage V_r	1 mV	0.001 mV	985 (B)
Probe voltage V_m	0.7622 mV	0.002 mV	2584 (B)
Calculated dc conductivity			Combined standard uncertainty
σ (9.84×10^6) [S/m]			u(σ) = 0.49×10^6 [S/m]

is independent, the combined root-mean-square standard uncertainty for $\Delta\sigma$ is

$$\Delta\sigma = \sqrt{\left(\frac{\partial\sigma}{\partial L}\Delta L\right)^2 + \left(\frac{\partial\sigma}{\partial d}\Delta d\right)^2 + \left(\frac{\partial\sigma}{\partial R_r}\Delta R_r\right)^2 + \left(\frac{\partial\sigma}{\partial V_r}\Delta V_r\right)^2 + \left(\frac{\partial\sigma}{\partial V_m}\Delta V_m\right)^2}. \tag{13}$$

Since we use Eq. (11) to calculate the conductivity σ, we can calculate all the partial derivatives in Eq. (13)

$$\frac{\partial\sigma}{\partial L} = \frac{4}{\pi d^2}\frac{1}{R_r}\frac{V_r}{V_m}, \tag{14}$$

$$\frac{\partial\sigma}{\partial d} = -\frac{8}{\pi d^3}\frac{L}{R_r}\frac{V_r}{V_m}, \tag{15}$$

$$\frac{\partial\sigma}{\partial R_r} = -\frac{4}{\pi d^2}\frac{L}{R_r^2}\frac{V_r}{V_m}, \tag{16}$$

$$\frac{\partial\sigma}{\partial V_r} = \frac{4}{\pi d^2}\frac{L}{R_r}\frac{1}{V_m}, \tag{17}$$

and

$$\frac{\partial\sigma}{\partial V_m} = -\frac{4}{\pi d^2}\frac{L}{R_r}\frac{V_r}{V_m^2}. \tag{18}$$

In Table 3.4 we show the uncertainty budget for stainless steel T17-4P4 metal alloy considered in the last section. The table lists the various sources of measurement uncertainty, the value and uncertainty of each measurement variable, and the associated uncertainty in the dc conductivity σ. We also denote whether each uncertainty source is a Type A or Type B uncertainty. Type A uncertainties may be statistically evaluated, while Type B uncertainties are those that are evaluated using methods other than statistical.

4. DC Conductivity Measurements

4.1 Verification of Measurement System

In order to verify that the dc conductivity measurement system was working properly, we measured a standard reference material (SRM) acquired from the National Institute of Standards and Technology (NIST). Specifically, we used SRM 1461, a standard reference material for the measurement of electrical resistivity as a function of temperature . A copy of the SRM certificate can be found in Appendix A.

Since the electrical conductivity is merely the inverse of the resistivity, SRM 1461 is an appropriate standard for verifying our measurement system. Figure 2 shows a comparison between our dc conductivity measurements and the data listed on the SRM certificate. The certified values for conductivity were sparse near ambient temperature, so we used a polynomial fit to several of the certified data points to compare with our measured conductivities. Within the temperature range of 15 to 40 °C, our conductivity measurements are in very good agreement with the certified SRM values.

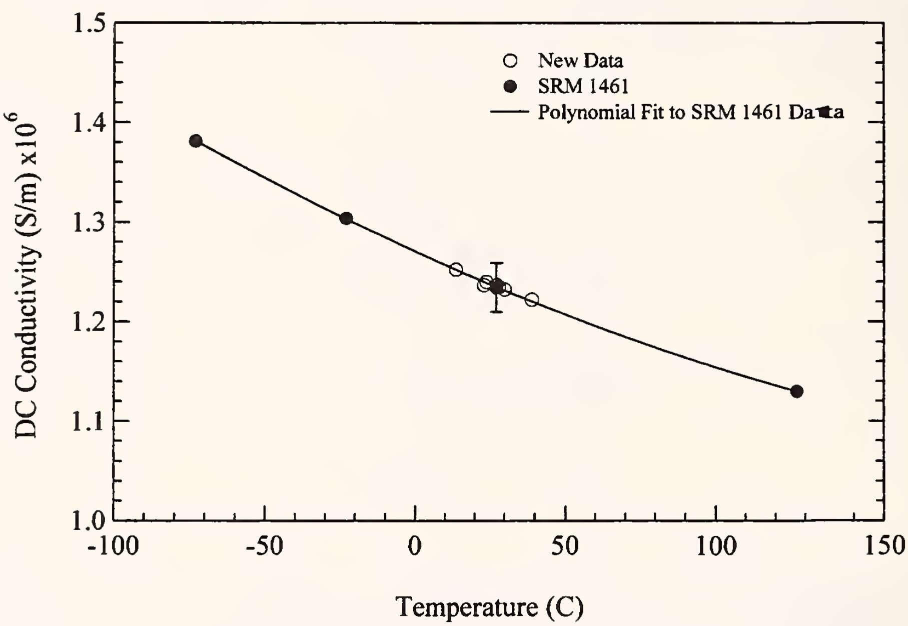

Figure 2: Measurements of dc conductivity on NIST SRM 1461 conductivity standard.

Table 3: DC conductivity of various metal alloys at 23 to 25 °C.

Metal alloy	Conductivity [MS/m]	
	Sample 1	Sample 2
Copper C10100	57.60	57.24
Aluminum 2011	21.11	21.13
Zamek 5	15.91	15.90
Brass C260	15.50	15.50
Alloy steel 4140	4.30	4.29
Stainless steel 430	1.77	1.77
Stainless steel 416	1.53	1.53
NIST SRM 1461	1.21	N/A
Stainless steel 17-4PH	0.98	0.98
Titanium 6Al-4V	0.58	0.58

4.2 Measurements of DC Conductivity

After we verified the conductivity measurement system with the SRM 1621 sample, we selected nine additional metal alloys having a wide range of conductivities. Based on information provided by law enforcement agencies, a majority of the nine selected metal alloys measured can be found in weapons such as handguns and knives. The high end of the conductivity range is represented by an oxygen-free copper alloy, with a conductivity of approximate 57 MS/m, while the low end is represented by a titanium alloy, with a conductivity of approximate 0.6 MS/m.

For each alloy to be measured, we machined two cylindrical rods 3 mm in diameter and 150 mm in length. The voltage difference across the knife-edge probe must be sufficient to read with a digital nanovolt meter. To accomplish this, either the current flowing through the metal rod must be sufficiently large or the diameter of the rod must be sufficiently small. Since we want to minimize the heating effects of the current flowing through the rod, we reduced the specimen's resistance by avoiding a diameter too small, and specified a metal rod diameter of 3 mm. To avoid any end effects with our knife-edge probe, we specified a metal rod length of 150 mm, approximately three times the length of our longest knife-edge probe.

Using the measurement system described in Section 3, we measured the dc conductivity of each sample at ambient temperature (23 to 25 °C). The results of these measurements are

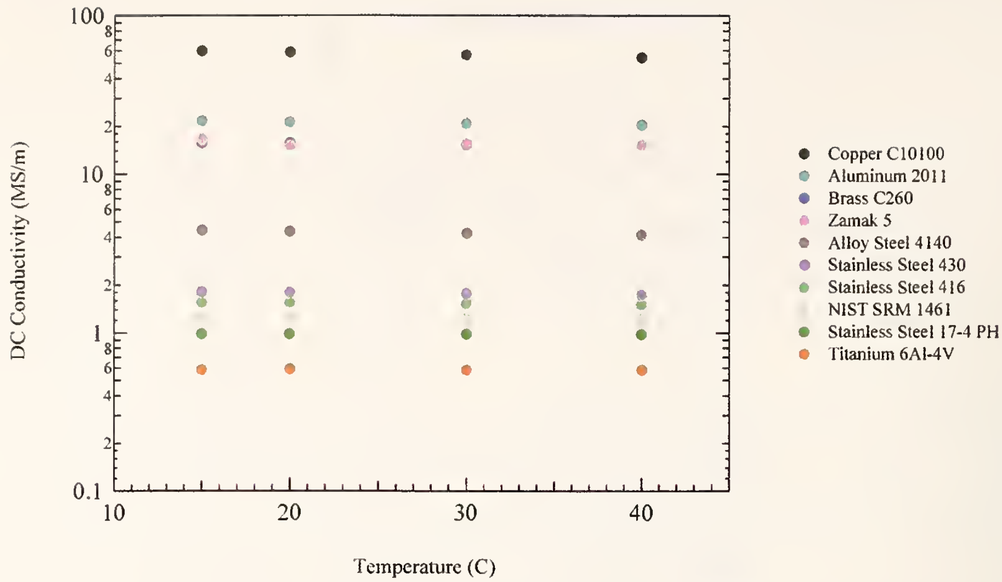

Figure 3: DC conductivity of metal alloys as a function of temperature.

shown in Table 3. Good agreement between measurements on each pair of metal rods was found for all of the metals characterized.

4.3 Measurements of Variable Temperature DC Conductivity

As mentioned previously, the dc conductivity of metals is inversely proportional to temperature, so we wanted to characterize the metal over the temperature range of interest. By placing the metal rod under test inside an environmental chamber, we were able to measure the dc conductivity over a temperature range of 15 to 40 °C. Our particular environmental test chamber had a volume of 0.06 m^3. Using a combination of resistance heaters and chilled gas from a liquid nitrogen dewar, we were able to achieve temperature stability of approximately 0.5 C.

In order to verify the accuracy of the temperature-dependent conductivity measurements, we first measured the sample of NIST SRM 1461 stainless steel over a temperature range of 15 to 40 °C. The results shown in Figure 2 agree well with the certified SRM data. After we had verified the system, we proceeded to measure the remaining metal alloys we had previously measured at ambient temperature. In Figure 3 we show the temperature-dependent results for dc conductivity for all 10 metal alloys. As expected, we observed a very small, but detectable, decrease in the dc conductivity as the temperature was increased.

5. Conclusion

In this publication we described a technique for accurately measuring the dc conductivity of metals. Using a relatively simple measurement system composed of two digital nanovolt meters, a dc power supply, and a standard resistor, we measured dc conductivities of cylindrical metal rods that ranged from 0.06×10^7 to 5.8×10^7 S/m. We derived an equation for calculating the conductivity of cylindrical metal rods and developed an uncertainty analysis. After verification of the measurement system with a NIST Standard Reference Material, we measured nine additional metal alloys that had a wide range of conductivities. In addition to measuring dc conductivity at ambient temperatures, we measured each of the ten metal alloys over a temperature range of 15 to 40 ° C. These data showed that conductivity decreased slightly with temperature, as expected.

Special thanks to George Free who developed the measurement system for this research. Funding for this research was provided by the National Institute of Justice through the Office of Law Enforcement Standards at the National Institute of Standards and Technology

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Appendix A. Certificate for SRM 1461

This appendix contains a copy of the NIST SRM certificate tabulating the values of electrical resistivity as a function of temperature for the SRM 1461 sample we used for verification of our measurement system.

U. S. Department of Commerce
Malcolm Baldrige
Secretary

National Bureau of Standards
Ernest Ambler, Director

National Bureau of Standards
Certificate
Standard Reference Materials 1460, 1461, and 1462

Austenitic Stainless Steel Thermal Conductivity (λ) and Electrical Resistivity (ρ) as a Function of Temperature from 2 to 1200 K

J. G. Hust and A. B. Lankford

These Standard Reference Materials (SRM's) are to be used in calibrating methods for measuring thermal conductivity and electrical resistivity. They are available in rod form. SRM 1460 is 0.64 cm in diameter; SRM 1461 is 1.27 cm in diameter; and 1462 is 3.4 cm in diameter. All rods are 5.0 cm in length.

T(K)	$\lambda (W \cdot m^{-1} \cdot K^{-1})$	ρ (nΩ·m)	T (K)	$\lambda (W \cdot m^{-1} \cdot K^{-1})$	ρ (nΩ·m)
			50	6.08	599
2	0.152	593	60	6.98	606
3	.249	593	70	7.72	613
4	.352	593	80	8.34	622
5	.462	594	90	8.85	630
6	.575	594	100	9.30	639
7	.693	594	150	10.94	683
8	.814	594	200	12.20	724
9	.938	594	250	13.31	767
10	1.064	594	300	14.32	810
12	1.323	594	400	16.16	885
14	1.588	594	500	17.78	944
16	1.858	593	600	19.23	997
18	2.132	593	700	20.54	1045
20	2.407	593	800	21.75	1088
25	3.092	592	900	22.86	1127
30	3.763	592	1000	23.90	1162
35	4.404	593	1100	24.86	1197
40	5.01	595	1200	25.77	1234
45	5.57	597			

The technical and support aspects involved in the preparation, certification, and issuance of this Standard Reference Material were coordinated through the Office of Standard Reference Materials by Lee J. Kieffer.

Washington, DC 20234
May 14, 1984
(Revision of Certificates dated 12-11-74, 3-5-75, and 1-17-79)

Stanley D. Rasberry, Chief
Office of Standard Reference Materials

(over)

Measurements

A. Before 1979

Based on low-temperature (below ambient) thermal conductivity, electrical resistivity, and thermopower measurements on three specimens; liquid helium and ice-point electrical resistivity measurements on twenty specimens; and other characterization data such as composition, hardness, density, and grain size [1], the homogeneity of this lot of austenitic stainless steel was determined to be excellent. These measurements indicated that the effect of material variability on thermal conductivity and electrical resistivity is no larger than ±1%.

High temperature (above ambient) data, reported by Fitzer [2] as a result of the AFML-AGARD (Air Force Materials Laboratory, Dayton, Ohio-Advisory Group for Aerospace Research and Development, NATO) reference program, form the basis for extending the temperature range of this SRM to 1200 K. These data have been analyzed and correlated with the low temperature data [1] to obtain the certified values.

B. After 1979

These SRM's were used in an international round-robin study of thermal and electrical properties under the auspices of the Task Group on Thermophysical Properties of CODATA (Committee on Data for Science and Technology). As a consequence of this cooperative program, a considerable quantity of new data and information were obtained [3]. The certified values are changed slightly from the previous values, however, they are within the previously reported uncertainty band except in the vicinity of 7 K.

The estimated uncertainties of the thermal conductivity data, including material variability, are: 2% below 100 K, increasing to 3% at ambient temperature, and 5% above ambient. The estimated uncertainties of the electrical resistivity data, including material variability, are: 1% below ambient and 2% above ambient temperature. The certified values are corrected for thermal expansion.

The chemical composition is given for information only:

Fe	62.0 wt. %	Mn	1.2 wt. %
Ni	20.2	Si	0.28
Cr	16.2	C	<0.01

The density is 8.007 ± 0.002 gm·cm^{-3}

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NIST Technical Publications

Periodical

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