Thermal Transport Properties of Niobium and Some Niobium Base Alloys from 80 to 1600 K*

J. P. Moore, R. S. Graves and R. K. Williams
Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

The electrical resistivities and absolute Seebeck coefficients of 99.8 at. % niobium with a RRR of 36, Nb-4.8 at. % W, Nb-5 at. % Mo, Nb-10 at. % Mo, and Nb-2.4 at. % Mo-2.4 at. % Zr were measured from 80 to 1600 K, and the thermal conductivities of the niobium and Nb-5 at. % W were measured from 80 to 1300 K. A technique is described for measuring the electrical resistivity and Seebeck coefficient of a specimen during radial heat flow measurements of the thermal conductivity. The transport property results, which had uncertainties of ±0.4% for electrical resistivity and ±1.4% for thermal conductivity, showed the influence of tungsten and molybdenum solutes on the transport properties of niobium and were used to obtain the electronic Lorenz function of pure niobium, which was found to approach the Sommerfeld value at high temperatures.

Introduction

The transport properties of niobium and its alloys have been the subject of several recent papers. This interest was because of the superconducting properties of niobium and many of its alloys and because of the relationship between the superconducting properties and the high temperature physical properties. In addition, interpretation of the physical properties such as the electrical resistivity, $\rho$, thermal conductivity, $\lambda$, and Seebeck coefficient, $S$, has led to a controversy between Allen [1976], Laubitz et al. [1977] and Allen and Chakraborty [1978]. Although $\rho$ and $S$ have been measured to high temperature with reasonable accuracy, the existing $\lambda$ data, which are more difficult to obtain, disagree in magnitude and temperature dependence.

In order to resolve the experimental disagreements and to provide an accurate data set for comparison with theoretical calculations, we decided to measure the $\lambda$ of a 99.8 at. % niobium from 80 to 1300 K. The $\rho$ and $S$ of the same material was measured from the superconducting transition temperature, $T_c$, to 1600 K. The same properties were also measured on a Nb–4.8 W (niobium plus 4.8 at. % tungsten) alloy over the same temperature ranges. The $\rho$ and $S$ of the binary alloys Nb–5 Mo and Nb–10 Mo, and an iso-electronic ternary alloy Nb–2.4 Mo–2.4 Zr were measured from immediately above $T_c$ to 1600 K.

The electrical resistivities of the niobium and niobium base alloys are discussed, and the thermal conductivities of the niobium and Nb–4.8 W are discussed for assumed lattice conduction components equal to zero and for lattice conduction components which include phonon scattering by other phonons, electrons, and the alloying element.
Specimen Description

Table 1 summarizes the characteristics of the specimen used in this study. The first specimen was a 99.8 at. % niobium cut from a block large enough to furnish a 76 mm diam and 228 mm long right circular cylinder for the high temperature $\lambda$ measurements and a 6.4 mm diam and 76 mm long rod for the $\rho$ and $S$ measurements at all temperatures and for the $\lambda$ measurements below 400 K. Tantalum ($\sim$250 ppm) was the primary metallic impurity in all specimens and the gas impurities within the niobium included nitrogen (0.021 at. %), hydrogen (0.13 at. %) and oxygen (0.008 at. %). Metallographic analyses showed evidence of cold work in the niobium, but comparison of the low temperature data to that obtained from another specimen which had been well annealed showed that the cold work did not significantly influence the high temperature results.

The alloys designated Nb–5 Mo, Nb–10 Mo, Nb–4.6 W, and Nb–2.4 Mo–2.4 Zr were all in the form of 76 mm long rods for the measurements of $\rho$ and $S$ only. These rod specimens were all annealed in high vacuum at temperatures near 2200 K prior to any measurements. Lattice parameter measurements indicated that the molybdenum concentration was between 4.75 and 5.25 at. % in the Nb–5 Mo and between 8.5 and 11.5 at. % in the Nb–10 Mo.

A 76 mm diam by 228 mm long right circular cylinder of Nb–4.8 W was fabricated for the high temperature thermal conductivity measurements. Since this specimen and the Nb–4.6 W rod were obtained from the same starting material, the compositions were probably identical.
Measurement Apparatus and Uncertainties

The measurement apparatus used in this study are listed in Table 2 which gives the properties measured in each, the normal temperature range of the apparatus and the determinate error of each property measurement. Since detailed descriptions can be found elsewhere, only a brief summary will be given here.

The knife edge apparatus was designed for measuring the $\rho$ and the temperature dependence of $\rho$ near room temperature. These measurements were sufficiently accurate ($\pm 0.1\%$) to detect significant specimen inhomogeneity and to determine the distances between adjacent thermocouples on rod type specimens for two of the other apparatus. The measurements were made using a standard 4-probe D.C. technique. The potential drop across a known specimen length was determined by measuring the voltage between spaced knife edges which contacted the specimen. These measurements were made while the specimens were in a temperature controlled box to prevent thermals from influencing the low level voltages. All voltages were measured with a nanovolt potentiometer to an accuracy of $\pm 0.0002\%$ plus a residual of $0.005 \mu$V.

The second apparatus listed in Table 2 was used to measure $\rho$ and $S$ from 295 K to near 1600 K. This apparatus (hence forth called the $\rho$-S apparatus) was described in detail by Fulkerson et al. (1966). The temperature measurements in this apparatus were made with Pt versus Pt-10% Rh thermocouples, and the $\rho$ measurements were made with a 4-probe reversible D.C. technique with care taken to eliminate problems with thermals and Peltier effects.
The low temperature longitudinal heat flow apparatus, LTL, was used for measurements of $\rho$, $S$, and $\lambda$ from 80 to 400 K. Temperatures in this apparatus were measured with calibrated Chromel versus constantan thermocouples. This is the same apparatus as that used by Moore et al. (1973) to measure the $\lambda$ of molybdenum to an accuracy of $\pm 0.5\%$ with the exception that the platinum resistance thermometer was omitted in these measurements and a less accurate potentiometer was employed for voltage measurements.

The RHFA apparatus was used for all high temperature $\lambda$ measurements and has been described in detail by Godfrey et al. (1965). The specimen in this apparatus consisted of a 228 mm high stack of 9 disks with an inner and outer diameter of 4 and 76.2 mm, respectively. A central carbon core heater was used to establish a temperature gradient in the radial direction. Measurement of the temperature gradient with Pt versus Pt–10% Rh thermocouples and measurement of the power dissipated in the central core heater permitted a calculation of the specimen $\lambda$. End guard heaters were used to block axial heat flow in the specimen, and a cylindrical muffle heater was used to establish the temperature of the specimen. The temperatures of the three section muffle heater and the guard heaters were controlled automatically. An "isothermal correction" described by Godfrey et al. (1965) was used for each datum. The determinate error of this apparatus was about $\pm 1.3\%$. The system differed from that described previously in that the wire wound $\text{Al}_2\text{O}_3$ core heater was replaced with a long spectrographic carbon electrode. The power dissipated in the carbon rod was greater, and this increased the temperature gradient in the radial direction. The system with a carbon rod core heater was analyzed using a finite difference heat conduction code. This analysis indicated that the error in this system due to non-radial heat flow at the specimen midplane would be less than $1\%$ for a niobium specimen.
Calculations also indicated that the use of an "isothermal correction" would reduce the thermal error to less than 0.1%. We conclude, therefore, that the total measurement uncertainty of the high temperature λ data is ±1.4%.

Results from the LTL, the previously described RHFA, and from apparatus operated by others have been extensively compared by Laubitz and McElroy (1971) and these comparisons indicated that the determinate errors in Table 2 are realistic.

Some ρ and S measurements were made in the RHFA. The S and ρ specimen, which was inserted in the stack of disks comprising the radial heat flow specimen, was machined as a 6.4 mm thick disk with inner and outer diameters equal to those of the specimen. Two slots were machined through the disk to leave a rod with a rectangular cross section with dimensions of 4.4 and 3.0 mm. The top and bottom of this disk were milled so that neither surface would contact the adjacent disks. Two electrically insulated platinum versus Pt-10% Rh thermocouples were welded to the top surface of the rod, and the distance between the attachment points was measured. Current leads were attached to the free end of the specimen and the disk so that a standard 4-probe D.C. technique could be used to determine ρ. The different gradients along the rod during the two thermal configurations required for each λ value permitted determination of the S.

Experimental Results

Electrical Resistivity

Smoothed values of the results at even temperature intervals are given in Table 3, and all data above 300 K have been corrected for geometry change due to thermal expansion using expansion results from Amonenko et al. (1964). Data for the Nb-5 Mo, Nb-10 Mo, and Nb-2.4 Mo-2.4 Zr include only the high temperature ρ and S
since the results at lower temperature will be published elsewhere as part of a study on a series of niobium base alloys and a high purity niobium.

The $\rho$ of Nb–5 Mo, Nb–10 Mo and Nb converge to within experimental error above 1100 K, whereas the $\rho$ of Nb–4.8 W crosses that of Nb near 700 K and is 2.5% lower at 1600 K. These differences can be seen in Fig. 1 which shows the deviations of the alloy resistivities from the present result on niobium. Results from White and Woods (1959) for niobium with a RRR of 500 are shown for temperatures below 300 K. The negative deviation of White and Wood’s (1959) results from the present values on niobium are an indication of the greater impurity of the present material. High temperature $\rho$ results from Peletsky are about $0.6 \times 10^{-8} \ \Omega\cdot m$ ($\sim 1\%$) above the present values, but this is well within the combined experimental uncertainties.

**Thermal Conductivity**

The thermal conductivity results from both apparatus are shown in Fig. 2 for the niobium and Nb–4.8 W. Discrete datum are shown about the smooth lines representing the high temperature results, but only smooth curves are shown for the low temperature results. Values given in Table 3 are from the solid curves which smooth the data over the temperature range of overlap where the results do not agree perfectly. The maximum deviation of any experimental value from the solid curves was 1.4%.

Figure 3 shows the percentage deviations between the present niobium results as represented by the solid curve in Fig. 2 and previous results as corrected for thermal expansion. Recommended values from TPRC (1967) are 3 to 5% above the present values, and results from Fieldhouse et al. (1958) are 9 to 13% below the present results. The high temperature $\lambda$ data from Peletsky, which were obtained on a specimen with a $\rho$ about 1%
above the present values, are about 5% below the present results near 1200 K. The worse disagreement is with the results of Pozdnyak (1970) which are 5% below and 24% above the present values at 400 and 1200 K, respectively. Figure 3 shows that the percentage spread of experimental data is large (\sim 35%) at high temperatures.

**Seebeck Coefficient**

The absolute Seebeck coefficients of the five specimens are shown in Fig. 4. The absolute values were determined using absolute values for platinum tabulated by Moore and Graves (1972) and Cusack and Kendall (1958) below and above 1200 K, respectively. The S of niobium is low compared to that observed in most transition metals and the presence of Mo or W has a small influence on S.

**Discussion of Results**

**Electrical Resistivity**

The electrical resistivity of a metal or alloy can be written as

$$\rho(T) = \rho_0 + \rho_i(T)$$

where $\rho_0$ is the resistivity due to impurities and $\rho_i(T)$ is the ideal $\rho$ of the solvent in the absence of impurities. If Matthiessen's rule is obeyed for a system, the first term is independent of temperature. It has been shown experimentally that $\rho_i(T)$ of non-magnetic metals above the Debye temperature, $\theta_D$, can be expressed as

$$\rho_i(T) = \rho(T) - \rho_0 = AT + BT^2 + C/T$$
where AT and C/T are approximations to the Bloch-Gruneisen equation and the BT^2 term accounts for the decrease in the Debye temperature, $\theta_D$, with increasing temperature. Usually the first two terms are positive and the last one is negative. The high temperature deviation from linearity (df$\varepsilon$) normally observed is positive. The df$\varepsilon$ of the niobium results is negative, and this has been the subject of several papers which ascribe this feature to several things including the details of the Fermi surface, the Fermi energy and a possible breakdown in the Boltzmann equation, [see, for example, Yamashita and Asano (1974), Allen (1976), Laubitz et al. (1977) and Inoue and Shimizu (1976)].

The $\rho$ of the alloys deviate strongly from Matthiessen's rule. This deviation is so great that two of the alloys (Nb–10 Mo and Nb–4.8 W) have electrical resistivities that are less than that of the pure niobium at high temperatures. Although Bass (1972) gives many reasons for deviations from Matthiessen's rule, the present deviations can be largely explained by differences in the Debye temperatures and the atomic masses. The linear term in Eq. (2) is inversely proportional to the product $\theta_D^2\bar{M}$ where $\bar{M}$ is the average atomic mass. Therefore, variation of either of these would have an influence on the high temperature $\rho$ since the linear term dominates at the highest temperatures used in these measurements. The other parameters in Eq. (2) are also affected by changes in $\theta_D$ but only secondarily. Data by Powell et al. (1977) indicate that the $\theta_D$ of niobium is 280 K while that of Nb–5 Mo and Nb–10 Mo should be near 288 and 296 K, respectively. Estimates based on $\theta_D$ values of Ta and W alloys [Bucher et al. (1964)] indicate that $\theta_D$ of the Nb–4.8 W is the same as that of pure Nb, and results from Ishikawa
and Cappelletti (1977) show that the $\theta_D$ of the ternary alloy is about 3 K below that of pure niobium. The $\bar{M}$ of all the alloys containing Mo are within 0.1% of that of niobium whereas the $\bar{M}$ of the Nb–4.8 W is 4.7% higher. Thus, we would expect deviations from Matthiessen's rule for all four alloys.

The magnitude of the deviations are difficult to determine since we do not know the magnitude of the linear term in Eq. (2) and have no unambiguous way of determining it. An attempt was made to determine the linear coefficient by fitting the $\rho$ data from 100 to 1600 K to Eq. (2) with the results shown in Table 4. The fifth column in the table gives the ratio of the "A" coefficient from each alloy to that from niobium and the sixth column gives the calculated factor $\delta^2(Nb) \bar{M}(Nb)/\delta^2(alloy)/\bar{M}(alloy)$ for comparison. In every case, except one, columns 5 and 6 agree, and this indicates that the differences in the $\theta_D$ and average atomic mass of the alloys cause much of the deviation from Matthiessen's rule. The calculation in column 6 for the Nb–2.4 Zr–2.4 Mo would indicate a positive deviation from Matthiessen's rule whereas a negative one is observed experimentally.

Variation of the density of states would also influence the linear term and Sousa (1968) interpretated low temperature thermal conductivity results in a Nb–Mo series based on a change in the density of states with alloying and Ishikawa and Cappelletti (1975) have shown that the density of states in the ternary alloy is not the same as that of niobium.
Thermal Conductivity

The thermal conductivity of a metal can be expressed as

$$\lambda(T) = \lambda_e(T) + \lambda_\xi(T)$$

(3)

where $\lambda_e(T)$ is due to conduction by electrons and $\lambda_\xi(T)$ is due to conduction by quantized lattice vibrations or phonons. The electronic component is related to the electrical resistivity through

$$\lambda_e = \frac{L(T)\rho}{T}$$

(4)

where $L(T)$ is the Lorenz function. When electron scattering is elastic, and the electron gas is degenerate, this function is equal to the Sommerfeld value, $L_0 = 2.443 \times 10^{-8} \text{ (V/K)}^2$. The Lorenz function is a fundamental parameter in thermal conduction in metals, and its reduced value is often calculated from experimental values of $\lambda$ and $\rho$ using

$$\frac{L(T)}{L_0} = \frac{\rho}{L_0 T} \left[\lambda(T) - \lambda_\xi\right]$$

(5)

where $\rho$ and $\lambda(T)$ are measured values. Since an estimate must be made for $\lambda_\xi$, it is usually assumed to be negligibly small and simply ignored. The values of $L(T)/L_0$ for niobium and Nb-4.8 W from the present data are shown in Fig. 5 on the assumption that $\lambda_\xi(T)$ is zero. The error bars represent combined errors from the thermal conductivity ($\pm 1.4\%$) and electrical resistivity ($\pm 0.4\%$) measurements. The $L(T)/L_0$ of niobium is below 1.0 at temperatures below 200 K, reaches a broad maximum of 1.06 near 500 K and then decreases to 1.03 at 1300 K. The $L(T)/L_0$ of Nb-4.8 W is slightly below 1.0 below room temperature, has a broad maximum of 1.026 near 500 K.
and then decreases to a value of 1.0 at 1200 K. The ripple in the curve below 400 K is probably insignificant since it is smaller than the data uncertainty.

The inclusion of a non-zero $\lambda(T)$ would lower $L(T)/L_0$ for both materials and the calculations of approximate $\lambda(T)$ values are described below. The lattice conductivity of a metal can be expressed as

$$\lambda^{-1}(T) = W_{pp} + W_{E-P} + W_{IP}$$

where $W_{pp}$, $W_{E-P}$, and $W_{IP}$ are due to scattering of conduction phonons by other phonons, electrons and impurities, respectively. The phonon-phonon term is given by

$$W_{pp} = \frac{5.98 \times 10^{-27} \gamma^2}{M \delta \phi^3} [T + 3 \alpha_v \gamma T^2] \text{ (m*K/W)}$$

where the first term is a modified form of the Leibfried-Schloman [1954] equation as given by Roufosse and Klemens [1973] and the second term is an approximation which corrects for a change in the Debye temperature due to lattice dilation with increasing temperature. In this equation

$\gamma$ = Gruneisen constant,

$M$ = atomic mass,

$\delta$ = cube root of the atomic volume,

and

$\alpha_v$ = volumetric expansion coefficient.

For niobium, $W_{IP}$ was negligibly small at high temperatures, and $W_{pp}$ was calculated to be

$$W_{pp} = 2.0 \times 10^{-4} \ [T + 2.2 \times 10^{-6} \ T^2] \text{ .}$$
A constant value of 0.141 was taken for $W_{\text{ep}}$ from Butler and Williams [1978]. Figure 6 shows that inclusion of the non-zero lattice conduction leads to a reduced Lorenz function that is less than 1.0 below 800 K but is within ±0.1% of the Sommerfeld value at higher temperatures.

A similar approximation was made for the $\lambda_2(T)$ of Nb-4.8 W alloy, and the $W_{\text{Ip}}$ was calculated using results from Abeles [1963] with an assumed strain parameter ($\varepsilon$) of 39. Figure 6 shows that the $L(T)/L_0$ of niobium and that of Nb-4.8 W, as corrected for lattice conduction, agree with each other from 300 to 600 K to within 0.4%. Above 600 K, the results diverge slowly until the $L(T)/L_0$ of Nb-4.8 W is about 2% below that of niobium. Although this difference may be real, it is well within the combined experimental uncertainties of the measurements.

As mentioned previously, there have been many recent calculations made in an attempt to explain the transport properties of niobium. Allen [1976] calculated the $\rho$ of niobium and concluded that the large $\text{df}_{\text{F}}$ was due to a breakdown in the Boltzmann equation. Laubitz et al. [1977] argued that slight shifts in the assumed Fermi energy would change the calculated $\rho$ predicted by Allen's model. Shifts by either +19 m Ry or -13 m Ry brought closer agreement between the model and the experimental $\rho$. Laubitz et al. [1977] also calculated the value of $L(T)/L_0$ from Allen's model, but none of the calculated curves agree with the present experimental curves for the case where $\lambda_2$ was assumed to be zero nor for the case where $\lambda_2$ was calculated using Eq. (6).

Allen and Chakraborty [1978] calculated the Seebeck coefficient of niobium. Assumed Fermi energies from -13 to +19 m Ry were inadequate to provide agreement between experimental and calculated values of $S$. They
felt that such a wide variation is improbable and reiterated Allen's hypothesis that the problem is due to a breakdown in the Boltzmann equation as the electron mean free path approaches the atomic spacing.

Whatever the cause of the negative df2 of the niobium $\rho$, the $\rho$ cannot be explained at the expense of predicting a Lorenz function that deviates markedly from unity at high temperatures as shown by the present study.

Acknowledgments

We gratefully acknowledge Fred Weaver for his assistance during many of the electrical resistivity measurements, D. L. McElroy for his continued support and careful text reviews and Sharon Buhl for her typing ability.
References


List of Figures

1. Deviations of the $\rho$ (as corrected for thermal expansion) of Nb-5 Mo ($\Delta$), Nb-10 Mo ($\square$), Nb-4.8 W ($\bullet$), Nb-2.4 Mo - 2.4 Zr (X), niobium values from Peletsky (+) and niobium values from White and Woods (○) from the present results on niobium. The dashed line represents the ±0.4% uncertainty range for the $\rho$ of niobium.

2. The thermal conductivity results for niobium (○) and Nb-4.8 W (●) from the two apparatus. The dashed curves represent results from the low temperature measurements, and the solid curves represent smooth values used in subsequent analysis.

3. Percentage deviations between the present niobium results and those obtained by Fieldhouse (○), Podznyak (▽), Peletsky (+) and "Recommended Values" from TPRC (●).

4. The absolute Seebeck coefficients of niobium (○), Nb-5 Mo ($\Delta$), Nb-10 Mo ($\square$), Nb-4.8 W (●), and Nb-2.4 Mo-2.4 Zr (X).

5. The reduced Lorenz function, $L(T)/L_0$, versus temperature for niobium (○) and Nb-4.8 W (●) assuming that $\lambda_z$ is zero and for niobium (-----) and Nb-4.8 W (-----) assuming that $\lambda_z$ is restricted by phonon, electron, and impurity scattering.
Table 1. Characterization of the Specimen Used in This Study

<table>
<thead>
<tr>
<th>Material</th>
<th>Alloy Concentration (^a,b) (at. %)</th>
<th>(\rho_0 ) (^c) (\times 10^8 \ \Omega\cdot m)</th>
<th>(T_c) (K)</th>
<th>Density (Mg/m(^3))</th>
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<tbody>
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<td>Nb</td>
<td>—</td>
<td>0.4</td>
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<td>Nb–5 Mo</td>
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<td>—</td>
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<tr>
<td>Nb–2.4 Mo–2.4 Zr</td>
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<td>8.32</td>
<td>8.548 (8.15–8.49)</td>
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</table>

\(^a\) Calibrated-quantitative spectrographic analysis with an uncertainty of ±5%.

\(^b\) Semi-quantitative spectrographic analysis with an uncertainty of +100% to -50% showed that metallic impurities were negligible with the exception of tantalum which could have been present in amounts up to 250 ppm.

\(^c\) \(\rho_0\) value is the electrical resistivity at temperatures immediately above \(T^0\) for all specimens except niobium where it is the \(\rho\) at 4.2 K in the normal state.
<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Property</th>
<th>Temperature Range (K)</th>
<th>Determinate Error</th>
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<td>ρ-S</td>
<td>ρ</td>
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<td></td>
<td>S</td>
<td>295–1600</td>
<td>±0.7 (μV/k)</td>
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<tr>
<td>Longitudinal Heat Flow (LTL)</td>
<td>ρ</td>
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<td>λ</td>
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<td></td>
<td>S</td>
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<td>±0.7 (μV/k)</td>
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Table 3. Smoothed Values of the High Temperature Electrical Resistivity and Thermal Conductivity Results. The thermal conductivity values were obtained from the solid curves in Figure 2.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Niobium $\lambda$ (W/m K) $\rho \times 10^8$ ((\Omega)-m)</th>
<th>Nb-4.8 W $\lambda$ (W/m K) $\rho \times 10^8$ ((\Omega)-m)</th>
<th>Nb-5 Mo $\rho \times 10^8$ ((\Omega)-m)</th>
<th>Nb-10 Mo $\rho \times 10^8$ ((\Omega)-m)</th>
<th>Nb-2.4 Mo-2.4 Zr $\rho \times 10^8$ ((\Omega)-m)</th>
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<td>59.6</td>
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<td>44.93</td>
<td>60.7</td>
<td>44.39</td>
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<td>57.32</td>
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<td>60.08</td>
<td>58.62</td>
<td>60.23</td>
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Table 4. Summary of the Fits of the Experimental $\rho$ Data from 100 to 1600 K (as Corrected for Thermal Expansion) to Eq. (2)

<table>
<thead>
<tr>
<th>Material</th>
<th>Coefficients$^a$</th>
<th>$A_{(\text{alloy})}$</th>
<th>$B_{(\text{alloy})}$</th>
<th>$C_{(\text{alloy})}$</th>
<th>$\frac{A_{(\text{alloy})}}{A_{(\text{Nb})}}$</th>
<th>$\frac{\rho^2(Nb)\bar{M}(Nb)}{\rho^2(\text{alloy})\bar{M}(\text{alloy})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td></td>
<td></td>
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<tr>
<td>Nb–5 Mo</td>
<td>0.04976</td>
<td>-0.8008</td>
<td>-70.73</td>
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<td>1.000</td>
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<tr>
<td>Nb–10 Mo</td>
<td>0.04650</td>
<td>-0.69051</td>
<td>-61.70</td>
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<td>0.9345</td>
<td>0.945</td>
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<td>0.042627</td>
<td>-0.5421</td>
<td>-60.01</td>
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<td>0.890</td>
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<td>Nb–4.8 W</td>
<td>0.04622</td>
<td>-0.72196</td>
<td>-52.45</td>
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<td>0.9289</td>
<td>0.9551</td>
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</table>

$^a\rho$ is in $\Omega\cdot m$. 