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Thermal Conductivity and Electrical Resistivity of Six Copper-Base Alloys

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Thermal Conductivity and Electrical Resistivity
of Six Copper-Base Alloys*, +

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ABSTRACT

Measurements of the thermal conductivity, λ , and electrical resistivity, ρ , of oxygen free copper and six copper-base alloys in the temperature range 298 to 924 K are presented. Except for copper, the λ and ρ values of copper alloys having the same chemical composition as those given in this paper have not been previously reported. The measured values of λ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and ρ ($\Omega\cdot\text{m}$) were found to conform, within 10 percent, to the predictions of the Smith-Palmer equation, $\lambda = 2.39 \times 10^{-8} T/\rho + 7.50$ [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$], where T is the thermodynamic temperature expressed in kelvins.

Key Words: Copper-base alloy properties; electrical resistivity; Smith-Palmer equation; thermal conductivity

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PHYSICS 551

1. Introduction

The thermal conductivity, λ , of copper and a large number of copper alloys have been previously measured [1]. In many instances, measurements were made at temperatures below 100 K.

It is known [2,3] that λ of a copper alloy usually can be predicted with sufficient accuracy for practical purposes from a measurement of its electrical resistivity, ρ . Specifically, measured values of λ and ρ of many copper alloys between 293 and 473 K were observed [2,3] to obey the Smith-Palmer equation, $\lambda = 2.39 \times 10^{-8} T/\rho + 7.50$ [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$], where T is the thermodynamic temperature expressed in kelvins, to within 10-15 percent. In the present investigation, it was desired to know the thermal conductivity of a number of specific copper alloys over a larger temperature range than that in which the Smith-Palmer equation is known to hold accurately.

Results of the measurements of λ and ρ of oxygen free copper and six copper-base alloys from 298 to 924 K are presented in this paper. Samples for measurement were provided by the National Aeronautics and Space Administration (NASA), Lewis Research Center, Cleveland, Ohio. Measured values were compared with those obtained from the Smith-Palmer equation. Except for oxygen free copper, λ and ρ values of copper alloys having the same chemical compositions as those found in this paper have not been previously reported.

2. Specimens and Apparatus

The copper-base metals provided by NASA for these measurements were in the form of either rectangular bars or right circular cylinders. Radiographs obtained from the exposure of these samples to the National Bureau of Standards cobalt-60 source (1.25 MeV gamma rays) showed that the samples did not contain observable voids. Results of laboratory determination of the chemical composition, thermal history and mechanical properties made on these copper alloys were supplied by NASA and are given in Tables 1a, 1b and 2.

Experimental data for calculating λ and ρ of the copper alloys were obtained using an apparatus which has been described in detail elsewhere by Watson and Robinson [4]. This apparatus employs an electric heater and a circulating water heat sink to maintain a steady-state longitudinal thermal gradient closely approximating one-dimensional heat flow in a rod-shaped specimen about 37 cm long and 0.64 cm in diameter. The specimen is mounted vertically and is coaxially surrounded by a stainless steel cylinder equipped with its own heater which is made to function as a thermal guard by adjusting its temperature profile to match, as closely as possible, that of the specimen, thereby reducing radial heat flows even further. A computerized analysis procedure is used to make final corrections to compensate for the small remaining amount of extraneous radial heat flow not eliminated by the apparatus. Alumina powder insulation surrounds both the specimen and the thermal guard.

Basically, λ was determined from measured input power to the specimen heater and the specimen temperature gradient, which was in turn determined using calibrated Pt /Pt -10%Rh thermocouples at seven known

positions spaced 3.5 cm apart along the specimen, creating six measurement intervals, or spans. Calculated values of λ were thus obtained at six different mean temperatures for each level of power input to the specimen heater (a "run").

While steady-state thermal conditions were being maintained for each run, electrical resistivity was measured by passing a measured direct current through leads attached to the ends of the specimen and measuring the voltage differences between adjacent platinum leads of the thermocouples along the specimen. Thermoelectric effects were accounted for by taking voltage measurements with current flowing in forward and reversed directions. All values of λ and ρ were computed using specimen dimensions determined at room temperature.

Vacuum and gas handling systems were added to the apparatus in order to make the particular measurements described in this paper in argon gas. This permitted higher temperatures than could be attained in air without encountering oxidation of the copper alloy specimens. All measurements were conducted with the specimen chamber backfilled with argon at a pressure of one atmosphere.

Typically, three runs were made with each specimen, starting at the lowest power input level to the specimen heater and increasing it for each subsequent run. The highest mean temperature of a span during the hottest run was about 925 K. After a complete set of measurements was made on specimen R2, it was completely removed and subsequently replaced in the apparatus. A second set of measurements was then obtained. Only two runs each were made for specimens R3 and R4, which limited the highest span mean temperatures to about 625 K in those cases. Specimens

were tested in the order: R2, R2 (repeat test), R9, R5, R14, R4 and R3. (For composition of the specimens, see Table 1.)

3. Results

Examination of the specimens after completion of measurements revealed that, except for oxygen free copper, R5, there was no significant amount of oxidation of the specimens. In the case of oxygen free copper, examination of the specimen after testing revealed that a crust about 0.01 cm thick and 7.6 cm long covered the hottest end of the specimen. This layer was observed to be detached from the specimen. Qualitative analysis made on a piece of crust material using an electron beam probe analyzer revealed the presence of an abundant amount of oxygen and copper. Thus, it is most likely that the crust formation was an oxide of copper. The maximum temperature range of the encrusted section of the specimen during the hottest run was about 775 K to 975 K, sufficiently high for the oxidation of copper. The change of cross-sectional area of the specimen as a result of oxidation was taken into account in the calculation of λ of R5.

Values of λ and ρ calculated from measured data are shown as individual points in Figures 1 and 2, respectively. R2 data is included from both sets of measurements made on the specimen. The curves shown in these figures represent cubic polynomials fitted to the individual specimen data points by the method of least squares, of the form $\lambda = \alpha_0 + \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3$ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and $\rho = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$ ($\Omega\cdot\text{m}$). For T in degrees Celsius, values of the coefficients of these polynomials are given in Table 3. Numerical results, called "smoothed

values", calculated from the above equations at uniform temperature intervals, are presented in Tables 4 and 5.

Below 833 K values of λ for specimen R2 obtained in the repeated measurement were in agreement to within 0.5 percent to that of the initial run. Between 833 and 920 K, results of the two successive measurements were in agreement to within 1.5 percent. Values of λ for oxygen-free copper obtained in this work agree within better than 3 percent with the values recommended by Touloukian, et al [1] over the full temperature range of the results obtained in the present effort, except for the highest temperature point (about 925 K, Fig. 1). This point is anomalously low and is most likely due to errors introduced because of heavy oxidation of the hottest span, and relatively large extraneous heat flows for which the computerized analysis could not completely compensate; it subsequently causes an anomalously large decreasing trend of the fitted curve with increasing temperature, particularly in the range of about 825 to 925 K.

The fitted curves for λ and ρ each tend to cluster into two groups, one with λ (ρ) near that of oxygen-free copper and the other with λ (ρ) somewhat lower (higher). The reason for this separation is not known. However, other measured data for both properties indicate such variation is not unreasonable for dilute copper alloys [3]. In addition, a consistency check was made by calculating the Lorenz function for each specimen from the smoothed data at even temperature intervals. Over the whole range of the data, the Lorenz function was almost temperature independent and close to the theoretical Lorenz number for all specimens except R14. Although the Lorenz functions are not presented, comparison

between measured and predicted values for λ using the Smith-Palmer equation are given in Table 6. The same conclusion about the consistency of the results is obtained. It is thus felt that the clustering of the curves into two groups is coincidental and has no other significance.

The results for specimen R14 are an exception to the above conclusion. In addition to an anomalously low calculated Lorenz function (compared to the other specimens) and a significant lack of agreement with predictions of the Smith-Palmer equation, there is also a large scatter in the electrical resistivity data (Fig. 2). Either the results for λ or ρ , or both, must be anomalous. Fictitious electrical resistivity values calculated from the Smith-Palmer relation using measured values of λ closely approximated a linear function of temperature with only a small amount of data scatter (about 2% standard deviation) and a fitted straight line closely matches the results of the measured ρ data of the other specimens both in slope and in magnitude. These facts lead to the belief that the λ results for R14 are probably valid, and thus that the ρ results for R14 are probably mostly anomalous (although there was close agreement between the fictitious calculated ρ values and most of the actual measured ρ data points in the temperature range 373-573 K).

The accuracy of the smoothed values of λ obtained with this apparatus was established from a comparison of results on round-robin specimens by NBS and other laboratories. It is estimated to be about ± 2 to 3 percent [5-8]. Because of the use of thermocouples as potential taps in the measurement of ρ , similar uncertainties exist in geometry and thermoelectric effects. Since these are the dominant sources of error, it is estimated that the accuracy of the smoothed values of ρ are about

the same as that for λ .

4. Conclusion

Measured values of the thermal conductivity and electrical resistivity of oxygen-free copper and six copper-base alloys are presented. With one exception, the measured λ values of these materials and the λ values predicted by the Smith-Palmer equation using measured ρ values agree to within about 3 percent. The exceptional case is believed to be due to erroneous ρ data, and not due to limits of validity of the Smith-Palmer equation.

5. Acknowledgment

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6. References

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Figure Captions

Figure 1 Thermal Conductivity of Oxygen Free Copper and Six Copper-Base Alloys

Figure 2 Electrical Resistivity of Oxygen Free Copper and Six Copper-Base Alloys

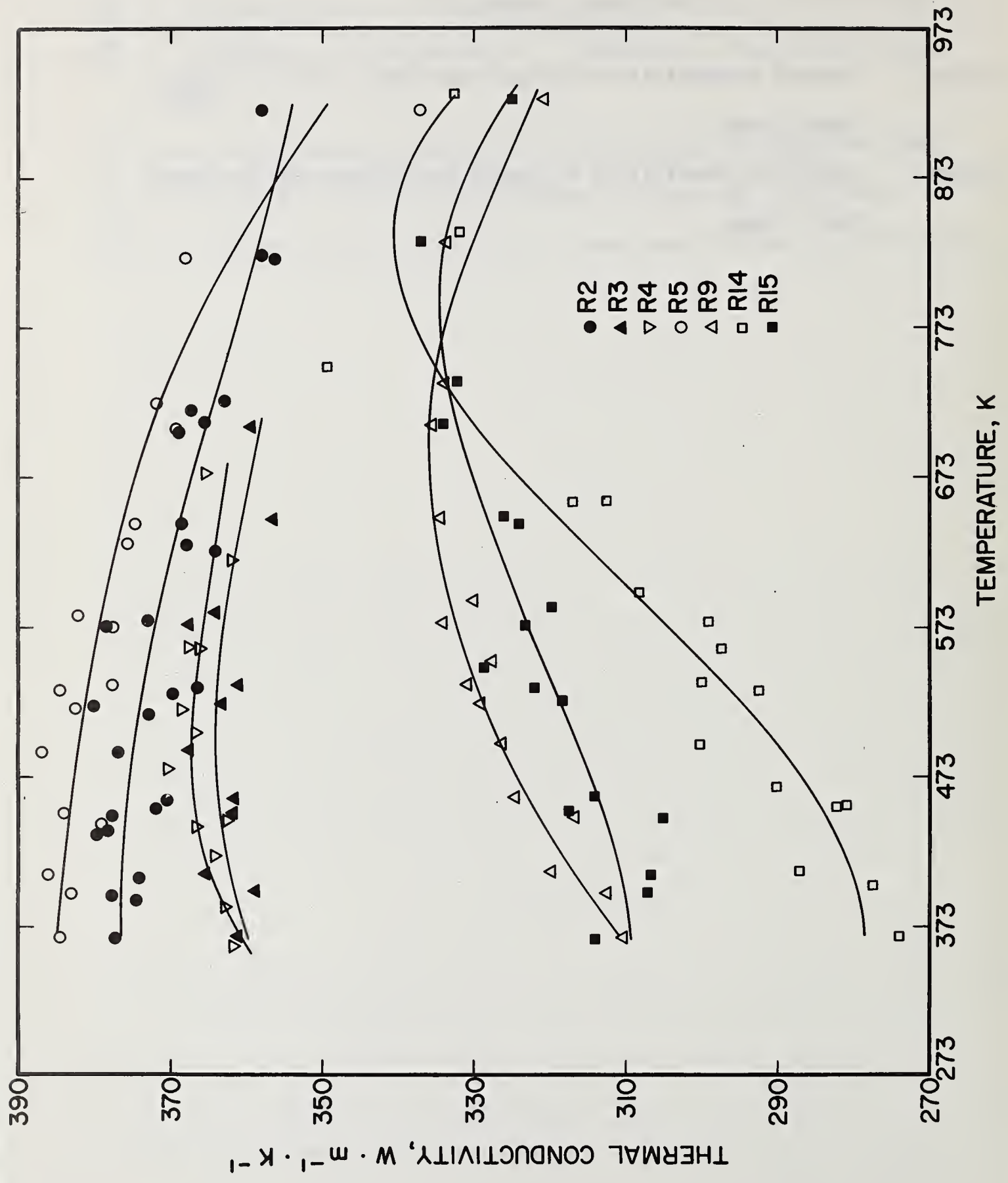


Figure 1 Thermal Conductivity of Oxygen Free Copper and Six Copper-Base Alloys

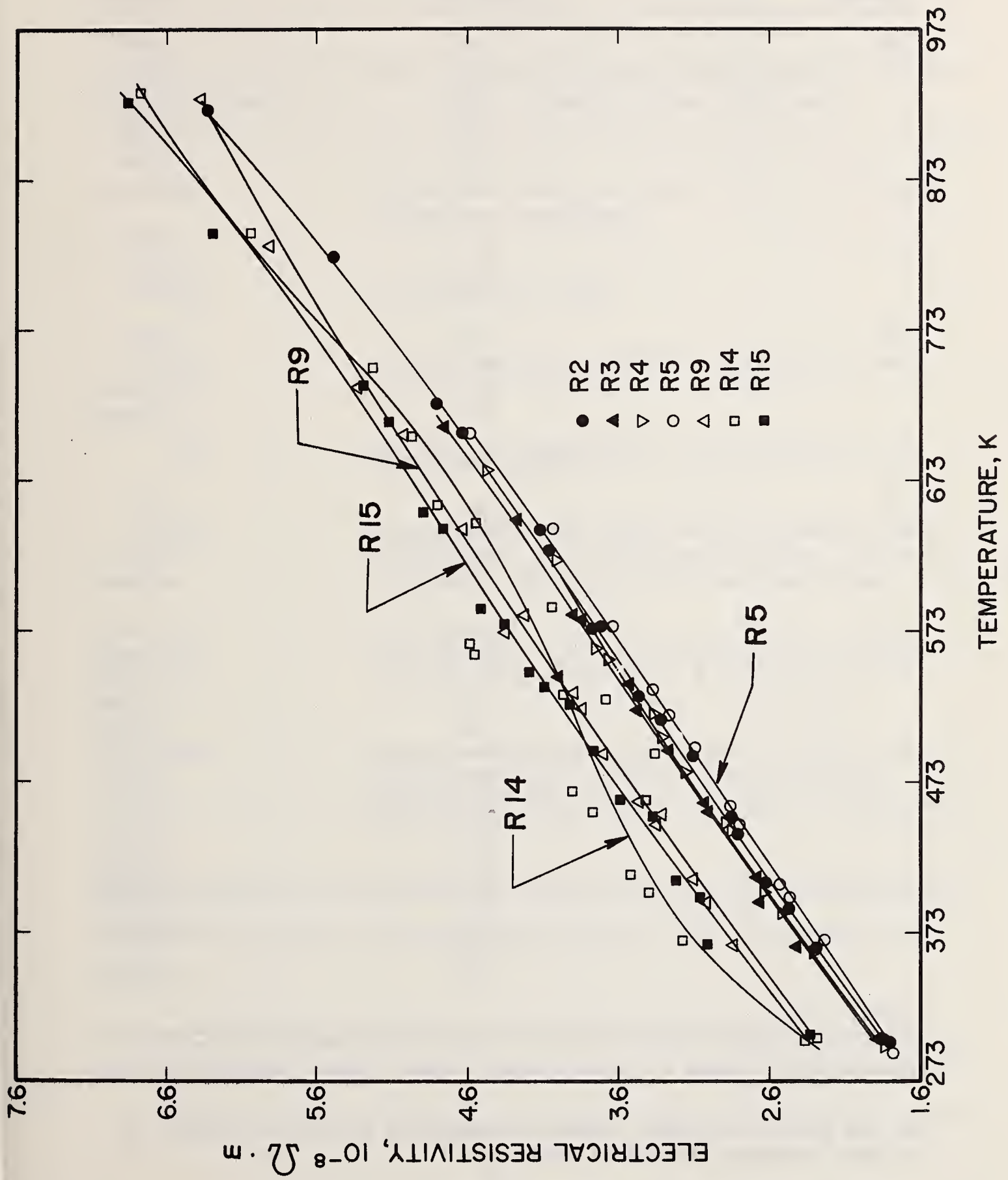


Figure 2 Electrical Resistivity of Oxygen Free Copper and Six Copper-Base Alloys

Table 1a Chemical Composition of the Copper Samples*

| Identification Number | Chemical Composition | Percent Weight |
|-----------------------|----------------------|----------------|
| R2 | Pb | 0.000 |
| | Sn | 0.000 |
| | Zn | 0.00 |
| | Fe | 0.002 |
| | Ni | 0.002 |
| | Zr | 0.20 |
| | Cu | Balance |
| R3 | P | 0.005 |
| | Te | 0.51 |
| | Cu | 99.50 |
| R4 | Mg | 0.00 |
| | Si | 0.02 |
| | Cr | 1.07/1.13 |
| | Cu | Balance |
| R5 ⁺ | Oxygen Free Copper | - |
| R9 | Mg | 0.05 |
| | Zr | 0.17 |
| | Cr | 0.48 |
| | Cu | Balance |
| R14 | Pb, Sn | 1 ppm |
| | Bi | <0.0001 |
| | Be | <0.0002 |
| | Si | <0.0001 |
| | Ca | <0.0003 |
| | Mn | <0.0003 |
| | Co | <0.001 |
| | Ni | <0.001 |
| | Zn | <0.001 |
| | As | <0.002 |
| | P | <0.002 |
| | Sb | <0.002 |
| | Zr | 0.49 |
| | Ag | 2.74 |
| | Cu | Balance |
| R15** | | |

* Information provided by Lewis Research Center, NASA, Cleveland, Ohio.

** R15 was made to the same chemical composition as R14 but differs in its heat treatment (shown in Table 1b).

+ Chemical composition not supplied by NASA.

Table 1b Thermal History of the Copper Samples*

| Identification No. | History of Heat Treatment |
|--------------------|--|
| R2 | Extruded at 1233 K and aged at 693 K in cracked natural gas atmosphere |
| R3 | Not provided by NASA |
| R4 | Solution annealed at 1273 K, quenched and aged at 773 K for 3 hours |
| R5 | Hot rolled at 1051-1109 K and cold drawn |
| R9 | Solution heat treated at 1331 K in neutral (barium chloride) salt, quenched in water, cold drawn and aged at 773 K for 2 1/2 hours and drawn |
| R14 | Centrifugally cast, hot forged at 940 to 1134 K, solution treated at 1451 ± 8 K for 2 hours |
| R15 | Conventionally cast, hot rolled at 1134 ± 8 K, solution annealed at 1451 ± 8 K for 1 hour, quenched in water, aged at 773 K for 3 hours and air cooled |

*Information provided by Lewis Research Center, NASA, Cleveland, Ohio.

Table 2 Mechanical Properties of the Copper Samples*

| Alloy | T (K) | Strength (MN/m ²) | | Reduction in Area (%) |
|-------|-------|-------------------------------|-----------|--------------------------|
| | | Yield | Tensile** | |
| R2 | 297 | 336 | 378 | 81.5 |
| | 811 | 213 | 216 | 84 |
| R3 | 297 | 355 | 360 | 37.5 |
| | 811 | 24.8 | 74.2 | 28 |
| R4 | 297 | 521 | 529 | 56.5 |
| | 811 | 255 | 262 | 17.5 |
| R5 | 297 | 309 | 317 | 82 |
| | 811 | 23.5 | 70.3 | 65 |
| R9 | 297 | 537 | 550 | 77 |
| | 811 | 296 | 309 | 40.5 |
| R14 | 297 | 82.4 | 295.1 | 53.8 |
| | 811 | 63.4 | 125.5 | 61.5 |
| R15 | 297 | 99.0 | 288.5 | 55 |
| | 811 | 85.1 | 127.0 | 53.5 |

* Information provided by Lewis Research Center, NASA, Cleveland, Ohio

** Tensile strain rate: $2 \times 10^{-3} \text{ sec}^{-1}$ in all tests

Table 3 Values of the Coefficients of the Least Squares Fit Cubic Equations*

| Coefficient | R2** | R3 | R4 | R5 | R9 | R14 | R15 |
|-------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| α_0 | 386.0 | 349.8 | 342.1 | 392.0 | 294.4 | 286.0 | 310.9 |
| α_1 | -1.061×10^{-2} | 1.421 | 0.2821 | -0.9031×10^{-1} | 1.946×10^{-1} | -1.761×10^{-1} | -5.545×10^{-2} |
| α_2 | -2.941×10^{-6} | -4.203×10^{-3} | -0.9871×10^{-3} | 3.022×10^{-4} | -2.147×10^{-4} | 1.147×10^{-3} | 4.837×10^{-4} |
| α_3 | -1.047×10^{-7} | 3.175×10^{-6} | 1.040×10^{-5} | -4.469×10^{-7} | -3.142×10^{-8} | -1.175×10^{-6} | -5.577×10^{-7} |
| β_0 | 1.631×10^{-8} | 1.656×10^{-8} | 1.667×10^{-8} | 1.533×10^{-8} | 2.111×10^{-8} | 2.159×10^{-8} | 2.075×10^{-8} |
| β_1 | 7.572×10^{-11} | 8.677×10^{-11} | 8.124×10^{-11} | 8.390×10^{-11} | 7.134×10^{-11} | 1.035×10^{-10} | 9.071×10^{-11} |
| β_2 | 3.267×10^{-14} | -8.661×10^{-14} | -5.945×10^{-14} | -8.760×10^{-14} | -2.214×10^{-15} | -1.722×10^{-13} | -7.821×10^{-14} |
| β_3 | 4.315×10^{-17} | 1.169×10^{-16} | 7.187×10^{-16} | 1.298×10^{-16} | -1.017×10^{-17} | 1.885×10^{-16} | 7.860×10^{-17} |

* Appropriate temperature ranges of applicability are given in Figures 1 and 2

** See Table 1 for chemical composition

Table 4 Smoothed Values of the Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)
of Oxygen Free Copper and Six Copper-Base Alloys

| T (K) | R2 | R3 | R4 | R5 | R9 | R14 | R15 |
|-------|-----|-----|-----|-----|-----|-----|-----|
| 373 | 376 | 360 | 361 | 385 | 312 | 279 | 310 |
| 423 | 376 | 363 | 366 | 384 | 319 | 281 | 311 |
| 473 | 375 | 364 | 367 | 383 | 324 | 287 | 315 |
| 523 | 373 | 364 | 367 | 382 | 329 | 295 | 319 |
| 573 | 372 | 363 | 366 | 380 | 333 | 305 | 323 |
| 623 | 370 | 362 | 364 | 377 | 335 | 314 | 327 |
| 673 | 367 | 360 | 364 | 375 | 336 | 324 | 330 |
| 723 | 364 | - | - | 371 | 336 | 332 | 333 |
| 773 | 361 | - | - | 367 | 334 | 338 | 334 |
| 823 | 359 | - | - | 362 | 331 | 341 | 334 |
| 873 | 356 | - | - | 356 | 327 | 339 | 331 |
| 923 | 354 | - | - | 349 | 321 | 333 | 326 |

Table 5 Smoothed Values of the Electrical Resistivity ($10^{-8}\Omega\cdot\text{m}$)
of Oxygen-Free Copper and Six Copper-Base Alloys

| T (K) | R2 | R3 | R4 | R5 | R9 | R14 | R15 |
|-------|------|------|------|------|------|------|------|
| 323 | 2.00 | 2.07 | 2.06 | 1.93 | 2.47 | 2.63 | 2.51 |
| 373 | 2.36 | 2.45 | 2.43 | 2.30 | 2.82 | 3.04 | 2.91 |
| 423 | 2.71 | 2.80 | 2.78 | 2.64 | 3.17 | 3.39 | 3.28 |
| 473 | 3.05 | 3.14 | 3.11 | 2.96 | 3.52 | 3.69 | 3.64 |
| 523 | 3.39 | 3.47 | 3.44 | 3.29 | 3.86 | 3.96 | 3.98 |
| 573 | 3.72 | 3.79 | 3.76 | 3.61 | 4.20 | 4.22 | 4.30 |
| 623 | 4.07 | 4.13 | 4.09 | 3.97 | 4.54 | 4.48 | 4.63 |
| 673 | 4.41 | 4.49 | 4.42 | 4.32 | 4.86 | 4.75 | 4.95 |
| 723 | 4.77 | - | - | 4.71 | 5.18 | 5.05 | 5.29 |
| 773 | 5.14 | - | - | - | 5.50 | 5.39 | 5.63 |
| 823 | 5.52 | - | - | - | 5.80 | 5.78 | 6.00 |
| 873 | 5.93 | - | - | - | 6.09 | 6.24 | 6.40 |
| 923 | 6.36 | - | - | - | 6.37 | 6.79 | 6.82 |

Table 6 Thermal Conductivity Values Computed Using the Smith-Palmer Equation,
 λ ($\text{W m}^{-1} \text{K}^{-1}$) and Comparison⁺ With Smoothed Values, λ_m ($\text{W m}^{-1} \text{K}^{-1}$)

| T (K) | R2 | | R3 | | R4 | | R5 | | R9 | | R14 | | R15 | |
|-------|-----------|------------------|-----------|------|-----------|------|-----------|------|-----------|-------|-----------|------|-----------|------|
| | λ | Dif ⁺ | λ | Dif | λ | Dif | λ | Dif | λ | Dif | λ | Dif | λ | Dif |
| 373 | 385 | -2.2 | 371 | -3.0 | 374 | -3.6 | 395 | -2.6 | 324 | -3.8 | 300 | -7.5 | 313 | -1.0 |
| 423 | 380 | -1.1 | 369 | -1.6 | 371 | -1.4 | 390 | -1.6 | 326 | -2.2 | 305 | -8.5 | 316 | -1.6 |
| 473 | 378 | -0.8 | 367 | -0.8 | 371 | -1.4 | 389 | -1.6 | 329 | -1.5 | 314 | -9.4 | 318 | -0.9 |
| 523 | 376 | -0.8 | 368 | -1.1 | 371 | -1.4 | 387 | -1.3 | 331 | -0.6 | 323 | -9.5 | 322 | -0.9 |
| 573 | 376 | -1.0 | 369 | -1.6 | 372 | -1.6 | 387 | -1.8 | 334 | -0.3 | 332 | -8.8 | 326 | -0.9 |
| 623 | 373 | -0.8 | 368 | -1.7 | 371 | -1.9 | 382 | -1.9 | 335 | -1.5 | 340 | -8.3 | 329 | -0.6 |
| 673 | 372 | -1.4 | 366 | -1.7 | 371 | -1.9 | 380 | -1.3 | 338 | -0.6 | 346 | -6.8 | 332 | -0.6 |
| 723 | 370 | -1.6 | - | - | - | - | 374 | -1.9 | 341 | -1.5 | 350 | -5.4 | 334 | -0.3 |
| 773 | 370 | -2.5 | - | - | - | - | - | - | 343 | -3.0 | 350 | -3.5 | 336 | -0.6 |
| 823 | 364 | -1.4 | - | - | - | - | - | - | 347 | -4.8 | 348 | -2.0 | 335 | -0.3 |
| 873 | 359 | -0.8 | - | - | - | - | - | - | 350 | -7.0 | 342 | -0.8 | 333 | -0.6 |
| 923 | 354 | 0 | - | - | - | - | - | - | 354 | -10.3 | 332 | 0.3 | 331 | -1.5 |

⁺ Difference = $\frac{\lambda_m - \lambda}{\lambda_m} \times 100\%$

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