NBS REPORT

9775

THERMAL CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND THERMOPOWER OF AEROSPACE ALLOYS FROM 4 TO 300K: III. ANNEALED INCONEL 718

J. G. Hust and L. L. Sparks

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Institute for Basic Standards
Boulder, Colorado 80302

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT		NBS REPORT
275.03-2750430	November 24, 1970	9775

THERMAL CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND THERMOPOWER OF AEROSPACE ALLOYS FROM 4 TO 300 K: III. ANNEALED INCONEL 718

J. G. Hust and L. L. Sparks

Cryogenics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado, 80302

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

TABLE OF CONTENTS

		Page
1.	Introduction	2
2.	Apparatus and Data Analysis	2
3.	Specimen Characterization	3
4.	Results	3
5.	Discussion	4
6.	References	6

LIST OF TABLES

		Page
Table 1.	Basic semi-processed temperature gradient data for annealed Inconel 718	9
Table 2.	Basic semi-processed isothermal electrical resistivity data for annealed Inconel 718	15
Table 3.	Parameters in equations 1, 2, and 3 for annealed Inconel 718	16
Table 4.	Thermal conductivity deviations for annealed Inconel 718	17
Table 5.	Electrical resistivity deviations for annealed Inconel 718	24
Table 6.	Thermovoltage deviations for annealed Inconel 718	25
Table 7.	Transport properties of annealed Inconel 718 . .	26

LIST OF FIGURES

		Page
Figure 1.	Thermal conductivity deviations for annealed Inconel 718	27
Figure 2.	Electrical resistivity deviations for annealed Inconel 718	28
Figure 3.	Thermovoltage deviations for annealed Inconel 718	29
Figure 4.	Thermal conductivity of annealed Inconel 718 . . .	30
Figure 5.	Electrical resistivity of annealed Inconel 718 . . .	31
Figure 6.	Lorenz ratio of annealed Inconel 718	32
Figure 7.	Thermopower of annealed Inconel 718	33

THERMAL CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND THERMOPOWER OF AEROSPACE ALLOYS FROM 4 TO 300 K: III. ANNEALED INCONEL 718*†

J. G. Hust and L. L. Sparks
Cryogenics Division, NBS-Institute for
Basic Standards, Boulder, Colorado, 80302

ABSTRACT

Thermal conductivity, electrical resistivity, Lorenz ratio, and the thermopower data are reported for an annealed specimen of Inconel 718 for temperatures from 4 to 300 K.

KEY WORDS

Cryogenics, electrical resistivity, Lorenz ratio, Seebeck effect, Inconel, thermal conductivity, transport properties.

---

* This work was carried out at the National Bureau of Standards under the sponsorship of the NASA-Space Nuclear Propulsion Office, Cleveland.

† The use in this paper of trade names of specific products is essential to a proper understanding of the work presented. Their use in no way implies any approval, endorsement, or recomendation by NBS. Inconel is a registered trade name for a nickel-chromium-iron alloy produced by International Nickel Corp.

1. Introduction

Design and development engineers in the aerospace industry continue to have urgent need for thermal and mechanical property data for new materials. For most materials, especially new or uncommon alloys, measured values of thermal conductivity are not available and predictions cannot be made with adequate confidence. To help satisfy these needs we have constructed an apparatus for the simultaneous measurement of thermal conductivity, electrical resistivity, and thermopower. Measurements have been conducted on several aerospace alloys, Hust, et al. [1], [2]. Another phase of this program, to establish standard reference data on several standard reference materials (or specimens), has begun. We intend to measure several specimens of materials which appear to be useful as standards. Also we plan to occasionally measure other aerospace alloys, as we have done here, to satisfy specific need in the industry. This paper contains the results of our measurements on the transport properties of annealed Inconel 718.

2. Apparatus and Data Analysis

The apparatus is based on the axial one-dimensional heat flow method. The specimen is a cylindrical rod 11.3 mm in diameter and 23 cm long with an electric heater at one end and a temperature controlled sink at the other. The specimen is surrounded by glass fiber and a temperature controlled shield. Eight thermocouples are mounted at equally spaced points along the length of the specimen to determine temperature gradients in the range 4 to 300 K.

The experimental data are represented by arbitrary functions over the entire range and smooth tables are generated from these functions. The number of terms used to represent each of the data sets is optimized, through the use of orthonormal functions, so that none of the

precision of the data is lost by underfitting nor are any unnecessary oscillations introduced by overfitting. A detailed description of this apparatus and the methods of data analysis are given by Hust, et al.[1]

3. Specimen Characterization

The Inconel 718 specimen was vacuum annealed at 1035°C for 1 hour and was then air cooled. The hardness and grain size are: B85 and 0.0433 mm respectively. The composition in weight percent for this material is as follows: Ni = 54.57, Cr = 18.06, Fe = 17.08, Nb + Ta = 5.12, Mo = 3.18, Ti = 0.85, Aℓ = 0.44, Mn = 0.29, Si = 0.24; Cu, C, and S are present at less than 0.1%. The density of the annealed specimen is 8.2608 g/cm^3 at 20°C.

4. Results

The transport properties of annealed Inconel 718 were measured in the thermal conductivity apparatus. These data are presented in tables 1 and 2.

The experimental data were functionally represented with the following equations:

$$\ell n\lambda = \sum_{i=1}^{n} a_i [\ell nT]^{i+1} \qquad (1)$$

$$\rho = \sum_{i=1}^{m} b_i [\ell nT]^{i-1} \qquad (2)$$

$$S = \sum_{i=1}^{\ell} c_i [\ell nT']/T'; \qquad T' = \frac{T}{10} + 1 \qquad (3)$$

where λ = thermal conductivity, ρ = electrical resistivity, S = thermopower, and T = temperature. Temperatures are based on the IPTS-68 scale above 20 K and the NBS P2-20 (1965) scale below 20 K. The parameters, a_i, b_i, and c_i, determined by least squares, are presented

in table 3. The deviations of the experimental data from these equations are given in tables 4 through 6 and in figures 1 through 3. The horizontal bars in figures 2 and 3 indicate the temperature span across the specimen for each run. The "observed" thermal conductivities are computed from the mean temperature gradients indicated by adjacent thermocouples. Calculated values of λ, ρ, S, and $L = \rho\lambda/T$ (Lorenz ratio) are presented in table 7 and in figures 4 through 7.

A detailed error analysis for these measurements has been presented previously by Hust, et al.[1] Based on this analysis of systematic and random errors the uncertainty estimates (with 95% confidence) are as follows:

thermal conductivity:	2.5% at 300 K, decreasing as T^4 to 0.70% at 200 K, 0.70% from 200 K to 50 K, increasing inversely with temperature to 1.5% at 4 K.
electrical resistivity:	0.25%
thermopower:	0.5% + 0.2 μV/K at 4 K, 0.2% + 0.5 μV/K at 30 K, and 0.1% + 0.03 μV/K above 76 K.

The thermopower values given here are absolute values although our measurements were carried out with respect to normal silver wire. The absolute thermopowers of normal silver reported by Borelius, et al.[3] were used to convert the experimental data to the absolute scale.

5. Discussion

This aerospace alloy is primarily a lattice conductor similar to other alloys measured by Hust, et al.[1],[2]. A component separation study has been done which indicates the amount of thermal conductivity due to the lattice and electronic components. The electrical

resistivity of the specimen is high and the residual resistance ratio is low. The resistivity minimum occurs at about 35 K. This specimen was also tested before being annealed [1]. A comparison of all data on Inconel will be made in a subsequent report.

6. References

1. J. G. Hust, R. L. Powell, and D. H. Weitzel, "Thermal Conductivity, Electrical Resistivity, and Thermopower of Aerospace Alloys from 4 to 300 K", NBS Report 9732 (1969).
2. J. G. Hust, "Thermal Conductivity of Aerospace Alloys from 4 to 300 K: II. AISI 347 Stainless Steel", NBS Report 9772 (1970).
3. G. Borelius, W. H. Keesom, C. H. Johansson, and J. O. Linde, "Establishment of an Absolute Scale for the Thermoelectric Force", Proc. Kon. Akad. Amsterdam 35, 10 (1932).

Notes Relating to Tables

Table 1

The data listed are, in part, card images of experimental data as read into the computer for data processing. These data are not clearly labelled. The following is a line by line explanation of this table:

1st line - Data identification.

2nd line - Thermocouple emfs (μV).

3rd line - Seebeck emf (μV), specimen current (mA), specimen voltage drop (μV).

4th line - Sample heater voltage (μV), current (mA), platinum resistance thermometer voltage (μV), platinum resistance thermometer current (mA), cryogenic bath pressure (mm of Hg), room temperature (°C), code indicating type of cryogenic bath (1 = liquid helium, 2 = liquid hydrogen, 3 = liquid nitrogen, 4 = dry ice-alcohol, 5 = ice-water).

5th line - Thermocouple temperatures (K).

6th line - Heater power (W), reference temperature (K), specimen resistance (Ω).

Table 2

The data listed are, in part, card images of experimental data as read into the computer for data processing. These data are not labelled clearly. The following is a line by line explanation of this table:

1st line - Data identification.

2nd line - Platinum resistance thermometer voltage (μV), cryogenic bath pressure (mm of Hg), room temperature (°C), platinum resistance thermometer current (mA), code indicating

type of cryogenic bath (1 = liquid helium, 2 = liquid hydrogen, 3 = liquid nitrogen, 4 = dry ice-alcohol, 5 = ice-water), specimen current (mA), specimen voltage (μV), mean emf of eight thermocouples (μV).

3rd line - Reference temperature (K), specimen resistance (Ω), specimen temperature (K).

Tables 4, 5, and 6

These data are semiprocessed computer output. Temperature is Kelvin, thermal conductivity is in $Wm^{-1} K^{-1}$, electrical resistance is in ohms, and thermovoltage is in μV.

Table 1. Basic semi-processed temperature gradient data for annealed Inconel 718.

```
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1430 7
   21.26    25.65    29.76    34.05    37.74    41.66    45.55    48.90
    0.01   100.00   216.78
  316615   3.2070    -0.00     -0.0    643.4     24.0      1.0
THERMOCOUPLE TEMPERATURES
   5.570    5.902    6.191    6.482    6.753    7.016    7.269    7.509
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.0154-003            4.038              2.1678-003
-------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1530 8
   63.17    70.65    77.78    84.91    91.29    97.81   104.21   110.02
   -0.00   100.00   216.46
  491488   4.9800    -0.00     -0.0    645.1     24.0      1.0
THERMOCOUPLE TEMPERATURES
   8.425    8.917    9.366    9.804   10.214   10.610   10.993   11.360
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.4476-003            4.040              2.1646-003
-------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1621 9
  113.36   131.97   148.97   165.52   180.43   195.04   209.25   222.43
   -0.29   100.00   216.13
  889120   9.0100    -0.00     -0.0    645.1     24.0      1.0
THERMOCOUPLE TEMPERATURES
  11.543   12.670   13.674   14.639   15.524   16.370   17.188   17.966
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 8.0110-003            4.040              2.1613-003
-------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1722 10
  250.98   276.12   299.27   321.95   342.64   362.97   382.89   401.68
   -2.06   100.00   215.77
 1287620  13.0450    -0.00     -0.0    645.0     24.0      1.0
THERMOCOUPLE TEMPERATURES
  19.604   21.075   22.420   23.736   24.960   26.150   27.314   28.438
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.6797-002            4.040              2.1577-003
-------------------------------------------------------------------
```

Table 1. (Continued)

```
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 21,70 1520 1
   60.52    68.36    76.06    83.85    91.03    98.40   105.77   112.68
    -0.80   100.00   215.76
  767954    7.7800   220.16      2.0    643.1     23.3      2.0
THERMOCOUPLE TEMPERATURES
  23.336   23.806   24.253   24.703   25.135   25.564   25.989   26.409
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 5.9747-003           19.839              2.1576-003
-----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 21,70 1745 2
  115.10   132.40   149.03   165.62   181.09   196.50   211.86   226.51
    -2.29   100.00   215.66
 1207354   12.2300   221.92      2.0    643.8     23.0      2.0
THERMOCOUPLE TEMPERATURES
  26.584   27.615   28.595   29.571   30.501   31.415   32.322   33.209
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.4766-002           19.887              2.1566-003
-----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 22,70 1100 4
  222.47   254.72   285.65   316.05   344.75   373.06   401.24   428.42
    -5.54   100.00   215.65
 1793812   18.1600   229.25      2.0    643.4     23.5      2.0
THERMOCOUPLE TEMPERATURES
  33.155   35.096   36.946   38.765   40.500   42.194   43.872   45.505
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.2576-002           20.084              2.1565-003
-----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 22,70 1348 5
  311.81   391.55   467.00   540.26   610.04   678.45   746.43   813.02
   -13.83   100.00   215.85
 2985715   30.2000   228.41      2.0    643.4     23.7      2.0
THERMOCOUPLE TEMPERATURES
  38.485   43.279   47.765   52.076   56.154   60.097   63.969   67.744
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 9.0169-002           20.062              2.1583-003
-----------------------------------------------------------------
```

Table 1. (Continued)

```
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 22,70 1730 6
  418.95   526.62   629.22   729.58   826.38   921.56  1016.92  1110.62
   -17.37    100.00    216.08
  3606635   36.4600   231.52       2.0      642.3       24.0        2.0
THERMOCOUPLE TEMPERATURES
  44.987   51.369   57.342   63.091   68.572   73.874   79.114   84.221
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.3150-001            20.144              2.1608-003
-------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 11,70 1315 11
   63.04    87.28   111.61   135.77   159.86   183.81   207.74   231.69
    -3.18    100.00    216.57
  1828170   18.4800   9311.20       2.0      643.3       23.9        3.0
THERMOCOUPLE TEMPERATURES
  79.510   80.833   82.157   83.465   84.768   86.058   87.347   88.630
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.3785-002            76.057              2.1657-003
-------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 11,70 1730 12
  127.04   176.31   225.75   274.74   323.51   371.87   420.51   468.97
    -5.62    100.00    216.84
  2616696   26.4400   9330.98       2.0      642.3       24.5        3.0
THERMOCOUPLE TEMPERATURES
  83.082   85.745   88.401   91.017   93.609   96.163   98.723  101.258
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 6.9185-002            76.147              2.1684-003
-------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 12,70 1615 13
  293.20   404.92   516.86   627.45   737.41   846.21   955.45  1064.00
    -8.35    100.00    217.54
  3962915   40.0000   9371.12       2.0      641.0       24.2        3.0
THERMOCOUPLE TEMPERATURES
  92.177   98.080  103.927  109.641  115.271  120.791  126.291  131.711
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.5852-001            76.330              2.1754-003
-------------------------------------------------------------------
```

Table 1. (Continued)

```
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 13,70 850 14
  293.52   405.36   517.40   628.07   738.12   846.90   956.23  1064.81
    -8.36    100.00    217.54
  3962555   40.0000   9365.90       2.0     641.6      22.6       3.0
THERMOCOUPLE TEMPERATURES
  92.171   98.080  103.932  109.651  115.285  120.808  126.308  131.730
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.5850-001            76.306              2.1754-003
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 14,70 828 15
  587.28   803.88  1020.62  1233.86  1445.30  1653.71  1861.84  2067.86
    -5.26    100.00    218.78
  5566500   56.1000   9461.44       2.0     642.3      23.2       3.0
THERMOCOUPLE TEMPERATURES
 107.958  119.029  129.924  140.486  150.824  160.893  170.846  180.604
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.1228-001            76.741              2.1878-003
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 14,70 1240 16
  693.69   952.06  1210.47  1464.28  1715.67  1963.03  2209.50  2453.09
    -2.41    100.00    219.24
  6102894   61.4400   9469.45       2.0     642.6      24.0       3.0
THERMOCOUPLE TEMPERATURES
 113.455  126.529  139.368  151.778  163.899  175.680  187.299  198.676
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.7496-001            76.777              2.1924-003
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 14,70 1700 17
  695.31   954.09  1212.81  1466.87  1718.48  1966.01  2212.54  2456.06
    -2.39    100.00    219.25
  6103020   61.4400   9463.35       2.0     644.5      24.1       3.0
THERMOCOUPLE TEMPERATURES
 113.512  126.605  139.459  151.879  164.010  175.797  187.418  198.790
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.7497-001            76.749              2.1925-003
------------------------------------------------------------
```

Table 1. (Continued)

```
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 18,70 1000 18
   99.39   151.58   204.99   257.37   309.76   361.72   413.90   465.96
    2.29   100.00   221.09
  2851030   28.7000  34428.90       2.0      627.9      23.1       4.0
THERMOCOUPLE TEMPERATURES
 197.440  199.886  202.347  204.775  207.198  209.599  212.005  214.402
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 8.1825-002           192.805              2.2109-003
----------------------- -----------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 18,70 1720 19
  201.92   309.23   417.26   523.79   630.04   735.12   840.38   945.08
    5.88   100.00   221.61
 4095875   41.2000  34463.90       2.0       -0.0       -0.0       4.0
THERMOCOUPLE TEMPERATURES
 202.371  207.340  212.326  217.226  222.098  226.903  231.703  236.467
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.6875-001           192.973              2.2161-003
-------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 19,70 1430 20
  412.26   637.29   862.54  1083.23  1301.79  1516.37  1729.88  1940.72
   16.55   100.00   222.65
 5972675   60.0000  34556.60       2.0      630.6      23.2       4.0
THERMOCOUPLE TEMPERATURES
 212.534  222.866  233.146  243.166  253.045  262.703  272.284  281.717
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.5836-001           193.417              2.2265-003
-------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 20,70 1615 21
   87.94   158.69   229.89   300.29   370.54   440.09   510.00   579.66
    7.15   100.00   224.13
 3485000   35.0000  50982.00       2.0       -0.0       -0.0       5.0
THERMOCOUPLE TEMPERATURES
 277.278  280.457  283.616  286.759  289.895  293.000  296.122  299.232
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.2197-001           273.336              2.2415-003
-------------------------------------------------------------
```

Table 1. (Continued)

```
THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 21,70 1115 22
   89.91   161.32   233.10   304.01   374.73   444.61   514.76   584.53
    7.18   100.00   224.14
 3484920  35.0000  50964.00      2.0      -0.0      -0.0      5.0
THERMOCOUPLE TEMPERATURES
 277.278  280.466  283.670  286.836  289.994  293.114  296.246  299.361
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.2197-001          273.247              2.2414-003
```

Annealed Inconel 718

Thermocouple positions (cm from floating sink)	2.2245	4.7645	7.3071	9.8448
	12.3879	14.9279	17.4686	20.0086
Specimen diameters (cm) between thermocouples starting from floating sink	1.1273	1.1275	1.1275	1.1273
	1.1273	1.1273	1.1273	

Table 2. Basic semi-processed isothermal electrical resistivity data for annealed Inconel 718.

ISOTHERMAL RESISTIVITY DATA FOR INCONEL 718(A) JULY 22,70 816 3

218.44	643.60	23.10	2.00	2.00	100.00	215.89	0.28

REFERENCE TEMPERATURE	SPECIMEN RESISTANCE	SPECIMEN TEMPERATURE
19.791	2.1589-003	19.807

Table 3. Parameters in equations 1, 2, and 3 for annealed Inconel 718.

COEFFICIENTS FOR		
THERMAL CONDUCTIVITY	ELECTRICAL RESISTIVITY	THERMOPOWER
-3.66635349+000	1.25202587-006	3.43583365+001
5.13398100+000	-5.41133462-008	-2.10863019+002
-2.92209498+000	3.49416343-008	4.99153327+002
8.97129708-001	-1.14951600-008	-5.75257805+002
-1.56517404-001	1.69418236-009	3.44051973+002
1.46169832-002	-7.95007556-011	-1.11065966+002
-5.67382252-004	-5.67382252-004	1.85244433+001
		-1.25259270+000

Table 4. Thermal conductivity deviations for annealed Inconel 718.

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1430 7

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
5.736	0.332	7.79-001	8.12-001	-4.2
6.046	0.289	8.95-001	8.59-001	4.1
6.337	0.292	8.85-001	9.04-001	-2.1
6.618	0.271	9.56-001	9.48-001	0.9
6.884	0.263	9.84-001	9.91-001	-0.7
7.142	0.253	1.02+000	1.03+000	-1.0
7.389	0.240	1.08+000	1.07+000	0.5

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1530 8

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
8.671	0.493	1.26+000	1.28+000	-1.4
9.141	0.448	1.39+000	1.36+000	2.2
9.585	0.439	1.42+000	1.43+000	-1.0
10.009	0.410	1.52+000	1.50+000	1.4
10.412	0.397	1.57+000	1.57+000	0.3
10.801	0.382	1.63+000	1.63+000	0.1
11.176	0.367	1.70+000	1.69+000	0.5

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1621 9

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
12.106	1.127	1.81+000	1.83+000	-1.4
13.172	1.004	2.03+000	2.00+000	1.7
14.157	0.935	2.11+000	2.14+000	-1.6
15.081	0.885	2.31+000	2.28+000	1.5
15.947	0.847	2.41+000	2.40+000	0.4
16.779	0.817	2.50+000	2.51+000	-0.7
17.577	0.779	2.62+000	2.62+000	0.0

Table 4. (Continued)

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 24,70 1722 10

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
20.340	1.472	2.91+000	2.97+000	-2.1
21.748	1.344	3.18+000	3.13+000	1.5
23.078	1.316	3.24+000	3.28+000	-1.2
24.348	1.224	3.50+000	3.42+000	2.1
25.555	1.189	3.59+000	3.55+000	1.3
26.732	1.165	3.67+000	3.67+000	0.1
27.876	1.124	3.80+000	3.78+000	0.6

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 21,70 1528 1

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
23.571	0.470	5.24+000	5.34+000	-3.1
24.029	0.447	5.41+000	5.39+000	0.5
24.478	0.450	5.37+000	5.44+000	-1.8
24.919	0.432	5.52+000	5.48+000	1.2
25.349	0.429	5.54+000	5.53+000	0.4
25.777	0.425	5.58+000	5.57+000	0.2
26.199	0.419	5.63+000	5.61+000	0.4

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 21,70 1745 2

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
27.100	1.031	5.64+000	5.70+000	-1.7
28.105	0.979	5.84+000	5.80+000	1.0
29.083	0.977	5.84+000	5.89+000	-1.3
30.036	0.930	4.05+000	5.98+000	1.6
30.958	0.914	4.11+000	4.06+000	1.2
31.868	0.908	4.14+000	4.14+000	-0.0
32.766	0.887	4.23+000	4.22+000	0.4

Table 4. (Continued)

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 22,70 1100 4

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
34.126	1.941	4.27+000	4.33+000	-1.4
36.021	1.850	4.48+000	4.48+000	0.0
37.856	1.819	4.55+000	4.62+000	-1.4
39.633	1.735	4.78+000	4.74+000	0.8
41.347	1.694	4.89+000	4.86+000	0.7
43.033	1.677	4.94+000	4.97+000	-0.5
44.689	1.634	5.08+000	5.07+000	0.0

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 22,70 1348 5

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
40.882	4.794	4.79+000	4.83+000	-0.9
45.522	4.487	5.12+000	5.12+000	-0.1
49.921	4.310	5.32+000	5.37+000	-1.0
54.115	4.078	5.63+000	5.58+000	0.9
58.126	3.942	5.82+000	5.76+000	1.0
62.033	3.872	5.93+000	5.92+000	0.1
65.856	3.775	6.08+000	6.06+000	0.2

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) JULY 22,70 1730 6

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
48.178	6.382	5.24+000	5.28+000	-0.6
54.355	5.973	5.61+000	5.59+000	0.3
60.216	5.750	5.81+000	5.85+000	-0.6
65.831	5.480	6.11+000	6.06+000	0.8
71.223	5.302	6.31+000	6.24+000	1.1
76.494	5.240	6.39+000	6.40+000	-0.2
81.668	5.107	6.55+000	6.54+000	0.2

Table 4. (Continued)

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 11,70 1315 11

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
80.172	1.323	6.50+000	6.50+000	-0.1
81.495	1.323	6.50+000	6.54+000	-0.6
82.811	1.309	6.56+000	6.57+000	-0.1
84.117	1.303	6.61+000	6.60+000	0.1
85.413	1.290	6.67+000	6.63+000	0.5
86.703	1.289	6.67+000	6.66+000	0.1
87.988	1.283	6.70+000	6.69+000	0.2

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 11,70 1730 12

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
84.413	2.663	6.61+000	6.61+000	0.0
87.073	2.656	6.63+000	6.67+000	-0.6
89.709	2.616	6.72+000	6.73+000	-0.1
92.313	2.592	6.80+000	6.79+000	0.2
94.886	2.555	6.89+000	6.84+000	0.7
97.443	2.560	6.88+000	6.89+000	-0.2
99.990	2.534	6.95+000	6.94+000	0.1

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 12,70 1615 13

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
95.128	5.903	6.85+000	6.85+000	-0.2
101.003	5.847	6.90+000	6.96+000	-0.9
106.784	5.715	7.05+000	7.07+000	-0.3
112.456	5.630	7.17+000	7.17+000	0.1
118.031	5.520	7.31+000	7.26+000	0.7
123.541	5.500	7.34+000	7.35+000	-0.1
129.001	5.420	7.44+000	7.43+000	0.2

Table 4. (Continued)

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 13,70 850 14

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
95.125	5.909	6.83+000	6.85+000	-0.3
101.006	5.852	6.90+000	6.96+000	-1.0
106.792	5.719	7.04+000	7.07+000	-0.3
112.468	5.634	7.17+000	7.17+000	0.0
118.047	5.522	7.30+000	7.26+000	0.6
123.558	5.501	7.34+000	7.35+000	-0.1
129.019	5.422	7.44+000	7.43+000	0.1

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 14,70 828 15

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
113.493	11.071	7.18+000	7.18+000	-0.1
124.477	10.895	7.30+000	7.36+000	-0.8
135.205	10.562	7.51+000	7.52+000	-0.1
145.655	10.338	7.70+000	7.68+000	0.2
155.859	10.069	7.89+000	7.83+000	0.8
165.870	9.953	7.99+000	7.98+000	0.1
175.725	9.758	8.14+000	8.13+000	0.2

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 14,70 1240 16

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
119.992	13.074	7.30+000	7.29+000	0.1
132.949	12.839	7.44+000	7.49+000	-0.7
145.573	12.410	7.68+000	7.68+000	0.0
157.838	12.121	7.88+000	7.86+000	0.3
169.789	11.781	8.10+000	8.04+000	0.7
181.490	11.620	8.22+000	8.22+000	-0.0
192.988	11.376	8.39+000	8.40+000	-0.1

Table 4. (Continued)

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 14,70 1700 17

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
120.059	13.093	7.29+000	7.29+000	-0.0
133.032	12.853	7.43+000	7.49+000	-0.8
145.669	12.420	7.67+000	7.68+000	-0.1
157.944	12.131	7.88+000	7.86+000	0.2
169.903	11.788	8.10+000	8.04+000	0.7
181.608	11.621	8.21+000	8.22+000	-0.1
193.104	11.372	8.39+000	8.40+000	-0.1

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 18,70 1000 18

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
198.663	2.446	8.51+000	8.49+000	0.3
201.117	2.461	8.47+000	8.52+000	-0.7
203.561	2.428	8.57+000	8.56+000	0.0
205.987	2.424	8.60+000	8.60+000	0.0
208.399	2.400	8.68+000	8.64+000	0.4
210.802	2.406	8.66+000	8.68+000	-0.2
213.204	2.397	8.69+000	8.72+000	-0.3

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 18,70 1720 19

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
204.856	4.969	8.64+000	8.58+000	0.7
209.833	4.985	8.62+000	8.66+000	-0.5
214.776	4.900	8.75+000	8.74+000	0.1
219.662	4.872	8.83+000	8.82+000	0.1
224.500	4.805	8.94+000	8.90+000	0.5
229.303	4.801	8.95+000	8.97+000	-0.3
234.085	4.763	9.02+000	9.05+000	-0.4

Table 4. (Continued)

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 19,70 1430 20

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
217.700	10.332	8.83+000	8.79+000	0.5
228.006	10.280	8.88+000	8.95+000	-0.9
238.156	10.021	9.09+000	9.11+000	-0.3
248.106	9.879	9.24+000	9.27+000	-0.3
257.874	9.658	9.44+000	9.42+000	0.2
267.493	9.581	9.52+000	9.57+000	-0.5
277.000	9.433	9.67+000	9.71+000	-0.4

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 20,70 1615 21

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
278.857	3.159	9.83+000	9.73+000	1.0
282.026	3.179	9.77+000	9.78+000	-0.1
285.187	3.143	9.86+000	9.82+000	0.4
288.327	3.136	9.91+000	9.86+000	0.5
291.448	3.105	1.00+001	9.91+000	0.9
294.561	3.121	9.95+000	9.95+000	0.0
297.677	3.110	9.98+000	9.99+000	-0.1

THERMAL CONDUCTIVITY DATA FOR INCONEL 718(A) AUG 21,70 1115 22

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
278.872	3.188	9.74+000	9.73+000	0.0
282.068	3.205	9.69+000	9.78+000	-0.9
285.253	3.166	9.79+000	9.82+000	-0.3
288.415	3.157	9.84+000	9.87+000	-0.2
291.554	3.120	9.95+000	9.91+000	0.4
294.680	3.132	9.91+000	9.95+000	-0.3
297.803	3.115	9.97+000	9.99+000	-0.2

Table 5. Electrical resistivity deviations for annealed Inconel 718.

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
6.593	1.938	2.168-003	2.168-003	-0.00
9.971	2.955	2.165-003	2.165-003	0.00
14.974	6.424	2.161-003	2.161-003	-0.00
24.239	8.834	2.158-003	2.158-003	-0.00
24.903	3.072	2.158-003	2.158-003	0.00
29.988	6.625	2.157-003	2.157-003	-0.00
39.529	12.350	2.157-003	2.156-003	0.00
53.779	29.259	2.158-003	2.158-003	0.00
65.423	39.234	2.161-003	2.161-003	0.00
84.100	9.119	2.166-003	2.166-003	-0.01
92.261	18.176	2.168-003	2.168-003	0.00
112.277	39.535	2.175-003	2.175-003	-0.00
112.287	39.559	2.175-003	2.175-003	-0.00
145.183	72.646	2.188-003	2.188-003	0.00
157.230	85.221	2.192-003	2.192-003	0.00
157.331	85.278	2.192-003	2.192-003	0.00
205.962	16.962	2.211-003	2.211-003	-0.00
219.573	34.095	2.216-003	2.216-003	0.00
247.761	69.183	2.226-003	2.227-003	-0.00
288.297	21.954	2.241-003	2.241-003	-0.00
288.378	22.083	2.241-003	2.241-003	0.00
19.807	0.000	2.159-003	2.159-003	-0.01

Table 6. Thermovoltage deviations for annealed Inconel 718.

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
7.509	5.570	0.01	0.01	0.00
11.360	8.425	-0.00	0.00	-0.01
17.966	11.543	-0.29	-0.29	0.00
28.438	19.604	-2.06	-2.07	0.01
26.409	23.336	-0.80	-0.78	-0.02
33.209	26.584	-2.29	-2.29	-0.00
45.505	33.155	-5.54	-5.55	0.00
67.744	38.485	-13.83	-13.83	0.00
84.221	44.987	-17.37	-17.36	-0.01
88.630	79.510	-3.18	-3.24	0.06
101.258	83.082	-5.62	-5.66	0.04
131.711	92.177	-8.35	-8.33	-0.02
131.730	92.171	-8.36	-8.34	-0.02
180.604	107.958	-5.26	-5.23	-0.02
198.676	113.455	-2.41	-2.43	0.02
198.790	113.512	-2.39	-2.41	0.02
214.402	197.440	2.29	2.33	-0.03
236.467	202.371	5.88	5.90	-0.02
281.717	212.534	16.55	16.54	0.01
299.232	277.278	7.15	7.14	0.00
299.361	277.278	7.18	7.19	-0.00

Table 7. Transport properties of annealed Inconel 718

Temp (K)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Electrical Resistivity (n ohm m)	Lorenz ratio $\times 10^8$ (V^2/K^2)	Thermo-power ($\mu V/K$)
6	0.852	1217	17.30	0.02
7	1.01	1216	17.50	0.01
8	1.17	1216	17.80	0.02
9	1.34	1215	18.00	0.02
10	1.50	1215	18.20	0.03
12	1.82	1214	18.40	0.08
14	2.12	1213	18.40	0.12
16	2.41	1213	18.20	0.15
18	2.67	1212	18.00	0.16
20	2.93	1212	17.70	0.16
25	3.49	1211	16.90	0.12
30	3.98	1210	16.10	0.07
35	4.40	1210	15.20	0.03
40	4.77	1210	14.40	0.01
45	5.09	1210	13.70	-0.00
50	5.37	1211	13.00	-0.01
55	5.62	1211	12.40	-0.00
60	5.84	1212	11.80	0.01
65	6.03	1213	11.30	0.03
70	6.21	1213	10.80	0.05
75	6.36	1214	10.30	0.08
80	6.50	1215	9.87	0.11
85	6.62	1216	9.47	0.14
90	6.74	1217	9.11	0.17
95	6.85	1218	8.77	0.21
100	6.94	1218	8.46	0.24
110	7.12	1220	7.90	0.32
120	7.29	1223	7.43	0.39
130	7.45	1225	7.01	0.47
140	7.60	1227	6.66	0.55
150	7.74	1229	6.34	0.62
160	7.89	1231	6.07	0.70
170	8.04	1233	5.83	0.77
180	8.20	1235	5.62	0.85
190	8.35	1237	5.44	0.92
200	8.51	1240	5.27	0.99
220	8.82	1244	4.99	1.14
240	9.14	1248	4.75	1.28
260	9.46	1252	4.55	1.41
280	9.75	1256	4.37	1.54

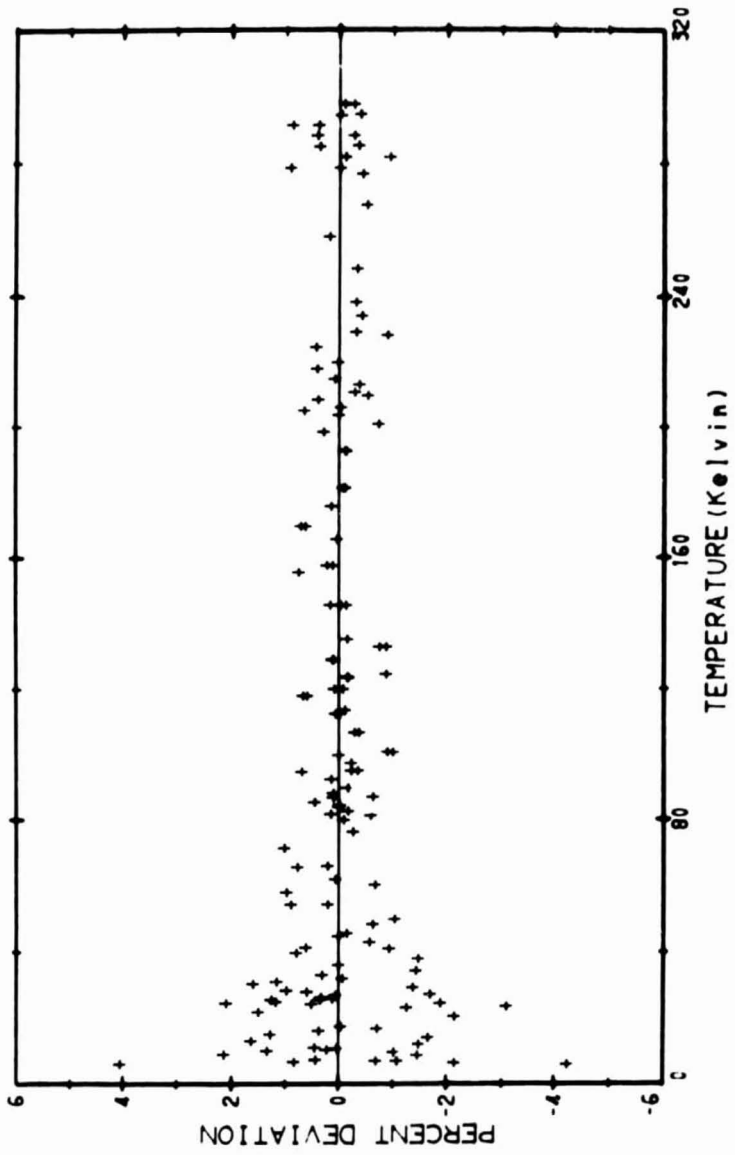

Figure 1. Thermal conductivity deviations for annealed Inconel 718.

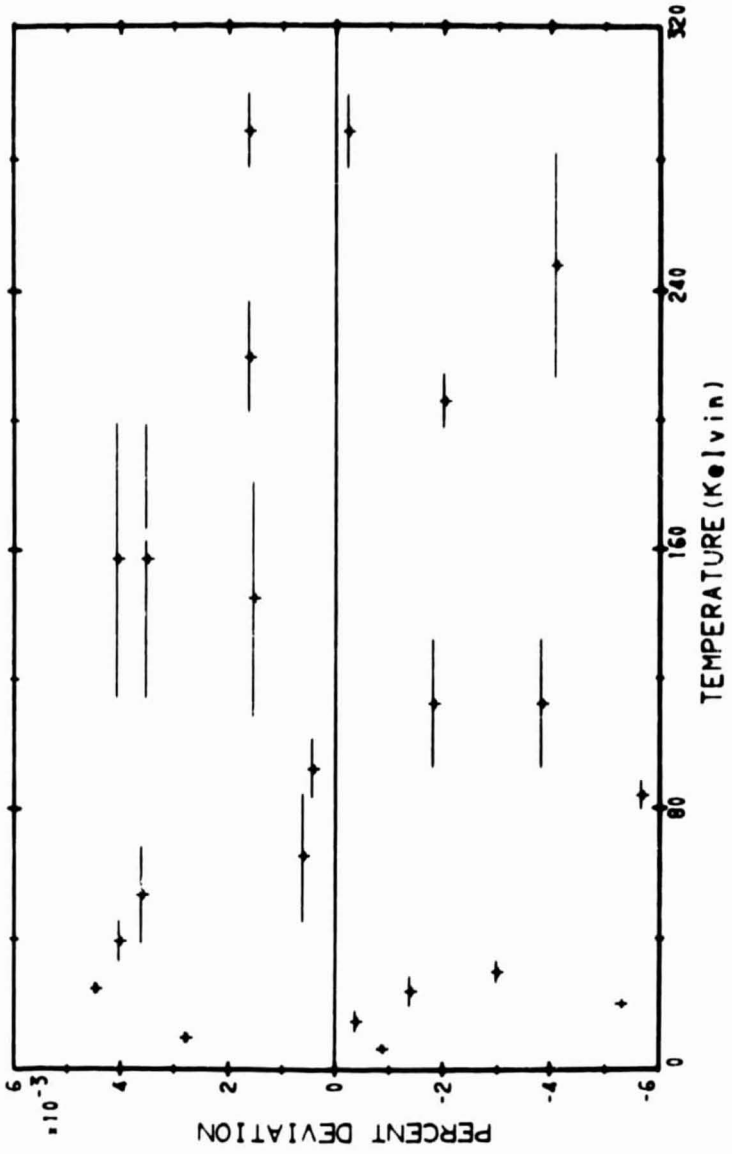

Figure 2. Electrical resistivity deviations for annealed Inconel 718.

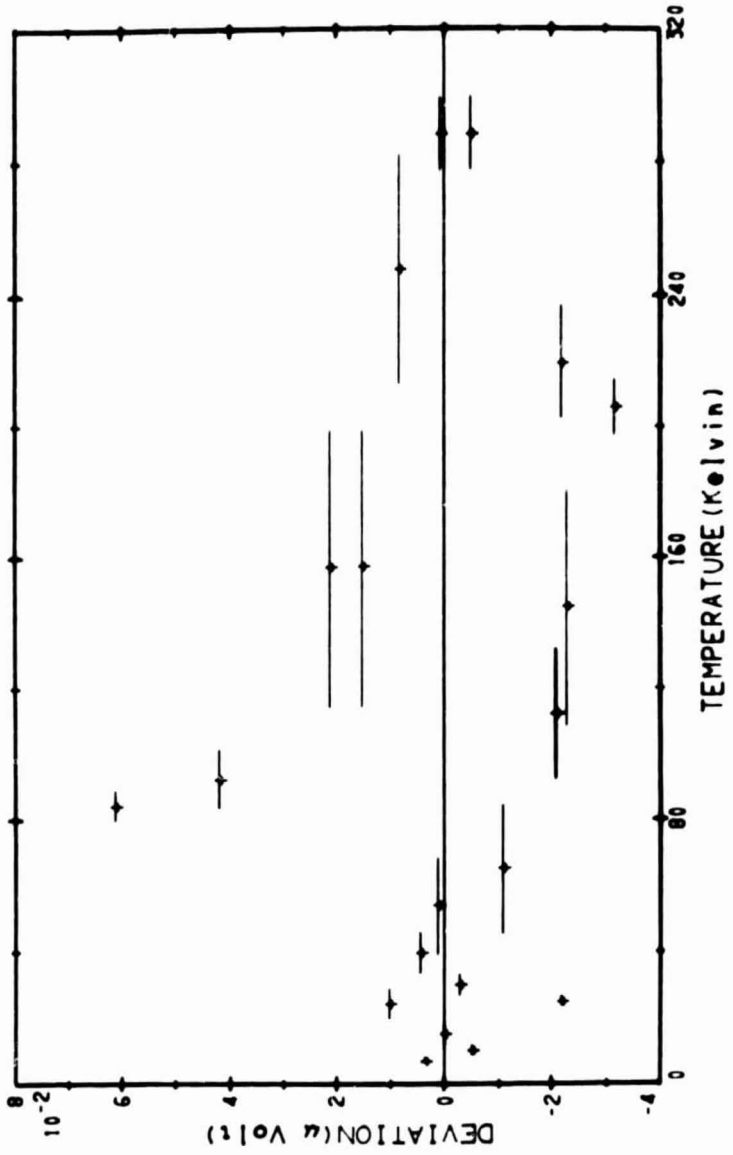

Figure 3. Thermovoltage deviations for annealed Inconel 718.

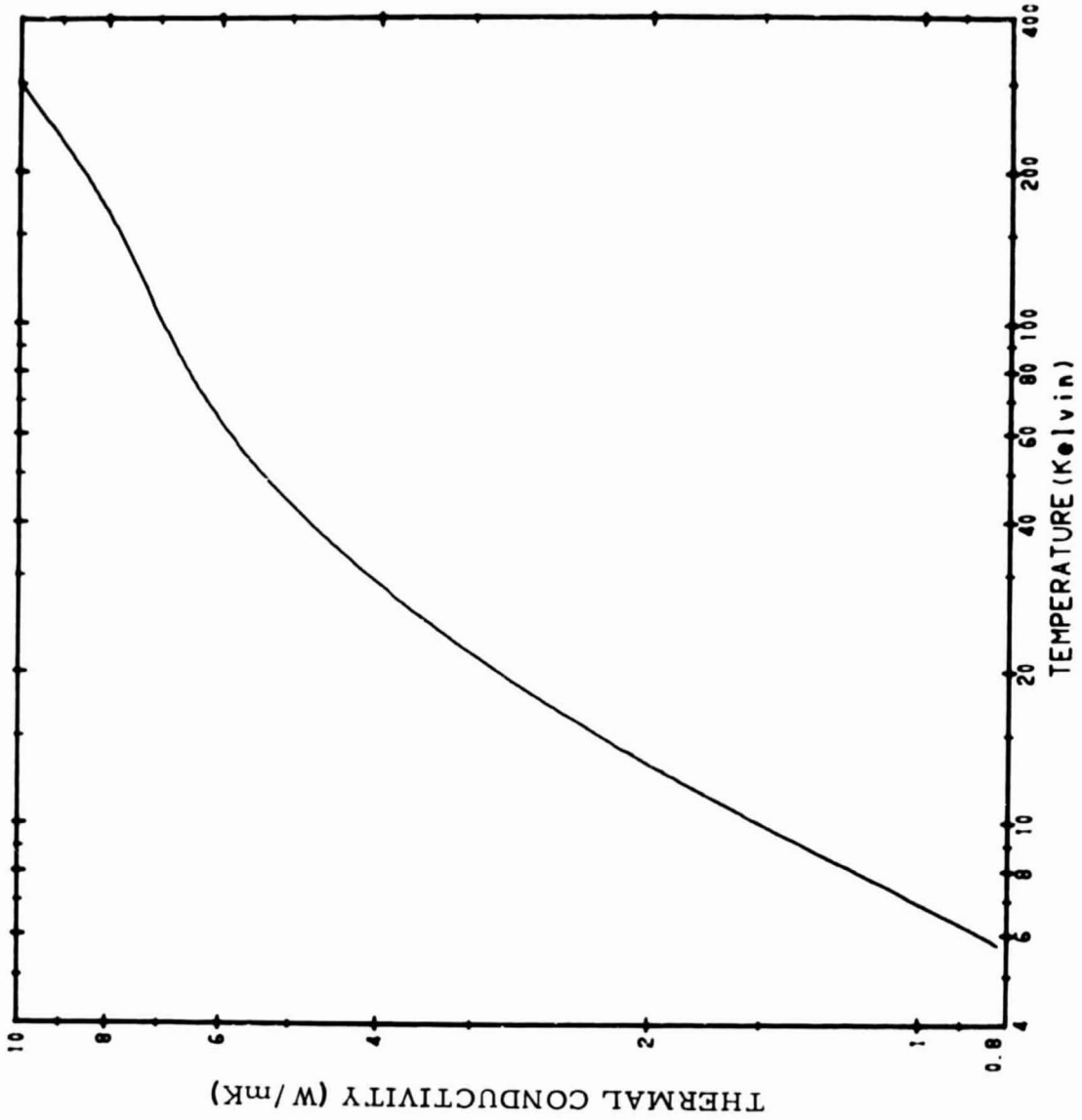

Figure 4. Thermal conductivity of annealed Inconel 718.

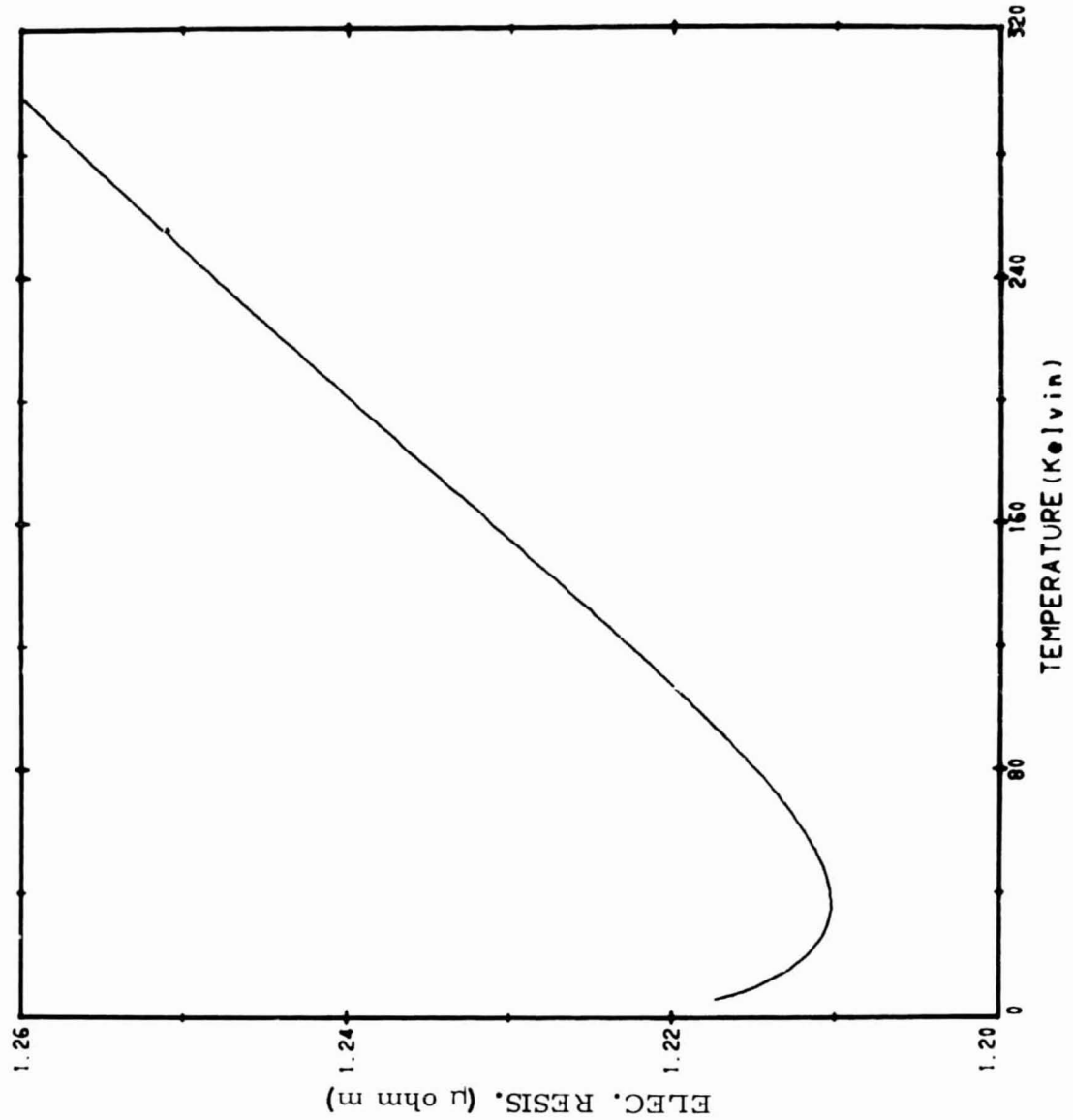

Figure 5. Electrical resistivity of annealed Inconel 718.

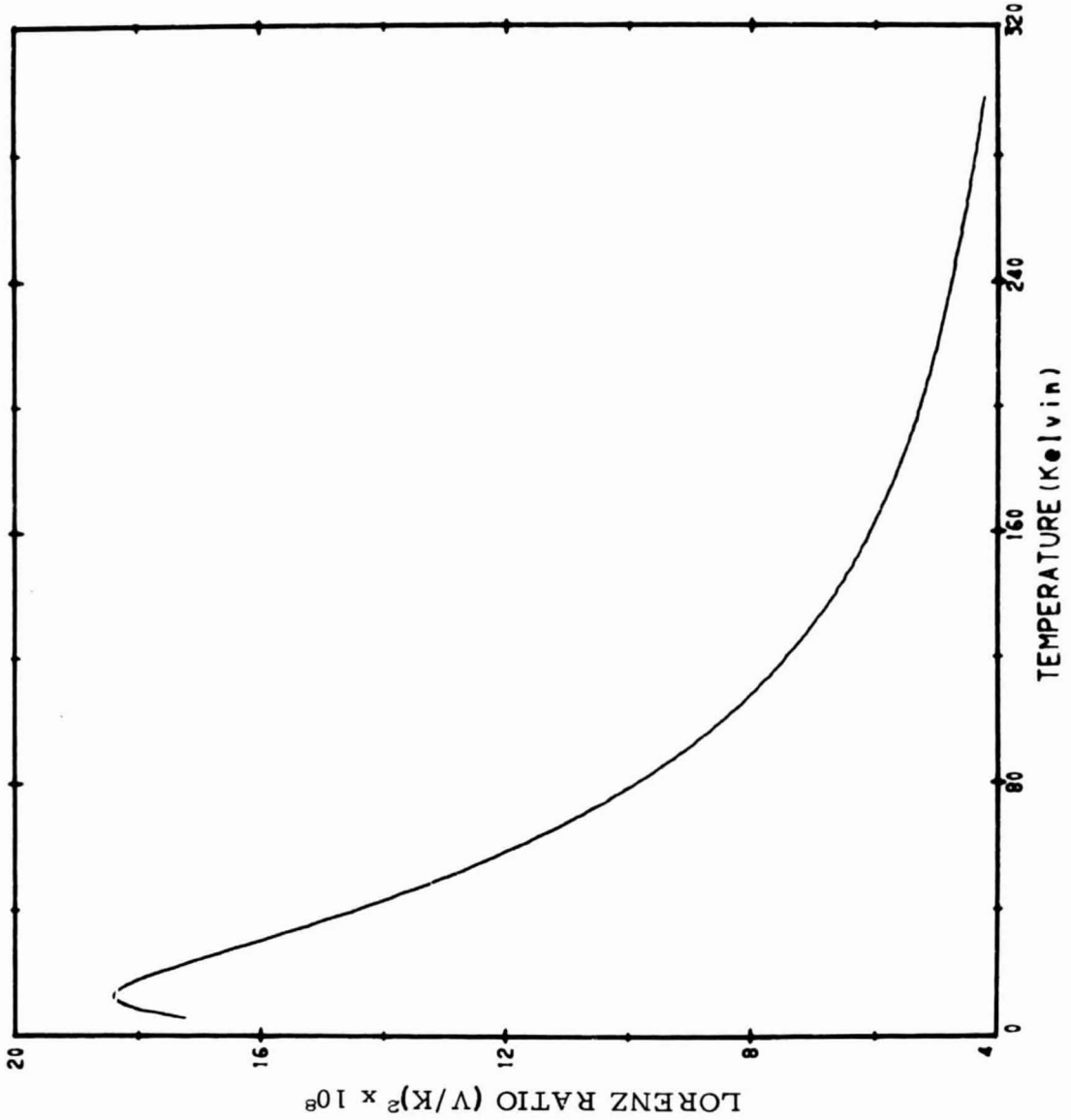

Figure 6. Lorenz ratio of annealed Inconel 718.

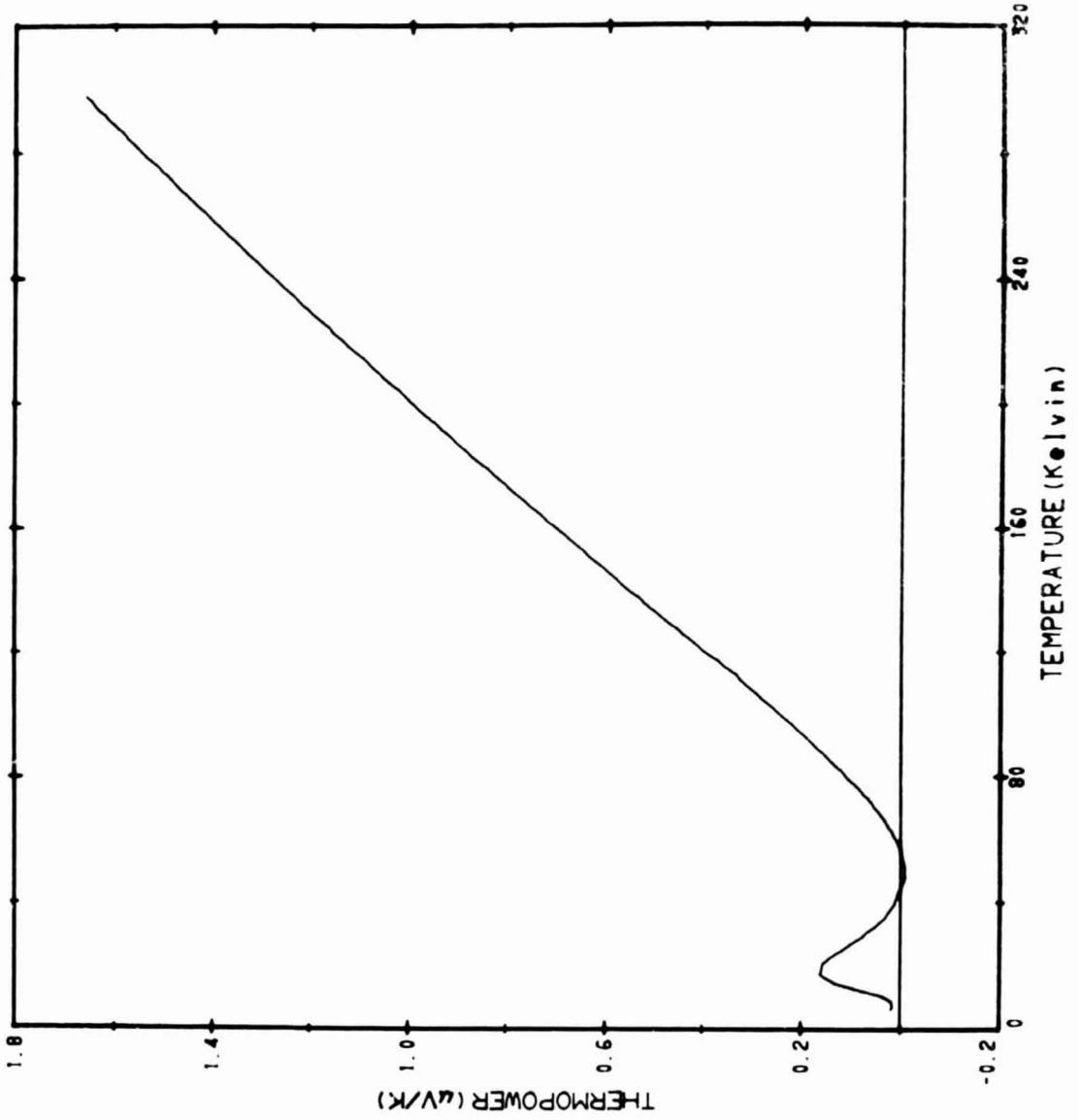

Figure 7. Thermopower of annealed Inconel 718.