

NBSIR 73-351

THERMAL CONDUCTIVITY STANDARD REFERENCE MATERIALS FROM 6 TO 280K: VI. NBS SINTERED TUNGSTEN

J.G. Hust

Cryogenics Division
Institute for Basic Standards
National Bureau of Standards
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Prepared for:
Office of Standard Reference Materials
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U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS Richard W. Roberts, Director

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ABSTRACT

Thermal conductivity, electrical resistivity, Lorenz ratio, and thermopower data are reported for two specimens of NBS sintered tungsten for temperatures from 6 to 280 K. Variability of this tungsten was studied by means of electrical resistivity and residual resistivity measurements on 39 specimens. These data indicate a material variability of about $\pm 10\%$ in thermal conductivity at helium temperatures. Above 90 K variation in thermal conductivity is only about $\pm 1\%$. To reduce the uncertainty caused by specimen variation at low temperatures, characterization by residual electrical resistivity data is described. By this procedure the low temperature uncertainty is reduced to about $\pm 3\%$.

Key words: Cryogenics, electrical resistivity, Lorenz ratio, Seebeck effect, standard reference material, thermal conductivity, transport properties, tungsten.

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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] and several standard reference materials, Hust, et al. [2-4]. We intend to measure several other materials which appear to be useful as standards. For some, material variability may be so great that only standard reference specimens (not standard reference materials) can be used. Standard reference specimens or materials are useful for intercomparison of existing apparatus, for debugging new apparatus, and for calibration of comparative apparatus. The apparent large differences between the results of various investigators for a given material (50% is not unheard of) is evidence of the need for intercomparisons, calibrations, and standardization. The availability of standard reference materials, SRM's, will result in more accurate transport property data for technically important solids.

This paper contains the results of our measurements on the transport properties of a NBS sintered tungsten material obtained from the Office of Standard Reference Materials, National Bureau of Standards. This tungsten has been investigated because of its potential as an extended temperature range SRM. Other tungsten materials have been extensively investigated for use as high temperature thermal conductivity standards by the Advisory Group for Aerospace Research and Development (AGARD), NATO. A sizeable portion of this earlier research was done by the Air Force Materials Laboratory at Dayton, Ohio.

2. Apparatus and Data Analysis

The apparatus is based on the axial one-dimensional heat flow method. The specimen is a cylindrical rod 3.1 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 300K.

The experimental data are represented by arbitrary functions over the entire range and 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. [2].

3. Specimen Characterization

Density of the NBS sintered tungsten material is $19.23 \text{ g/cm}^3 \pm 0.05 \text{ g/cm}^3$ and the DPH hardness using a 1 kilogram load is 405 for an annealed specimen and 514 for an unannealed specimen.

A resistivity variability study was conducted on this tungsten to determine if the material variability was small enough for use as a SRM. The results of this study are shown as residual resistivity ratios in table 1. The ratio given is resistivity at 273.15K to resistivity at 4K. A discussion of the connection between electrical resistivity and thermal conductivity variability is given by Hust, et al. [3]. Based on

39 residual resistivity ratio measurements made on these specimens in various states of anneal, it is concluded that the thermal conductivity variability from specimen to specimen in these lots is about 60% at liquid helium temperatures. If one restricts the analysis to the data for the specimens annealed at the highest temperature, 2020°C, the variation is significantly less, $\pm 10\%$. This variation is still large for a good low temperature standard. Because of the adjudged value of this material at high temperatures where variability does not pose a problem, we feel that a greater than normally acceptable variability at low temperatures is tolerable. The thermal conductivity variability will be comparable to the electrical resistivity variability. However, the thermal conductivity uncertainty for each specimen need not be this large if one characterizes each specimen by measuring its residual electrical resistivity. The method to obtain corrected thermal conductivities from such an electrical measurement is further explained in the discussion. The method essentially assumes that the Lorenz ratios of the specimens are more nearly identical than the thermal conductivities. This has been shown to be true for many pure metals. See, for example, Hust et al. [5].

4. Results

The transport properties of NBS sintered tungsten specimens in the unannealed and annealed (2020°C) conditions were measured in the thermal conductivity apparatus. These data are presented in tables 2 through 4.

The experimental data were functionally represented with the following equations:

$$\ln \lambda = \sum_{i=1}^n a_i [\ln T]^{i+1} \quad (1)$$

$$\rho = \sum_{i=1}^m b_i [\ln T]^{i-1} \quad (2)$$

$$S = \sum_{i=1}^l c_i [\ln T']^i / T'; \quad T' = \frac{T}{10} + 1 \quad (3)$$

where λ = thermal conductivity, ρ = electrical resistivity, S = thermopower, and T = temperature. Temperatures are based on the IPTS-68 scale above 20K and the NBS P2-20 (1965) scale below 20K. The parameters, a_i , b_i , and c_i determined by least squares, are presented in table 5. Further details of this procedure are described by Hust, et al. [1]. The deviations of the experimental data from these equations are given in tables 6 through 11 and in figures 1 through 6. The horizontal bars in figures 2, 3, 5, and 6 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) for both specimens are presented in tables 12 and 13 and figures 7 through 10.

A detailed error analysis for this system 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 300K, decreasing as T^4 to 0.70% at 200K, 0.70% from 200K to 50K, increasing inversely with temperature to 1.5% at 4K.
electrical resistivity:	0.5%
thermopower:	0.2 μ V.

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. [6] were used to convert the experimental data to the absolute scale.

5. Discussion

The research to establish this tungsten as an SRM is continuing. Because of the time required to complete this program, it is considered desirable to make the current results available for interim use. As pointed out earlier, the variability of this tungsten is greater at low temperatures (below about 90K) than desired. The electrical residual resistivity ratio measurements suggest a variation in thermal conductivity from specimen-to-specimen of as much as $\pm 10\%$ if the specimens are annealed at 2020°C for 1 hour. Other electrical measurements as well as the thermal conductivity measurements show an appreciably larger variation for lower temperature anneals. At the time, 2020°C was the maximum temperature attainable with the existing furnace. It is almost certain that an anneal of 2500°C or above will further reduce the material variability at low temperatures.

Figure 11 shows the thermal conductivity difference between the unannealed and annealed specimens up to a temperature of 90K. Above this temperature, the thermal conductivity differences become progressively smaller. Inadvertently, the unannealed specimen was measured over the total temperature range; the intent was to measure the annealed specimen. This discrepancy is troublesome but not crucial in the analyses of these data.

The intent of the following analysis is to show that the uncertainty ($\pm 10\%$) in low temperature thermal conductivity of the proposed annealed SRM can be considerably reduced on the basis of a simple residual resistivity measurement for each specimen. Consider, first, the definition of

Lorenz ratio, $L = \rho\lambda/T$, and the inverse equation for the computation of thermal conductivity, $\lambda = LT/\rho$. It is clear that the uncertainty in λ now becomes the combined uncertainties of L and ρ at a given temperature. From figure 12 we see that the maximum difference in L for the unannealed and annealed specimens is less than 12% and appears at about 30K. At this temperature, the λ difference is about 35%. Thus, Lorenz ratio variability is about one-third that of thermal conductivity variability for this material.

To determine the uncertainty caused by ρ in the calculation of λ for a particular specimen, we examine the validity of Matthiessen's rule which states that $\rho = \rho_0 + \rho_i$ where ρ_0 is the residual resistivity of the specimen and ρ_i is the intrinsic temperature dependent resistivity of the pure material. It is known that this rule is not satisfied exactly and that a generally small correction term, $\Delta(\rho_0 + \rho_i)$, exists. If this term is sufficiently small, one can reconstruct an adequately accurate ρ vs T curve for a given specimen from knowledge of ρ_i and a measurement of ρ_0 (only one simple measurement). To investigate this possibility, we compute ρ_i from the data for the annealed specimen, neglecting the Δ term. Then we compute Δ from this ρ_i and the data for the unannealed specimen. Figure 13 illustrates the magnitude of Δ with respect to ρ annealed. We see that the variability in ρ_i is one-tenth that in λ , i. e., we can compute ρ for a particular specimen with one tenth the uncertainty which exists in λ due to material variability. It is concluded that the combined uncertainty in L and ρ is at most one third as large as the measured variability in λ . Thus, the $\pm 10\%$ variability in λ can be effectively reduced to about $\pm 3\%$ simply on the basis of a ρ_0 measurement for each specimen. The thermal conductivity, λ , of a standard reference specimen of annealed tungsten can be computed from

$$L = \frac{LT}{\rho} = \frac{LT}{\rho_i + \rho_0}$$

where L and ρ_i are given in table 14 and ρ_0 is determined by a liquid helium resistivity measurement. The values of L and ρ_i listed are for tungsten annealed at 2020°C. Smoothing in the vicinity of 90K was necessary because the annealed specimen was only measured up to 90K.

Data and theory supporting the validity of the above method has been summarized by Hust and Sparks [5]. Further improvement in the calculated values of λ by the above method can be obtained through interpolation of the deviations shown in figures 12 and 13. This interpolation would be performed on the basis of the measured ρ_0 . The resulting corrections in L and ρ as a function of temperature would probably produce values of λ for each standard reference specimen accurate to better than 1%. Because of the additional complexity of this latter refinement, it is not described in detail. Further information can be obtained from the author.

6. Acknowledgments

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Table 1. Residual resistivity ratio (ρ_{273K} / ρ_{4K}) of NBS sintered tungsten.

<u>Specimen</u>	<u>Heat Treatment</u>	<u>Diameter</u>	<u>RRR</u>
1-1	1200°C, 60 hr	0.625 cm	66.2
1-2	1200°C, 60 hr	0.625 cm	48.8
3-1	1200°C, 60 hr	0.625 cm	69.5
2-2	1200°C, 60 hr	0.625 cm	63.9
6-1	1200°C, 60 hr	0.625 cm	44.2
3-2	1200°C, 60 hr	0.625 cm	65.4
			RRR = 59.6
			$\sigma = 9.2$
10-2	1200°C, 60 hr	0.312 cm	56.6
10-7	1200°C, 60 hr	0.312 cm	46.6
14-2	1200°C, 60 hr	0.312 cm	43.5
14-7	1200°C, 60 hr	0.312 cm	45.2
18-2	1200°C, 60 hr	0.312 cm	61.9
18-7	1200°C, 60 hr	0.312 cm	62.5
			RRR = 52.7
			$\sigma = 8.6$
1-1	2020°C, 1 hr	0.636 cm	78.0
2-2	2020°C, 1 hr	0.636 cm	76.1
3-1	2020°C, 1 hr	0.636 cm	83.2
4-2	2020°C, 1 hr	0.636 cm	93.5
5-1	2020°C, 1 hr	0.636 cm	82.8
6-1	2020°C, 1 hr	0.636 cm	79.0
6-2 (1)	2020°C, 1 hr	0.636 cm	79.9
6-2 (2)	2020°C, 1 hr	0.636 cm	83.1
6-2 (3)	2020°C, 1 hr	0.636 cm	80.8
6-2 (4)	2020°C, 1 hr	0.636 cm	82.3
6-2 (5)	2020°C, 1 hr	0.636 cm	83.1
			RRR = 82.0
			$\sigma = 4.5$

Table 1. Residual resistivity ratio (ρ_{273K} / ρ_{4K}) of NBS sintered tungsten (continued).

<u>Specimen</u>	<u>Heat Treatment</u>	<u>Diameter</u>	<u>RRR</u>
10-2	2020°C, 1 hr	0.318 cm	73.6
11-2	2020°C, 1 hr	0.318 cm	79.0
12-6	2020°C, 1 hr	0.318 cm	80.1
13-1	2020°C, 1 hr	0.318 cm	75.5
14-7	2020°C, 1 hr	0.318 cm	74.9
15-7	2020°C, 1 hr	0.318 cm	81.3
16-4	2020°C, 1 hr	0.318 cm	79.4
17-5 (1)	2020°C, 1 hr	0.318 cm	69.8
17-5 (2)	2020°C, 1 hr	0.318 cm	71.2
17-5 (3)	2020°C, 1 hr	0.318 cm	69.8
17-5 (4)	2020°C, 1 hr	0.318 cm	70.4
17-5 (5)	2020°C, 1 hr	0.318 cm	70.8
17-8	2020°C, 1 hr	0.318 cm	71.5
18-6 (1)	2020°C, 1 hr	0.318 cm	76.8
18-6 (2)	2020°C, 1 hr	0.318 cm	75.1
			RRR = 74.6
			$\sigma = 4.0$
14-7	as fabricated	0.318 cm	39.8

Notes Relating to Tables

Tables 2 and 3

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 these tables:

- 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 ($^{\circ}\text{C}$), 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 4

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 these tables:

- 1st line - Data identification.
- 2nd line - Platinum resistance thermometer voltage (μV) cryogenic bath pressure (mm of Hg), room temperature ($^{\circ}\text{C}$), 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 6 through 11

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

Table 2 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
380.50	501.10	640.80	799.30	976.20	1164.60	1367.00	1577.80	1MAY73 1530 8
-273.59	200.00	29.59						
8106750	84.2000	234.55	2.0	654.0	22.0		2.0	
THERMOCOUPLE TEMPERATURES								
42.773	49.948	58.089	67.116	76.967	87.199	97.941	108.915	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
6.8259-001		20.224		1.4795-004				

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
326.56	404.78	492.07	588.20	694.65	808.63	933.13	1064.00	1MAY73 1745 8A
-161.91	200.00	18.43						
6832000	71.0000	233.55	2.0	654.0	22.0		2.0	
THERMOCOUPLE TEMPERATURES								
39.511	44.209	49.386	55.011	61.161	67.623	74.558	81.744	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
4.8507-001		20.197		9.2150-005				

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
20.31	23.19	26.27	29.30	31.83	34.75	37.58	40.05	2MAY73 1200 9
-0.71	300.00	8.34						
869485	9.0500	35.07	2.0	654.0	22.0		1.0	
THERMOCOUPLE TEMPERATURES								
5.516	5.740	5.958	6.165	6.358	6.557	6.742	6.927	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
7.8688-003		4.055		2.7800-005				

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
45.82	52.01	58.28	64.39	69.83	75.52	81.05	86.10	2MAY73 1330 10
-1.79	300.00	8.35						
387870	14.4500	-0.00	-0.0	655.0	22.0		1.0	
THERMOCOUPLE TEMPERATURES								
7.297	7.723	8.131	8.519	8.882	9.238	9.577	9.906	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
2.0055-002		4.056		2.7833-005				

Table 2 (continued)

HERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN					2MAY73 1445 11		
99.06	112.40	125.50	138.00	149.35	160.73	171.74	182.05
-4.09	300.00	8.41					
2336500	24.3300	-0.00	-0.0	655.0	22.0	22.0	1.0
THERMOCOUPLE TEMPERATURES							
10.686	11.509	12.293	13.030	13.714	14.379	15.016	15.631
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
5.6847-002	4.056			2.8033-005			

HERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN					2MAY73 1600 12		
209.80	235.35	260.27	284.20	306.35	328.47	350.27	371.47
-0.96	300.00	8.81					
3891700	40.5000	-0.00	-0.0	655.0	22.0	22.0	1.0
THERMOCOUPLE TEMPERATURES							
17.227	18.721	20.164	21.547	22.850	24.138	25.407	26.667
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
1.5761-001	4.056			2.9367-005			

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN					4MAY73 2150 14		
82.97	138.20	193.91	249.57	305.54	361.34	417.71	474.14
-42.94	200.00	156.39					
3761000	39.0000	34397.10	2.0	630.0	22.0	22.0	4.0
THERMOCOUPLE TEMPERATURES							
196.523	199.094	201.682	204.262	206.853	209.431	212.031	214.629
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
1.4668-001	192.653			7.8195-004			

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN					5MAY73 1340 15		
168.79	279.38	391.39	503.56	616.85	730.12	844.95	960.27
-75.31	200.00	169.32					
5310000	55.0700	34399.00	2.0	-0.0	-0.0	-0.0	4.0
THERMOCOUPLE TEMPERATURES							
200.524	205.652	210.826	215.990	221.189	226.370	231.608	236.854
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
2.9242-001	192.662			8.4660-004			

Table 2 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
593.64	748.96	907.25	1065.89	1225.99	1386.59	1549.67	1713.57	5MAY73 2000 16
-70.49	100.00	99.09						
622000	64.4500	34837.00	2.0	-0.0	-0.0	-0.0	4.0	
THERMOCOUPLE TEMPERATURES								
222.187	229.284	236.490	243.686	250.925	258.163	265.493	272.844	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
4.0088-001	194.762	9.9090-004						

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
1082.97	1261.63	1444.53	1627.65	1812.20	1997.47	2185.83	2374.98	6MAY73 0040 17
-41.70	100.00	112.81						
6591000	68.3000	35113.50	2.0	-0.0	-0.0	-0.0	4.0	
THERMOCOUPLE TEMPERATURES								
245.748	253.817	262.049	270.268	278.537	286.808	295.218	303.663	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
4.5017-001	196.090	1.1281-003						

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN								
107.86	179.43	252.30	325.09	398.24	471.50	545.52	619.72	9MAY73 1800 18
-16.28	100.00	113.27						
4149550	43.0000	48122.00	2.0	-0.0	-0.0	-0.0	4.0	
THERMOCOUPLE TEMPERATURES								
264.116	267.329	270.598	273.861	277.141	280.412	283.716	287.029	
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE								
1.7843-001	259.269	1.1327-003						

Table 3. Basic semi-processed temperature gradient data for NBS sintered tungsten (annealed)

LOC OF GRADIENT		ATC		ISOTHERMAL RUNS		NBS SINTERED TUNGSTEN		ANNEAL	
THERMOCOUPLE POSITIONS AND AVERAGE DIAMETERS (CM)									
1	0.0000	2.54076	5.08000	7.61924	10.16025	12.70000	15.23949	17.77975	
2	0.31750	0.31750	0.31750	0.31750	0.31750	0.31750	0.31750	0.31750	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1115 1									
64.26	73.34	82.77	92.30	101.29	110.67	120.18	129.41		
-2.44	300.00	5.26							
3218300	33.5000	223.10	2.0	653.7	23.5	2.0			
THERMOCOUPLE TEMPERATURES									
23.636	24.178	24.726	25.279	25.818	26.367	26.919	27.476		
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE									
1.0781-001		19.919							

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1300 2									
118.80	136.85	155.54	174.97	194.07	214.25	235.07	256.32		
-2.41	300.00	6.11							
4476000	46.5700	224.97	2.0	653.7	23.5	2.0			
THERMOCOUPLE TEMPERATURES									
26.886	27.962	29.064	30.211	31.358	32.557	33.793	35.078		
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE									
2.0845-001		19.970							

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1430 3									
191.32	226.74	265.31	306.76	351.14	399.50	452.94	510.80		
-32.95	200.00	6.21							
5962150	62.0000	227.10	2.0	654.7	24.0	2.0			
THERMOCOUPLE TEMPERATURES									
31.239	33.363	35.668	38.148	40.824	43.717	46.891	50.324		
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE									
3.6965-001		20.027							

Table 3 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
322.12	393.60	475.99	571.16	679.39	798.60	ANNEAL 16MAY73 1600
-144.72	200.00	15.50				931.17 1073.20
7352200	76.4000	231.00	2.0	654.7	24.0	2.0
THERMOCOUPLE TEMPERATURES						
39.175	43.472	48.368	53.951	60.221	66.994	74.386
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
5.6171-001	20.130					7.7500-005

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
366.40	460.16	571.74	701.60	850.40	1011.54	ANNEAL 16MAY73 1705
-209.28	200.00	22.00				1188.90 1375.18
8019150	83.3000	232.35	2.0	654.7	24.0	2.0
THERMOCOUPLE TEMPERATURES						
41.869	47.470	54.027	61.517	69.938	78.848	88.442
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
6.6800-001	20.166					1.1000-004

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
28.33	30.55	33.15	35.67	37.64	40.16	ANNEAL 18MAY73 1500
-1.23	400.00	5.81				42.49 44.55
1133620	11.8000	-0.00	-0.0	655.0	24.5	1.0
THERMOCOUPLE TEMPERATURES						
6.094	6.265	6.444	6.610	6.761	6.929	7.077
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
1.3377-002	4.056					1.4525-005

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
57.03	61.99	67.17	72.29	76.65	81.60	ANNEAL 18MAY73 1540
-3.06	400.00	5.84				86.23 90.57
1786370	18.6000	-0.00	-0.0	655.0	24.5	1.0
THERMOCOUPLE TEMPERATURES						
8.039	8.374	8.705	9.023	9.313	9.620	9.899
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
3.3226-002	4.056					1.4600-005

Table 3 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN							8
112.51	122.86	133.31	143.52	152.65	162.23	ANNEAL	18MAY73 1625
-7.02	400.00	5.94					180.16
288.1270	30.0000	-0.00	-0.0	655.0	24.5		1.0
THERMOCOUPLE TEMPERATURES							
11.503	12.138	12.758	13.356	13.908	14.467	14.997	15.521
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
8.6438-002	4.056						1.4850-005

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN							9
232.39	253.61	275.04	296.19	316.02	336.55	ANNEAL	18MAY73 1710
-8.78	400.00	6.59					377.50
4775870	49.7000	-0.00	-0.0	655.0	24.5		1.0
THERMOCOUPLE TEMPERATURES							
18.537	19.780	21.022	22.245	23.414	24.611	25.808	27.022
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
2.3736-001	4.056						1.6475-005

Table 4. Basic semi-processed isothermal electrical resistivity data for NBS sintered tungsten (unannealed)

ISOTHERMAL RESISTIVITY DATA FOR NBS SINTERED TUNGSTEN				2MAY73	1720	13
35.07	655.00	22.00	2.00	1.00	300.00	8.33
REFERENCE TEMPERATURE	SPECIMEN RESISTANCE	SPECIMEN RESISTANCE	SPECIMEN TEMPERATURE			2.06
4.056	2.7767-005		4.222			

Table 5. Parameters in equations 1, 2, and 3 for NBS sintered tungsten.

Unannealed Specimen

THERMAL CONDUCTIVITY	ELECTRICAL RESISTIVITY	THERMOPOWER
1.23083187+002	2.32248252-007	-4.77902140+003
-3.58896755+002	-6.90059760-007	3.74959331+004
4.76863807+002	8.74523656-007	-1.22859131+005
-3.71460419+002	-6.13855629-007	2.21164325+005
1.86515932+002	2.60856484-007	-2.43908435+005
-6.29083223+001	-6.86620382-008	1.73778224+005
1.44225570+001	1.09229515-008	-8.17454896+004
-2.21990545+000	-9.59844355-010	2.52569176+004
2.19723698-001	3.57364089-011	-4.93402176+003
-1.26431486-002		5.52827982+002
3.21572593-004		-2.70746565+001

Annealed Specimen

THERMAL CONDUCTIVITY	ELECTRICAL RESISTIVITY	THERMOPOWER
7.82605854+001	-2.30392836-008	5.55599828+002
-1.96102930+002	4.89385144-008	-2.24304536+003
2.24227329+002	-4.00878173-008	2.86171709+003
-1.47464497+002	1.62832450-008	-1.46600982+003
6.02616459+001	-3.28337817-009	2.54315461+002
-1.55810593+001	2.63473568-010	1.73778224+005
2.48203550+000	1.09229515-008	-8.17454896+004
-2.22430802-001	-9.59844355-010	2.52569176+004
8.58323382-003	3.57364089-011	-4.93402176+003
-1.26431486-002		5.52827982+002
3.21572593-004		-2.70746565+001

Table 6. Thermal conductivity deviations for NBS sintered tungsten (unannealed)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				26APR73 1050 1
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
84.998	2.544	2.09+002	2.09+002	0.2
87.562	2.584	2.06+002	2.07+002	-0.5
90.150	2.593	2.05+002	2.05+002	-0.0
92.755	2.615	2.04+002	2.04+002	-0.1
95.370	2.616	2.03+002	2.02+002	0.4
98.002	2.647	2.01+002	2.01+002	-0.2
100.655	2.659	2.00+002	2.00+002	-0.0

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				26 APR73 1720 2
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
88.552	5.734	2.07+002	2.06+002	0.3
94.348	5.858	2.02+002	2.03+002	-0.3
100.234	5.915	2.00+002	2.00+002	-0.0
106.191	5.999	1.98+002	1.98+002	-0.4
112.193	6.004	1.97+002	1.97+002	0.3
118.243	6.098	1.94+002	1.95+002	-0.6
124.354	6.124	1.94+002	1.94+002	-0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				26APR73 2140 3
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
103.148	11.087	2.00+002	1.99+002	0.2
114.362	11.341	1.95+002	1.96+002	-0.5
125.758	11.452	1.93+002	1.94+002	-0.2
137.292	11.616	1.91+002	1.92+002	-0.4
148.913	11.625	1.90+002	1.89+002	0.5
160.634	11.818	1.87+002	1.88+002	-0.2
172.482	11.878	1.86+002	1.86+002	0.3

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN							26APR73 2330 4
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION			
151.846	10.851	1.90+002	1.89+002	0.3			
162.787	11.032	1.86+002	1.87+002	-0.5			
173.823	11.041	1.86+002	1.86+002	0.3			
184.908	11.127	1.85+002	1.84+002	0.3			
196.043	11.145	1.84+002	1.83+002	0.7			
207.279	11.326	1.81+002	1.82+002	-0.3			
218.633	11.383	1.81+002	1.81+002	-0.1			

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN							1 MAY 73 1045 5
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION			
24.355	0.513	3.91+002	3.97+002	-1.5			
24.861	0.499	4.02+002	3.99+002	0.8			
25.363	0.506	3.96+002	4.00+002	-1.0			
25.866	0.499	4.02+002	4.01+002	0.1			
26.363	0.495	4.05+002	4.02+002	0.8			
26.859	0.497	4.03+002	4.02+002	0.2			
27.358	0.501	4.01+002	4.02+002	-0.4			

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN							1MAY73 1200 6
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION			
27.269	1.201	4.01+002	4.02+002	-0.3			
28.464	1.190	4.04+002	4.01+002	0.8			
29.665	1.211	3.97+002	3.99+002	-0.3			
30.875	1.208	3.98+002	3.95+002	0.9			
32.088	1.218	3.95+002	3.90+002	1.4			
33.321	1.249	3.85+002	3.84+002	0.4			
34.581	1.271	3.79+002	3.77+002	0.5			

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				1MAY73 1330 7	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
31.987	2.512	3.92+002	3.90+002	0.6	
34.547	2.607	3.78+002	3.77+002	0.2	
37.215	2.731	3.61+002	3.61+002	-0.1	
40.022	2.882	3.42+002	3.44+002	-0.5	
42.966	3.007	3.28+002	3.26+002	0.6	
46.079	3.220	3.06+002	3.08+002	-0.6	
49.385	3.392	2.91+002	2.91+002	-0.0	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				1MAY73 1530 8	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
46.360	7.175	3.05+002	3.06+002	-0.3	
54.019	8.141	2.69+002	2.70+002	-0.5	
62.602	9.027	2.43+002	2.42+002	0.1	
72.041	9.851	2.22+002	2.23+002	-0.4	
82.083	10.232	2.14+002	2.11+002	1.4	
92.570	10.742	2.04+002	2.04+002	-0.0	
103.428	10.974	2.00+002	1.99+002	0.2	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				1MAY73 1745 8A	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
41.860	4.698	3.32+002	3.32+002	-0.2	
46.797	5.177	3.01+002	3.04+002	-1.1	
52.198	5.625	2.77+002	2.78+002	-0.4	
58.086	6.150	2.53+002	2.56+002	-0.9	
64.392	6.462	2.41+002	2.38+002	1.2	
71.091	6.934	2.24+002	2.25+002	-0.2	
78.151	7.186	2.17+002	2.15+002	0.8	

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	2MAY73 1200	9
5.628	0.224	1.13+002	1.13+002	-0.6		
5.849	0.218	1.16+002	1.18+002	-1.4		
6.062	0.206	1.22+002	1.22+002	0.6		
6.262	0.194	1.30+002	1.26+002	3.6		
6.457	0.198	1.27+002	1.30+002	-1.8		
6.649	0.185	1.36+002	1.34+002	1.8		
6.834	0.185	1.36+002	1.38+002	-0.9		

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	2MAY73 1330	10
7.510	0.426	1.51+002	1.52+002	-0.2		
7.927	0.408	1.58+002	1.60+002	-1.6		
8.325	0.388	1.66+002	1.68+002	-1.2		
8.701	0.363	1.77+002	1.75+002	1.2		
9.060	0.356	1.81+002	1.82+002	-0.9		
9.407	0.339	1.90+002	1.89+002	0.6		
9.742	0.330	1.95+002	1.95+002	0.1		

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	2MAY73 1445	11
11.098	0.823	2.22+002	2.20+002	0.7		
11.901	0.784	2.33+002	2.35+002	-0.9		
12.662	0.737	2.48+002	2.49+002	-0.4		
13.372	0.684	2.67+002	2.61+002	2.0		
14.047	0.665	2.74+002	2.73+002	0.3		
14.697	0.636	2.86+002	2.85+002	0.5		
15.323	0.616	2.96+002	2.96+002	0.2		

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN				2MAY73 1600 12	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
17.974	1.494	3.39+002	3.38+002	0.3	
19.443	1.443	3.50+002	3.57+002	-2.0	
20.856	1.383	3.66+002	3.73+002	-2.0	
22.199	1.303	3.88+002	3.85+002	1.0	
23.494	1.288	3.93+002	3.93+002	-0.1	
24.772	1.269	3.98+002	3.99+002	-0.0	
26.037	1.260	4.02+002	4.01+002	0.0	

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN				4MAY73 2150 14	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
197.809	2.570	1.83+002	1.83+002	0.2	
200.388	2.588	1.82+002	1.83+002	-0.4	
202.972	2.581	1.82+002	1.82+002	0.0	
205.558	2.590	1.82+002	1.82+002	-0.2	
208.142	2.578	1.83+002	1.82+002	0.3	
210.731	2.600	1.81+002	1.82+002	-0.4	
213.330	2.598	1.81+002	1.81+002	-0.1	

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN				5MAY73 1340 15	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
203.088	5.127	1.83+002	1.82+002	0.4	
208.239	5.175	1.81+002	1.82+002	-0.3	
213.408	5.164	1.82+002	1.81+002	0.2	
218.590	5.198	1.81+002	1.81+002	-0.2	
223.779	5.182	1.81+002	1.80+002	0.3	
228.989	5.238	1.79+002	1.80+002	-0.5	
234.231	5.246	1.79+002	1.79+002	-0.3	

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY		CALCULATED THERMAL CONDUCTIVITY	5MAY73 2000 16	
		CONDUCTIVITY	CONDUCTIVITY		PERCENT DEVIATION	PERCENT DEVIATION
225.735	7.097	1.81+002	1.80+002	1.80+002	0.6	
232.887	7.206	1.78+002	1.80+002	1.80+002	-0.6	
240.088	7.197	1.79+002	1.79+002	1.79+002	-0.1	
247.306	7.239	1.78+002	1.78+002	1.78+002	-0.2	
254.544	7.238	1.78+002	1.77+002	1.77+002	0.2	
261.828	7.329	1.75+002	1.76+002	1.76+002	-0.6	
269.169	7.352	1.75+002	1.76+002	1.76+002	-0.3	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY		CALCULATED THERMAL CONDUCTIVITY	6MAY73 0040 17	
		CONDUCTIVITY	CONDUCTIVITY		PERCENT DEVIATION	PERCENT DEVIATION
249.783	8.069	1.79+002	1.78+002	1.78+002	0.7	
257.933	8.232	1.75+002	1.77+002	1.77+002	-0.9	
266.159	8.220	1.76+002	1.76+002	1.76+002	-0.1	
274.403	8.268	1.75+002	1.75+002	1.75+002	0.0	
282.672	8.272	1.75+002	1.74+002	1.74+002	0.6	
291.013	8.410	1.72+002	1.72+002	1.72+002	-0.4	
299.441	8.445	1.71+002	1.71+002	1.71+002	-0.0	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY		CALCULATED THERMAL CONDUCTIVITY	5MAY73 1800 18	
		CONDUCTIVITY	CONDUCTIVITY		PERCENT DEVIATION	PERCENT DEVIATION
265.723	3.213	1.78+002	1.76+002	1.76+002	1.3	
268.963	3.269	1.75+002	1.76+002	1.76+002	-0.2	
272.229	3.263	1.75+002	1.75+002	1.75+002	0.2	
275.501	3.280	1.75+002	1.75+002	1.75+002	0.0	
278.776	3.271	1.75+002	1.74+002	1.74+002	0.5	
282.064	3.305	1.73+002	1.74+002	1.74+002	-0.3	
285.373	3.313	1.73+002	1.73+002	1.73+002	-0.2	

Table 7. Thermal conductivity deviations for NBS sintered tungsten (annealed)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL 16MAY73 1115	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
23.907	0.542	6.38+002	6.39+002	-0.1	1
24.452	0.548	6.30+002	6.37+002	-1.1	
25.003	0.553	6.26+002	6.35+002	-1.6	
25.549	0.539	6.42+002	6.32+002	1.5	
26.092	0.548	6.31+002	6.29+002	0.3	
26.643	0.552	6.26+002	6.24+002	0.3	
27.197	0.557	6.21+002	6.19+002	0.2	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL 16MAY73 1300	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
27.424	1.077	6.21+002	6.17+002	0.7	2
28.513	1.102	6.07+002	6.05+002	0.2	
29.638	1.146	5.83+002	5.91+002	-1.4	
30.784	1.147	5.83+002	5.75+002	1.4	
31.958	1.200	5.57+002	5.58+002	-0.1	
33.175	1.236	5.41+002	5.39+002	0.3	
34.435	1.285	5.21+002	5.20+002	0.1	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL 16MAY73 1430	
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION	
32.301	2.124	5.58+002	5.53+002	1.0	3
34.515	2.304	5.14+002	5.19+002	-0.8	
36.908	2.480	4.78+002	4.82+002	-0.9	
39.486	2.676	4.43+002	4.45+002	-0.4	
42.270	2.892	4.10+002	4.09+002	0.3	
45.504	3.174	3.74+002	3.75+002	-0.3	
48.607	3.433	3.45+002	3.44+002	0.5	

Table 7 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL	16MAY73	1600	4
MEAN	TEMPERATURE	DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
41.324	4.297		4.20+002	4.21+002	-0.3		
45.920	4.895		3.68+002	3.68+002	-0.1		
51.160	5.584		3.23+002	3.24+002	-0.4		
57.086	6.270		2.88+002	2.89+002	-0.4		
63.608	6.772		2.66+002	2.63+002	1.1		
70.690	7.392		2.44+002	2.45+002	-0.5		
78.283	7.795		2.31+002	2.32+002	-0.2		

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL	16MAY73	1705	5
MEAN	TEMPERATURE	DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
44.670	5.601		3.83+002	3.81+002	0.4		
50.748	6.557		3.27+002	3.27+002	-0.0		
57.772	7.490		2.86+002	2.85+002	0.2		
65.728	8.421		2.55+002	2.57+002	-0.9		
74.393	8.910		2.41+002	2.38+002	1.1		
83.645	9.594		2.23+002	2.25+002	-0.6		
93.386	9.888		2.17+002	2.16+002	0.2		

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL	18MAY73	1500	6
MEAN	TEMPERATURE	DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
6.179	0.171		2.51+002	2.47+002	1.6		
6.354	0.179		2.40+002	2.53+002	-5.3		
6.527	0.166		2.58+002	2.59+002	-0.3		
6.686	0.151		2.84+002	2.64+002	6.8		
6.845	0.167		2.56+002	2.70+002	-5.3		
7.003	0.149		2.89+002	2.76+002	4.6		
7.155	0.155		2.77+002	2.81+002	-1.6		

Table 7 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL	18MAY73	1540	7
MEAN	TEMPERATURE	DIFFERENCE	CONDUCTIVITY	PERCENT	PERCENT	PERCENT	
TEMPERATURE			CONDUCTIVITY	DEVIATION	DEVIATION	DEVIATION	
			CONDUCTIVITY				
8.206	0.336		3.18+002			-0.2	
8.540	0.330		3.22+002			-2.3	
8.864	0.319		3.35+002			-1.9	
9.168	0.290		3.68+002			4.5	
9.466	0.306		3.48+002			-3.6	
9.759	0.280		3.81+002			2.8	
10.041	0.284		3.76+002			-0.9	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL	18MAY73	1625	8
MEAN	TEMPERATURE	DIFFERENCE	CONDUCTIVITY	PERCENT	PERCENT	PERCENT	
TEMPERATURE			CONDUCTIVITY	DEVIATION	DEVIATION	DEVIATION	
			CONDUCTIVITY				
11.820	0.635		4.37+002			0.6	
12.448	0.621		4.47+002			-1.4	
13.057	0.598		4.64+002			-1.5	
13.632	0.552		5.03+002			3.2	
14.188	0.559		4.96+002			-1.1	
14.732	0.530		5.23+002			1.3	
15.259	0.524		5.29+002			-0.2	

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN				ANNEAL	18MAY73	1710	9
MEAN	TEMPERATURE	DIFFERENCE	CONDUCTIVITY	PERCENT	PERCENT	PERCENT	
TEMPERATURE			CONDUCTIVITY	DEVIATION	DEVIATION	DEVIATION	
			CONDUCTIVITY				
19.158	1.243		6.13+002			0.7	
20.401	1.242		6.13+002			-1.8	
21.633	1.223		6.22+002			-1.9	
22.830	1.170		6.51+002			2.0	
24.012	1.196		6.36+002			-0.3	
25.209	1.197		6.36+002			0.3	
26.415	1.214		6.27+002			0.1	

Table 8. Electrical resistivity deviations for NBS sintered tungsten (unannealed)

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
92.784	18.257	2.268-004	2.262-004	0.30
106.302	41.731	2.925-004	2.919-004	0.20
137.512	80.817	4.465-004	4.469-004	-0.10
185.045	77.905	6.825-004	6.823-004	0.03
25.861	3.509	3.045-005	3.055-005	-0.33
30.895	8.547	3.335-005	3.309-005	0.78
40.314	20.350	4.465-005	4.444-005	0.47
73.300	66.142	1.479-004	1.484-004	-0.33
58.939	42.233	9.215-005	9.263-005	-0.52
6.249	1.411	2.780-005	2.775-005	0.18
8.667	2.609	2.783-005	2.797-005	-0.49
13.300	4.945	2.803-005	2.782-005	0.75
22.111	9.440	2.937-005	2.962-005	-0.88
205.561	18.105	7.820-004	7.829-004	-0.12
218.617	36.330	8.466-004	8.467-004	-0.02
247.365	50.658	9.909-004	9.894-004	0.16
274.485	57.915	1.128-003	1.129-003	-0.05
275.518	22.913	1.133-003	1.133-003	-0.02
4.222	0.000	2.777-005	2.777-005	-0.02

Table 9. Electrical resistivity deviations for NBS sintered tungsten (annealed)

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
25.549	3.840	1.753-005	1.734-005	1.11
30.847	8.192	2.037-005	2.043-005	-0.33
39.913	19.085	3.105-005	3.124-005	-0.63
58.296	43.006	7.750-005	7.697-005	0.68
67.192	56.461	1.100-004	1.104-004	-0.34
6.678	1.139	1.452-005	1.454-005	-0.08
9.149	2.144	1.460-005	1.456-005	0.30
13.591	4.018	1.485-005	1.491-005	-0.43
22.808	8.485	1.647-005	1.652-005	-0.29

Table 10. Thermovoltage deviations for NBS sintered tungsten (unannealed)

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
101.984	83.727	-81.09	-81.03	-0.06
127.416	85.685	-179.18	-179.45	0.27
178.421	97.604	-303.90	-303.81	-0.09
224.325	146.420	-217.44	-217.50	0.06
27.608	24.099	-1.53	-1.40	-0.13
35.216	26.669	-10.47	-9.95	-0.52
51.081	30.731	-50.85	-51.05	0.20
108.915	42.773	-273.59	-273.42	-0.17
81.744	39.511	-161.91	-162.03	0.12
6.927	5.516	-0.71	-0.60	-0.11
9.906	7.297	-1.79	-2.00	0.21
15.631	10.686	-4.09	-3.86	-0.23
26.667	17.227	-0.96	-1.25	0.29
214.629	196.523	-42.94	-42.81	-0.13
236.854	200.524	-75.31	-75.29	-0.02
272.844	222.187	-70.49	-70.53	0.04
303.663	245.748	-41.70	-41.81	0.11
287.029	264.116	-16.28	-15.95	-0.33

Table 11. Thermovoltage deviations for NBS sintered tungsten (annealed)

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
27.476	23.636	-2.44	-2.61	0.17
55.078	26.886	-2.41	-6.47	4.06
50.324	31.239	-32.95	-31.23	-1.72
82.181	39.175	-144.72	-145.25	0.53
98.330	41.869	-209.28	-209.08	-0.20
7.233	6.094	-1.23	-0.74	-0.49
10.183	8.039	-3.06	-3.60	0.54
15.521	11.503	-7.02	-7.31	0.29
27.022	18.537	-8.78	-7.09	-1.69

Table 12. Transport properties of NBS sintered tungsten
(unannealed)

Temp (K)	Thermal Conductivity ($\text{Wm}^{-1} \text{K}^{-1}$)	Electrical Resistivity ($\text{n } \Omega \text{ m}$)	Lorenz Ratio (V^2 / K^2) 10^8	Thermo- power ($\mu\text{V} / \text{K}$)
6	120	1.229	2.47	-0.41
7	141	1.253	2.52	-0.41
8	162	1.252	2.53	-0.63
9	181	1.242	2.50	-0.85
10	200	1.233	2.47	-0.97
12	237	1.229	2.42	-0.88
14	273	1.241	2.42	-0.52
16	307	1.260	2.42	-0.13
18	338	1.280	2.40	0.17
20	364	1.298	2.36	0.31
25	399	1.347	2.15	0.09
30	398	1.439	1.91	-0.59
35	374	1.610	1.72	-1.35
40	344	1.884	1.62	-2.02
45	314	2.268	1.58	-2.56
50	288	2.759	1.59	-2.98
55	266	3.352	1.62	-3.29
60	250	4.036	1.68	-3.52
65	237	4.800	1.75	-3.69
70	227	5.635	1.82	-3.81
75	219	6.528	1.91	-3.89
80	213	7.472	1.99	-3.94
85	209	8.456	2.08	-3.96
90	205	9.475	2.16	-3.96
95	203	10.52	2.24	-3.93
100	200	11.59	2.32	-3.89
110	197	13.77	2.47	-3.76
120	195	15.99	2.60	-3.57
130	193	18.22	2.70	-3.35
140	191	20.46	2.79	-3.12
150	189	22.68	2.86	-2.87
160	188	24.90	2.92	-2.62
170	186	27.10	2.97	-2.37
180	185	29.29	3.01	-2.12
190	184	31.47	3.04	-1.87
200	183	33.64	3.07	-1.61
220	181	37.99	3.12	-1.09
240	179	42.38	3.16	-0.53
260	177	46.85	3.18	0.05
280	174	51.47	3.20	0.65

Table 13. Transport properties of NBS sintered tungsten
(annealed)

Temp (K)	Thermal Conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)	Electrical Resistivity ($\text{n}\Omega\text{m}$)	Lorenz Ratio (V^2/K^2) 10^8	Thermo- power ($\mu\text{V}/\text{K}$)
7	275	0.6493	2.56	-0.85
8	311	0.6488	2.52	-1.34
9	345	0.6478	2.49	-1.66
10	378	0.6487	2.45	-1.83
12	440	0.6559	2.40	-1.85
14	497	0.6662	2.36	-1.64
16	548	0.6773	2.32	-1.32
18	590	0.6892	2.26	-1.00
20	620	0.7033	2.18	-0.72
25	635	0.7614	1.93	-0.31
30	586	0.8749	1.71	-0.30
35	511	1.065	1.55	-0.58
40	438	1.342	1.47	-1.04
45	378	1.713	1.44	-1.59
50	332	2.178	1.45	-2.14
55	300	2.738	1.49	-2.66
60	276	3.389	1.56	-3.10
65	259	4.127	1.64	-3.45
70	246	4.950	1.74	-3.71
75	237	5.854	1.85	-3.87
80	229	6.833	1.96	-3.92
85	223	7.885	2.07	-3.89
90	218	9.005	2.19	-3.76

Table 14. Intrinsic resistivity and Lorenz ratio of annealed NBS sintered tungsten.

Temperature (K)	Lorenz Ratio (V^2/K^2) 10^8	Electrical Resistivity ($n\Omega m$)	Temperature (K)	Lorenz Ratio (V^2/K^2) 10^8	Electrical Resistivity ($n\Omega m$)
7	2.56	.00	80	1.96	6.21
8	2.52	.00	85	2.07	7.23
9	2.49	.00	90	2.18	8.24
10	2.45	.00	95	2.28	9.28
12	2.40	.00	100	2.37	10.35
14	2.36	.01	110	2.51	12.53
16	2.32	.02	120	2.61	14.75
18	2.26	.04	130	2.70	16.98
20	2.18	.06	140	2.79	19.22
25	1.93	.11	150	2.86	21.44
30	1.71	.21	160	2.92	23.66
35	1.55	.39	170	2.97	25.86
40	1.47	.67	180	3.01	28.05
45	1.44	1.05	190	3.04	30.23
50	1.45	1.52	200	3.07	32.40
55	1.49	2.10	220	3.12	36.75
60	1.56	2.77	240	3.16	41.14
65	1.64	3.52	260	3.18	45.61
70	1.74	4.35	280	3.20	50.23
75	1.85	5.25			

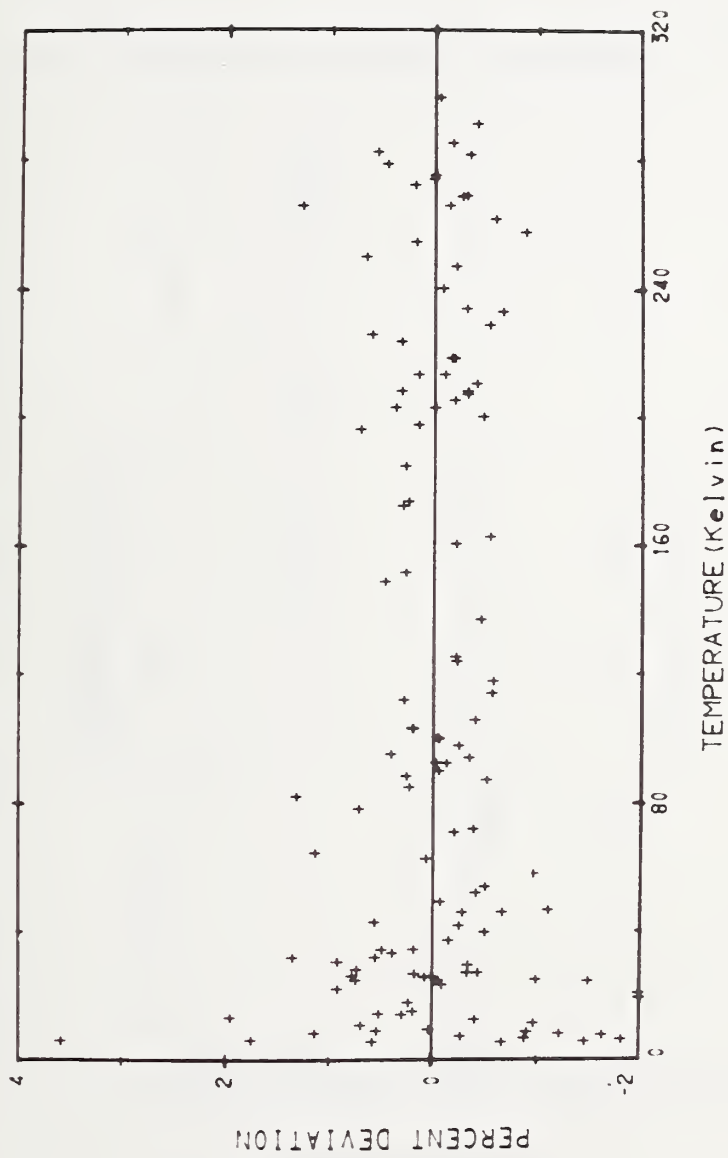


Figure 1. Thermal conductivity deviations for NBS sintered tungsten (unannealed)

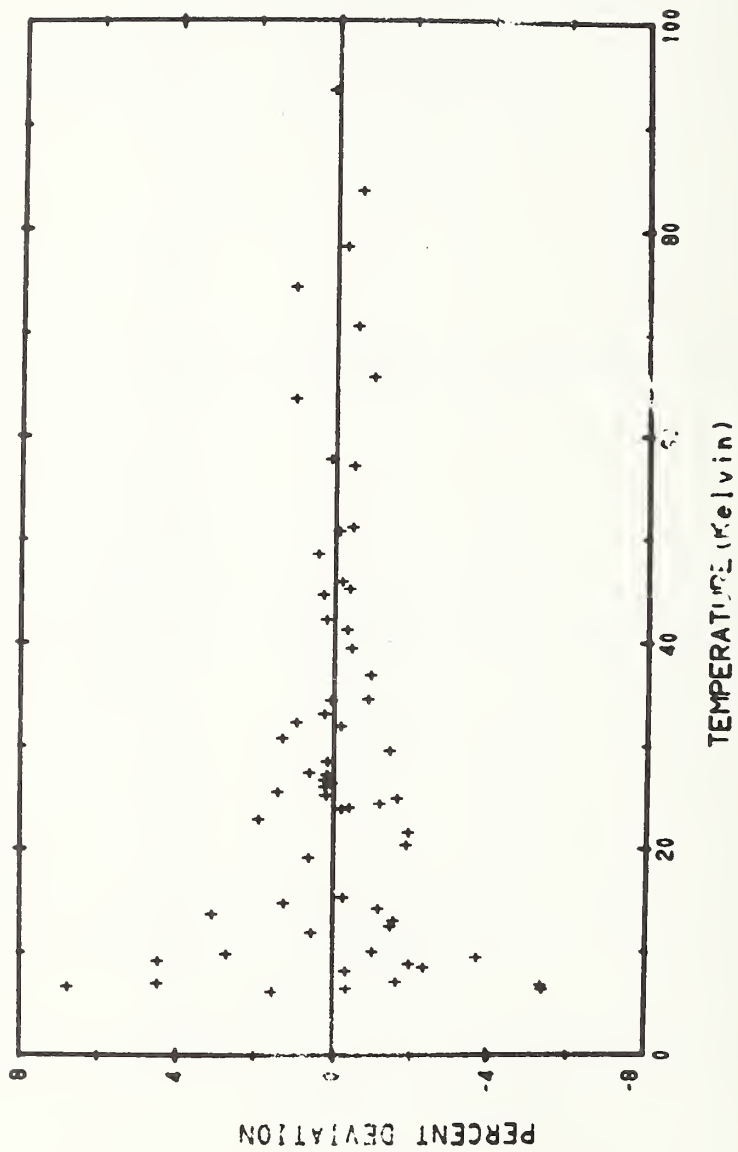


Figure 2. Thermal conductivity deviations for NBS sintered tungsten (annealed)

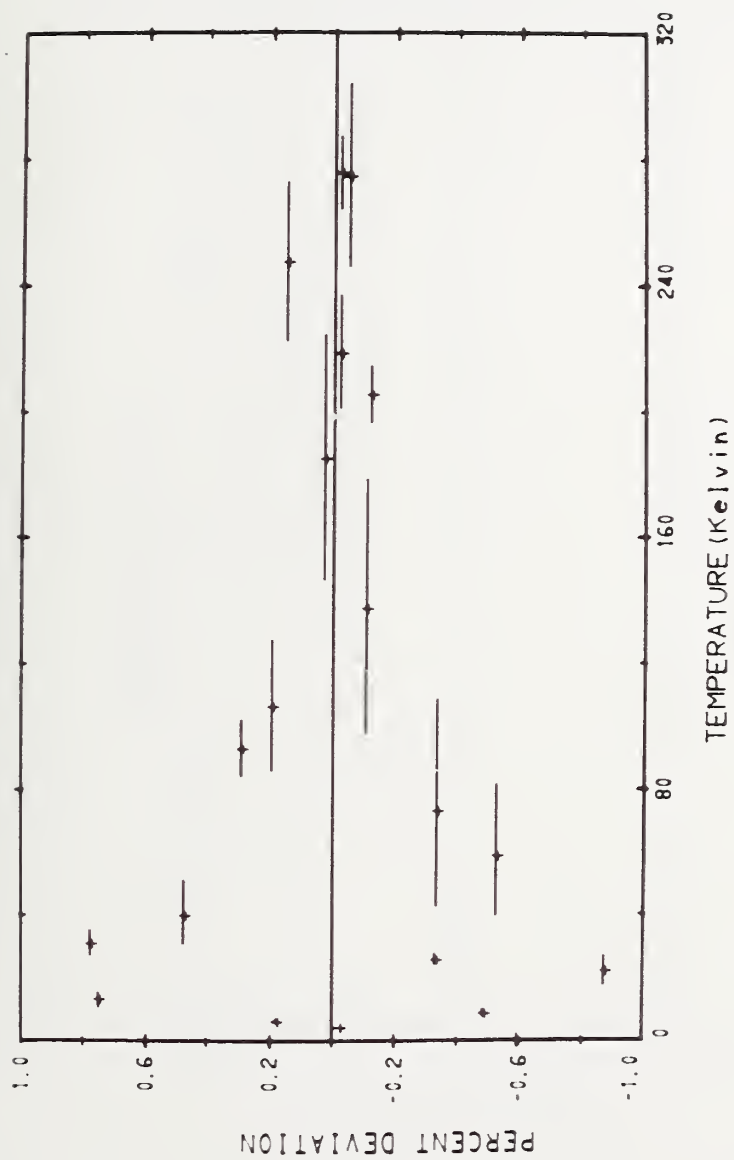


Figure 3. Electrical resistivity deviations for NBS sintered tungsten (unannealed)

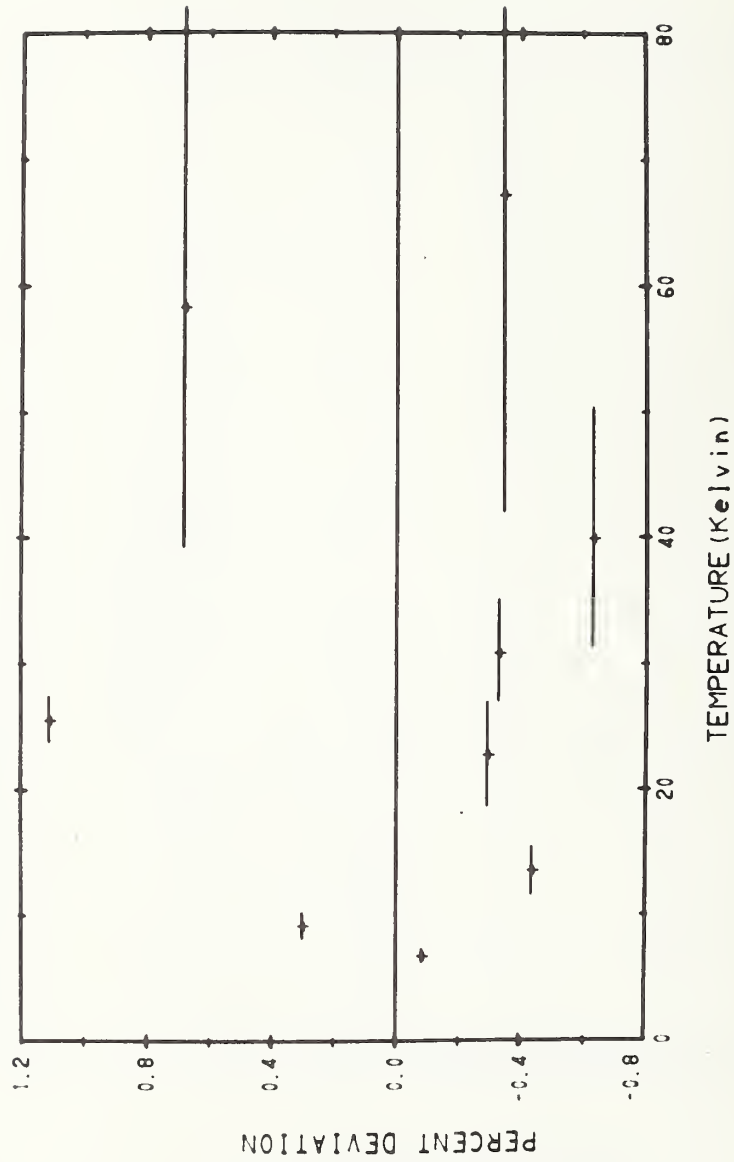


Figure 4. Electrical resistivity deviations for NBS sintered tungsten (annealed)

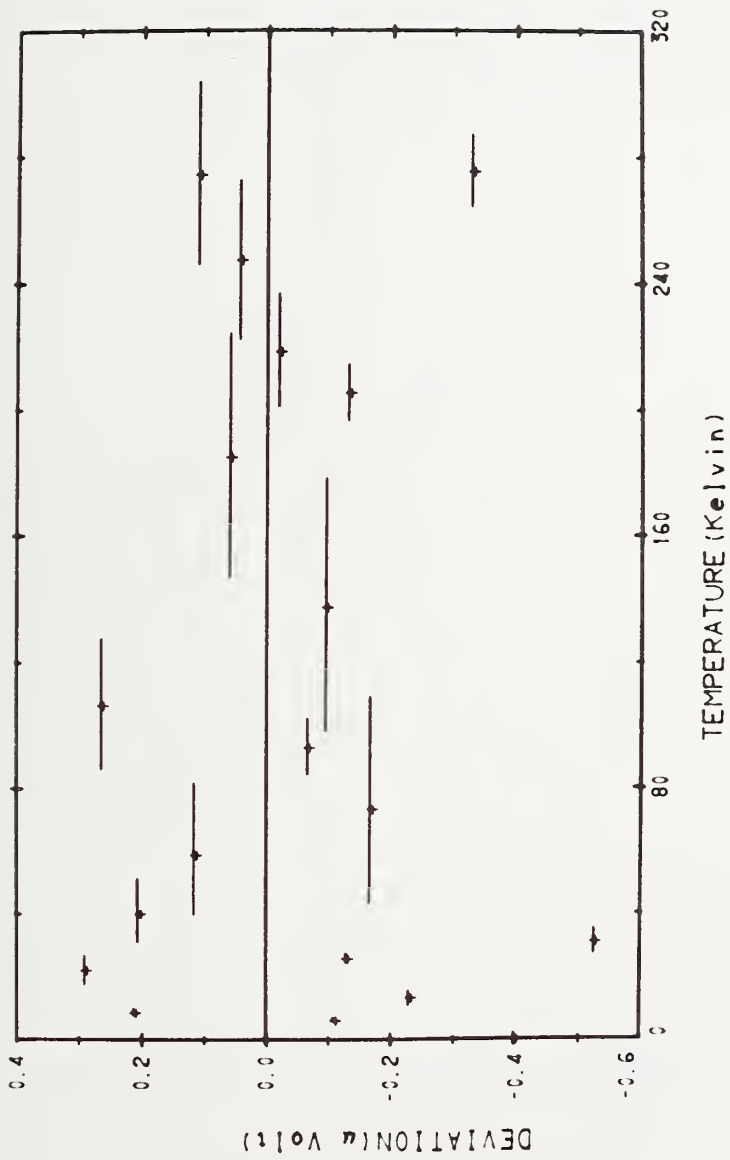


Figure 5. Thermovoltage deviations for NBS sintered tungsten (unannealed)

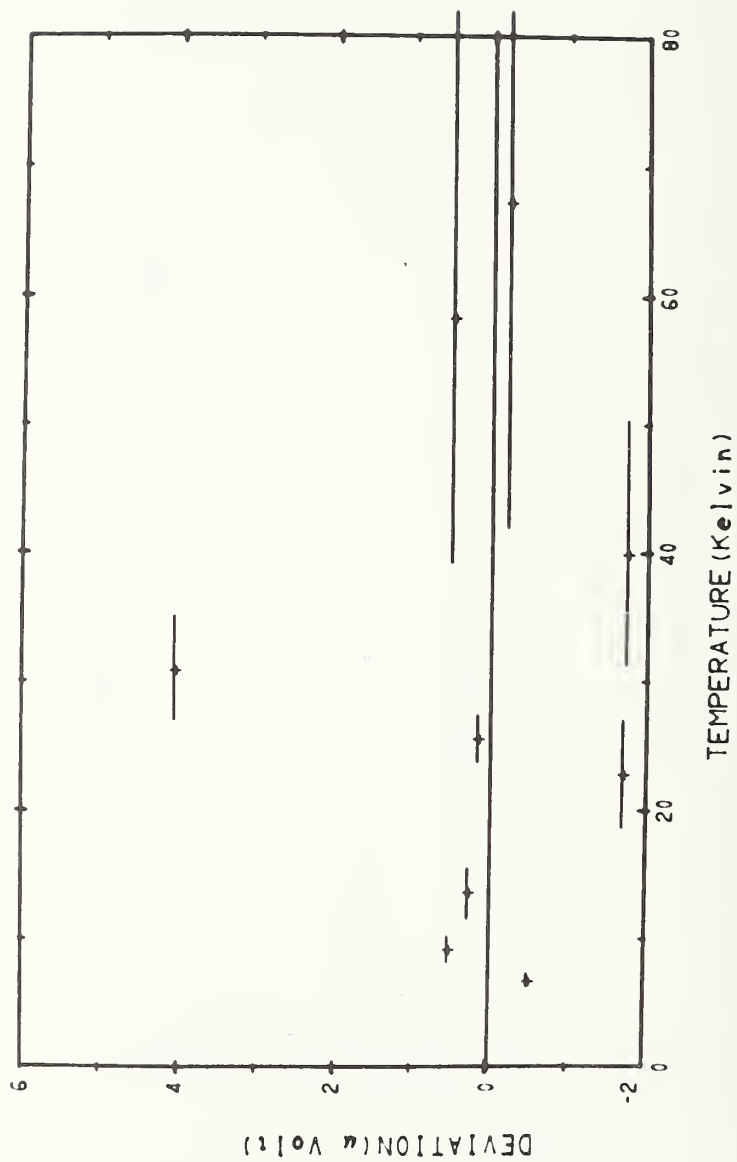


Figure 6. Thermovoltage deviations for NBS sintered tungsten (annealed)

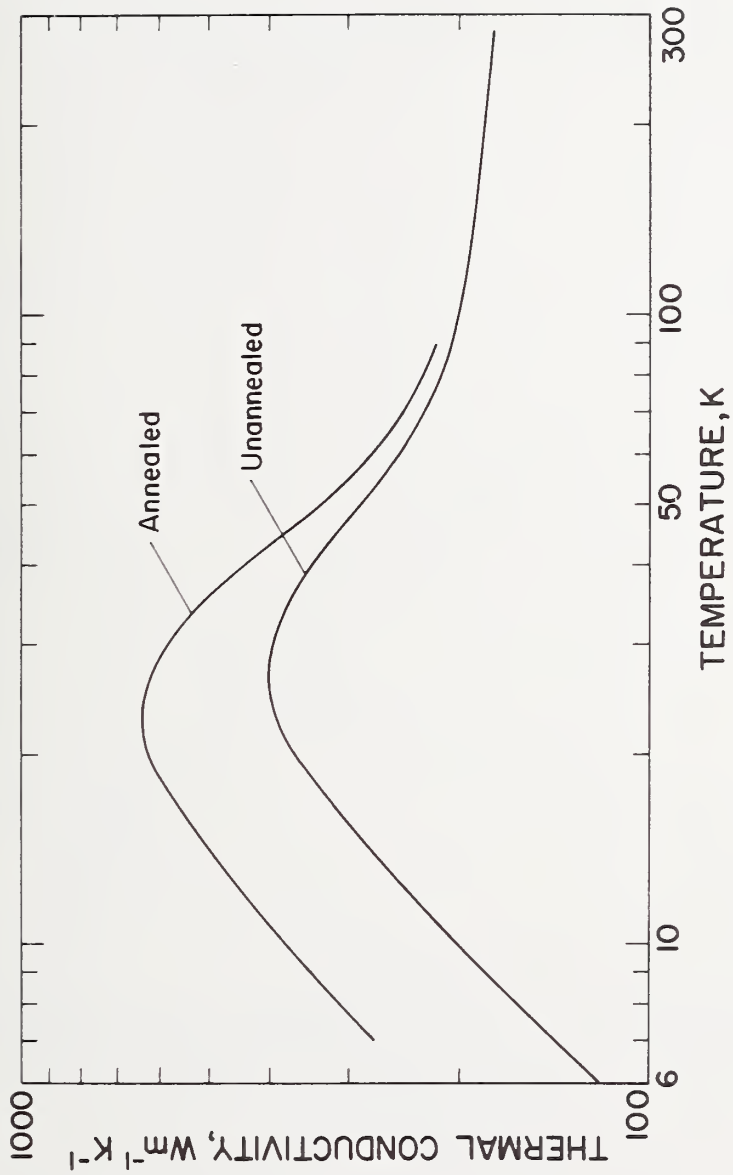


Figure 7. Thermal conductivity of NBS sintered tungsten.

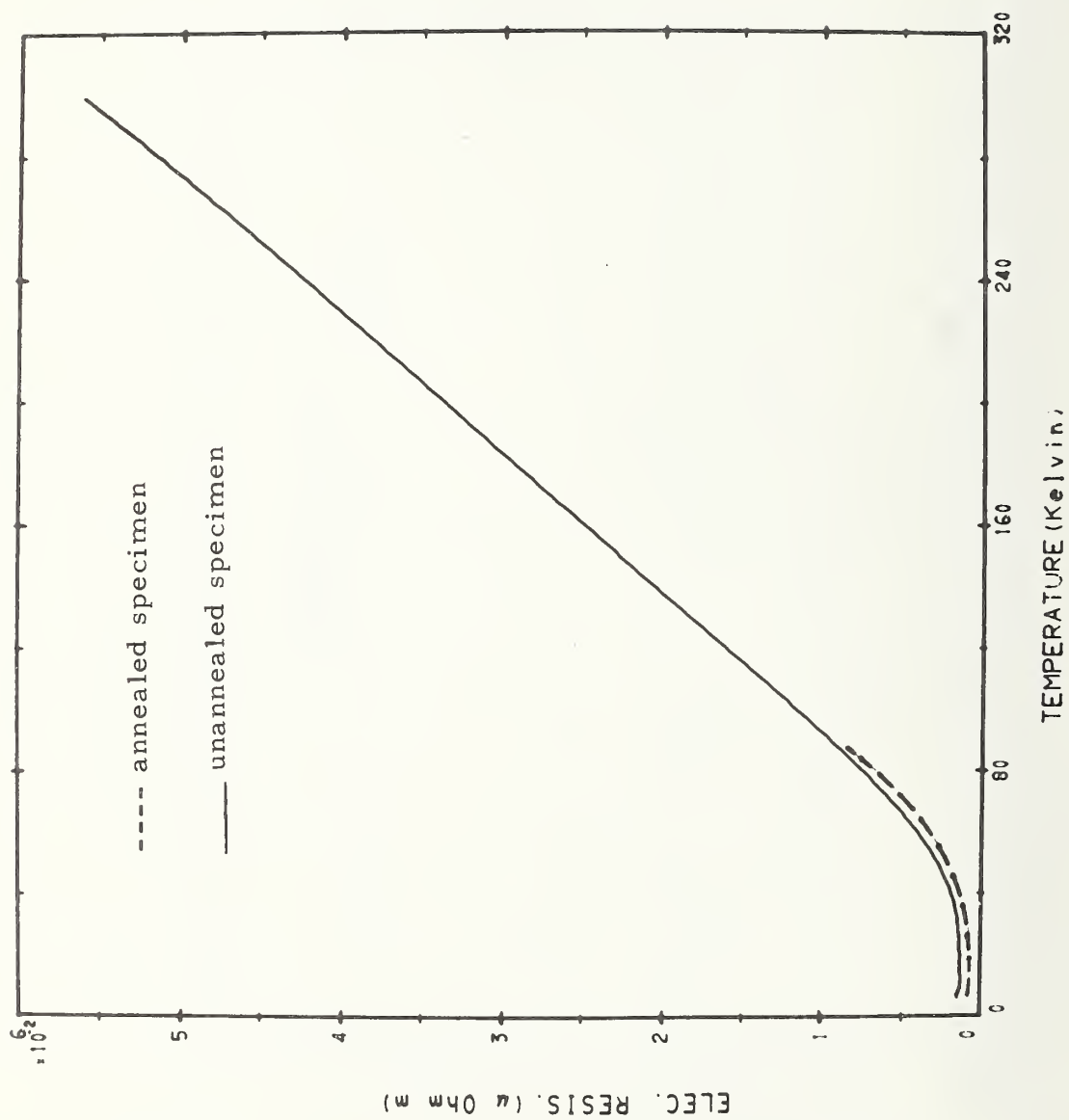


Figure 8. Electrical resistivity of NBS sintered tungsten.

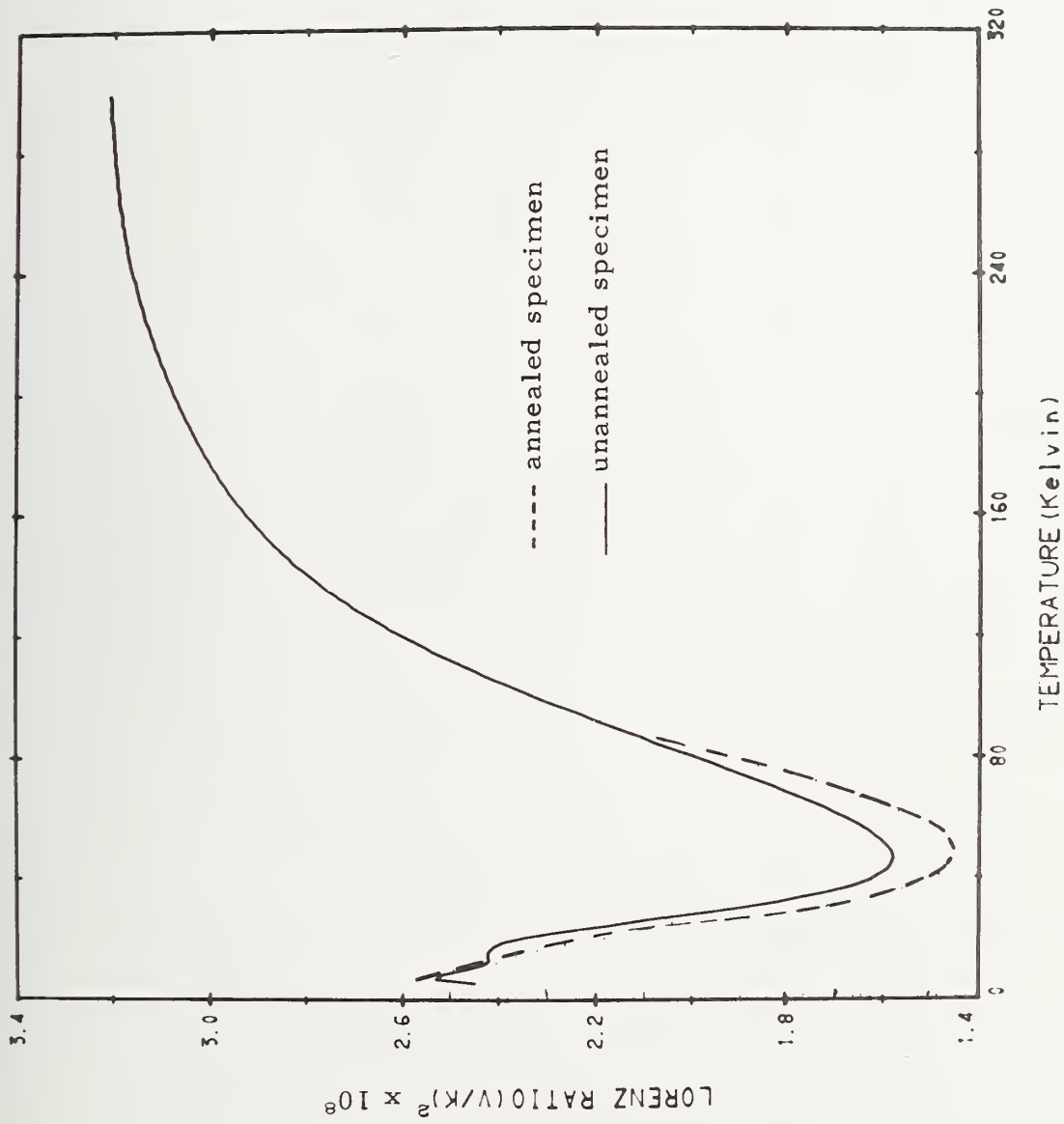


Figure 9. Lorenz ratio of NBS sintered tungsten.

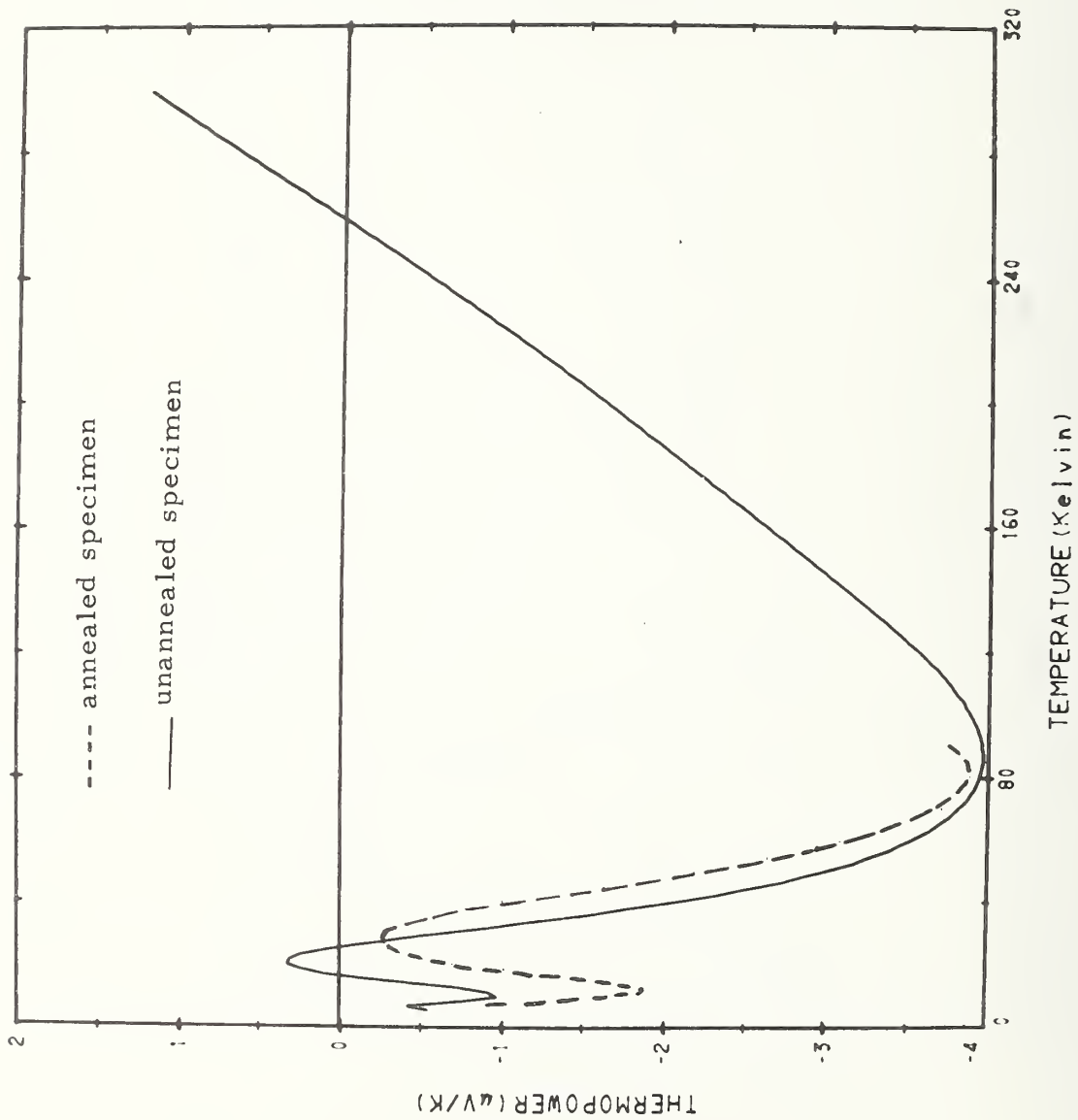


Figure 10. Thermopower of NBS sintered tungsten.

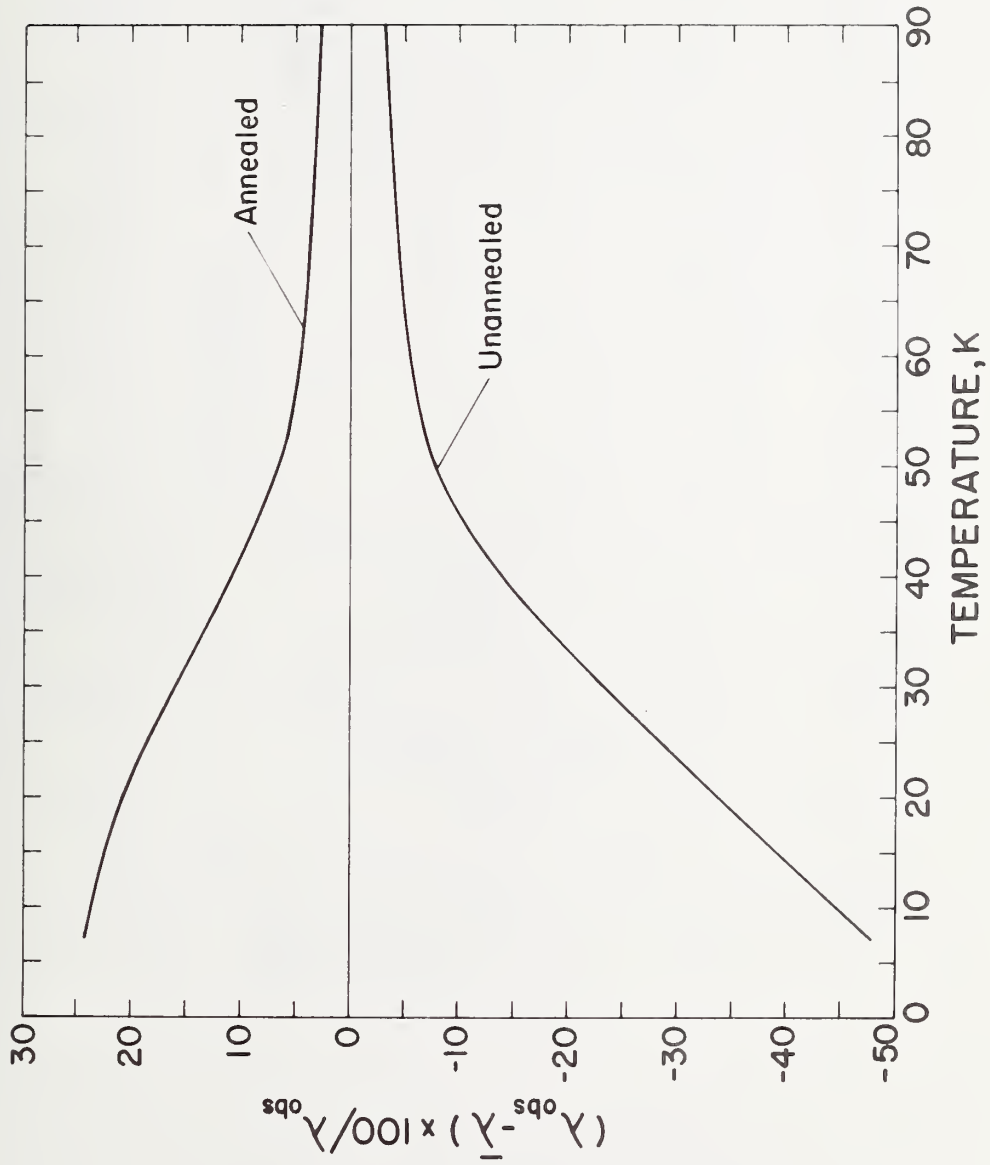


Figure 11. Thermal conductivity differences between annealed and unannealed specimens

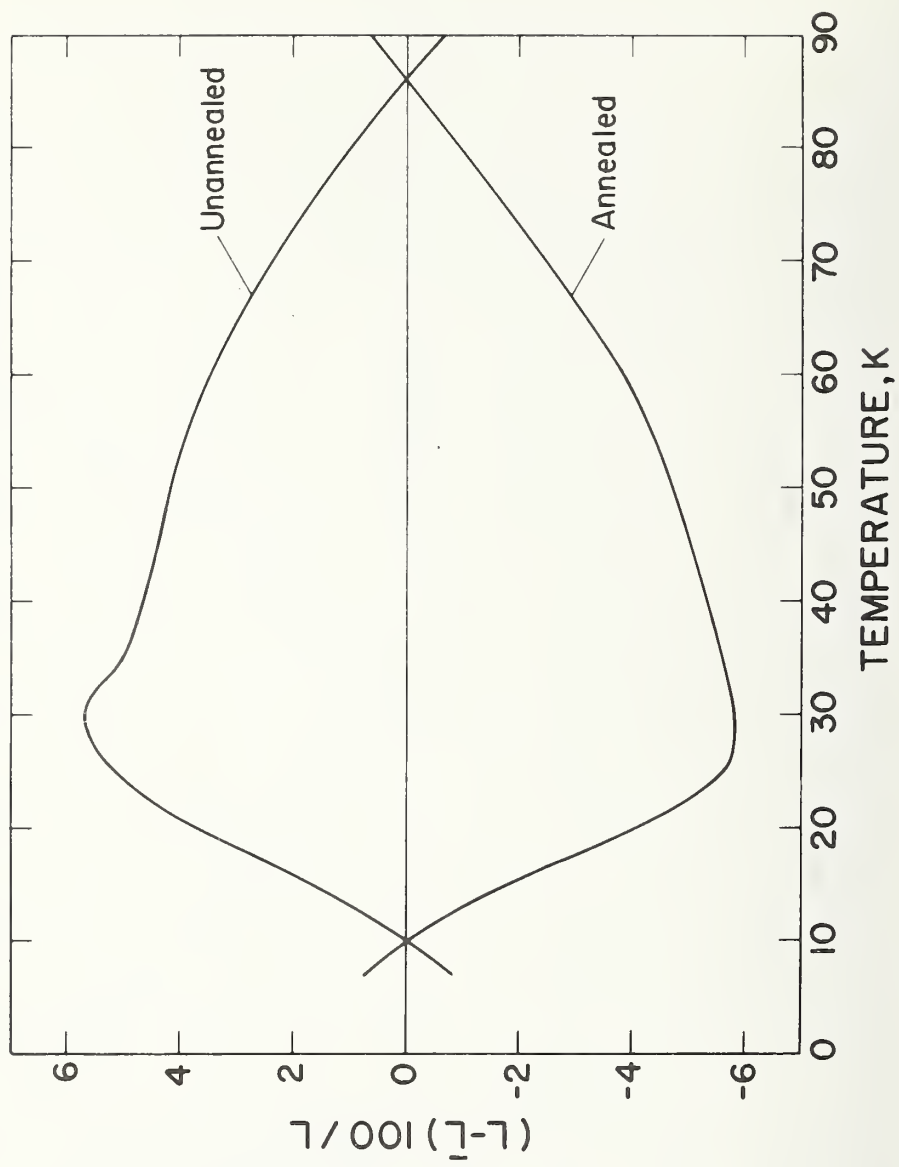


Figure 12. Lorenz ratio difference between annealed and unannealed specimens

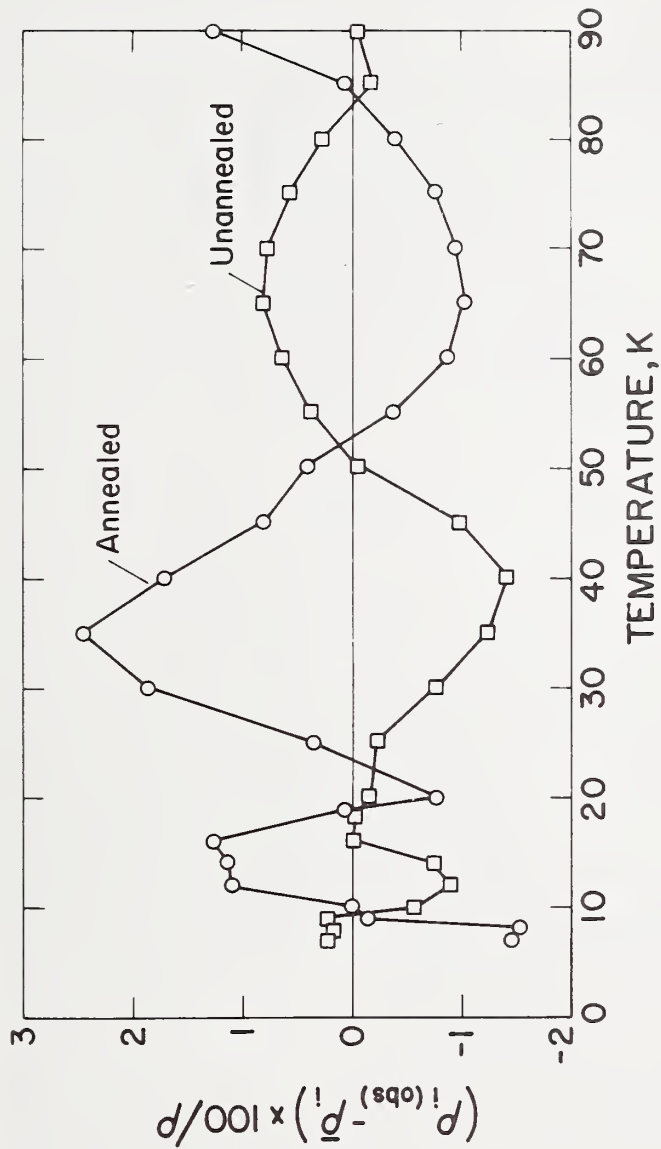


Figure 13. Deviations of intrinsic resistivities (Matthiessen's rule deviations) as computed from data for annealed and unannealed tungsten specimens.

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<p>16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)</p> <p>Thermal conductivity, electrical resistivity, Lorenz ratio, and thermopower data are reported for two specimens of NBS sintered tungsten for temperatures from 6 to 280K. Variability of this tungsten was studied by means of electrical resistivity and residual resistivity measurements on 39 specimens. These data indicate a material variability of about $\pm 10\%$ in thermal conductivity at helium temperatures. Above 90K variation in thermal conductivity is only about $\pm 1\%$. To reduce the uncertainty caused by specimen variation at low temperatures, characterization by residual electrical resistivity data is described. By this procedure the low temperature uncertainty is reduced to about $\pm 3\%$.</p>			
<p>17. KEY WORDS (Alphabetical order, separated by semicolons)</p> <p>Cryogenics; electrical resistivity; Lorenz ratio; Seebeck effect; standard reference material; thermal conductivity; transport properties; tungsten.</p>			
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