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THERMAL CONDUCTIVITY STANDARD REFERENCE MATERIALS

FROM 4 TO 300 K: II. OSRM IRON-1265

J. G. Hust and L. L. Sparks



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THERMAL CONDUCTIVITY STANDARD REFERENCE MATERIALS

FROM 4 TO 300K: II. OSRM IRON-1265

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THERMAL CONDUCTIVITY STANDARD REFERENCE
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ABSTRACT

Thermal conductivity, electrical resistivity, Lorenz ratio, and thermopower data are reported for a specimen of OSRM iron-1265 for temperatures from 4 to 300 K. Variability of this iron was studied by means of electrical residual resistivity ratio measurements on 63 specimens. This study showed that with a two-hour anneal at 1000°C one can expect a thermal conductivity standard reference material which has variability of less than 1% in thermal conductivity.

KEY WORDS

Cryogenics, electrical resistivity, iron, Lorenz ratio, Seebeck effect, 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.

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] Another phase of this program, to establish standard reference data on several standard reference materials has begun. We intend to measure several specimens of materials which appear to be useful as standards. For some materials, material variability may be so great that only standard specimens (not standard materials) will be useful. 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 will result in more accurate and more permanent transport property data for technically important solids.

This paper contains the results of our measurements on the transport properties of an iron supplied by the National Bureau of Standards, Office of Standard Reference Materials (OSRM). This iron is designated as OSRM iron-1265. OSRM iron-1265 was investigated

primarily to find a material similar to Armco iron* but less variable.

2. Apparatus and Data Analysis

The apparatus is based on the axial one-dimensional heat flow method. The specimen is a cylindrical rod 3.6 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 is given by Hust, et al.[1]

3. Specimen Characterization

Density as measured by air and water weighings is 7.867 g/cm^3 . Rockwell hardness and grain size are B23.5 and 0.0507 mm respectively. Each of these values is for the material in the annealed state as described in the following discussion. The composition of OSRM iron-1265 is as follows:

* 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 recommendation by NBS. Armco iron is a registered trade name of a commercially pure iron produced by Armco Steel Corporation.

<u>Element</u>	<u>%</u>	<u>Element</u>	<u>ppm</u>
C	.010	B	1.5
Mn	.008	Pb	.3
P	.002	Zr	.4
S	.008	Sb	.5
Si	.013	Bi	.1
Cu	.006	Ag	.02
Ni	.037	Ca	.4
Cr	.007	Mg	<.2
V	.0005	Se	<.02
Mo	.005	Te	<.05
W	.00005	Zn	2
Co	.007	O ₂	60
Ti	.004	N ₂	10
As	.003	Ge	10
Sn	.0002		
Al	.002	H ₂	~ 1
Nb	<.0001	Ce	.02
Ta	<.001	La	.01
		Pr	<.01

An extensive resistivity variability study was conducted on OSRM iron-1265, the object being to determine if it could be heat treated in such manner that the thermal conductivity would be the same for each specimen. This was achieved with a 2-hour, 1000°C anneal in either a vacuum or helium atmosphere. The results of this study are shown as residual resistivity ratios in table 1. The ratio given is resistivity at 273.15 K to resistivity at 4 K. Specimens labeled C2T, A6L, C5L, ALL, and A5T were obtained from 1/4" diameter rods; the remaining specimens were machined from 1-1/4" rods. Based on the 63 residual resistivity ratio measurements made on these specimens in various stages of heat treatment, the following is concluded: The large 1-1/4" diameter specimens are significantly different in residual resistivity

ratio from the smaller 1/4" diameter specimens in the as received condition. The ratio of the small rods is 22.01 ± 0.20 while the ratio of the larger rods is 19.52 ± 0.44 .

Various heat treatments were tried to remove the differences in ratio of the two sets of rods. After 500°C for 1 hour the ratios increased but were still different (small rods = 23.53 ± 0.20 ; large rods = 22.14 ± 0.34). Raising the temperature to 1000°C for 2 hours produced rods which are indistinguishable, (small rods = 23.39 ± 0.28 ; large rods = 23.29 ± 0.20 ; all rods = 23.33 ± 0.24). The variation shown is $2s$, where s is the estimated standard deviation, and includes material and measurement variability. In order to study the possibility of a change in these ratios with age, one set of rods was measured after about 50 days from the 1000°C treatment; no significant change was detected (ratio = 23.40 ± 0.20). It was also believed that aging could be simulated by heating to 400°C for $2\frac{1}{2}$ days; however, this changed the ratio to 24.94 ± 0.26 with no difference between the large and small rods. This change cannot be explained at the present time.

These measurements show that OSRM iron-1265 can be used as a thermal conductivity standard below room temperature with a variability of about 1% if annealed at 1000°C for 2 hours. We plan to measure some of these specimens from time to time during the next year to determine the effect of long term aging, i. e., more than 50 days.

4. Results

The transport properties of OSRM iron-1265, specimen A5T, were measured in the thermal conductivity apparatus. These data are presented in tables 2 and 3.

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 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 4. 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 5 through 7 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 8 and in figures 4 through 7.

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 300 K, decreasing as T^4 to 0.70% at 200 K, 0.70% from 200 K to 50 K, increasing inversely with tem- perature to 1.5% at 4 K.
electrical resistivity:	0.25%
thermopower:	0.5% + 0.2 $\mu\text{V}/\text{K}$ at 4 K, 0.2% + 0.05 $\mu\text{V}/\text{K}$ at 30 K, and 0.1% + 0.03 $\mu\text{V}/\text{K}$ 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 iron is purer than the Armco iron previously measured. [2] The residual resistance ratio is near 23 compared to 13 for Armco iron. Also the Lorenz ratio shows a more pronounced dip at 65 K as is expected for a more pure material. A preliminary examination of the intrinsic resistivity, ρ_i , computed from Mathiessen's rule reveals a dependence of ρ_i on ρ_0 . An attempt will be made in the future to correlate both the Lorenz ratios and apparent intrinsic resistivity changes with the residual resistivity.

6. Acknowledgments

We wish to thank R. E. Michaelis of NBS, OSRM for supplying these specimens along with helpful discussions. This measurement program has been carried out under the helpful guidance of R. L. Powell.

7. 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 Standard Reference Materials from 4 to 300 K. I. Armco Iron," NBS Report 9740 (1969).
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 2

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 ($^{\circ}\text{C}$), 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 3

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 ($^{\circ}\text{C}$), 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 5, 6, and 7

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

Table 1. Residual resistivity ratio (ρ_{273K}/ρ_{4K}) of OSRM iron-1265

Specimen	Ratio					
	As received	500°C 1 hr	500°C 8 hr	1000°C 2 hr	400°C 2½ days	Aging 50 days
C2T	21.97(a)	23.53	24.12	23.31(e)	24.84	25.00
A6L	22.16	-----	-----	23.22(f)	24.85	24.97
C5L	21.94	-----	-----	23.40(f)	-----	23.47
A1L	22.04	-----	-----	23.59(c)	-----	23.52
A5T	22.03(b)	-----	-----	23.42(f)	-----	23.42
2A-1-1	19.35	21.96	22.32	23.47(e)	25.12	25.24
2A-1-2	19.50	-----	-----	23.31(c)	-----	23.35
2A-1-3	19.30	-----	-----	-----	-----	-----
2A-1-4	19.38	-----	-----	23.27(f)	-----	-----
2A-3-1	19.77	21.83	22.25	23.20(e)	24.94	25.01
2A-3-2	19.92	-----	-----	23.20(c)	-----	23.25(d)
2A-3-3	19.73	-----	-----	-----	-----	-----
2A-3-4	19.93	-----	-----	-----	-----	-----
2C-1-1	19.42	21.70	22.00	23.23(e)	-----	23.44
2C-1-2	19.12	-----	-----	23.41(c)	-----	23.40
2C-1-3	19.46	-----	-----	-----	-----	-----
2C-1-4	19.56	-----	-----	-----	-----	-----
2C-3-1	19.34	21.93	21.99	23.27(e)	-----	23.40
2C-3-2	19.49	-----	-----	-----	-----	-----
2C-3-3	19.57	-----	-----	-----	-----	-----
2C-3-4	19.40	-----	-----	-----	-----	-----

- (a) repeat measurement = 21.91
 (b) ratio of A5T thermal conductivity specimen = 21.89
 (c) these were heat treated in vacuum, the remaining were heated to 1000°C in a helium atmosphere (1 atm pressure).
 (d) repeat measurements = 23.39, 23.31
 (e, f) these were done in separate heat treatments to detect reproducibility of heat treatment

Table 2. Basic semi-processed temperature gradient data for OSRM iron-1265

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28.70 950 8						
15.69	17.67	21.65	25.64	29.07	32.79	36.42
-0.08	200.00	13.00				39.70
695129	6.1500	-0.00	-0.0	636.3	21.2	1.0
THERMOCOUPLE TEMPERATURES						
5.000	5.313	5.601	5.880	6.141	6.397	6.639
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
4.2627-005		4.027		6.4900-005		6.880

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28.70 1045 9						
28.95	37.86	46.15	54.32	61.65	69.04	76.26
-0.07	200.00	13.02				82.85
1104174	9.8000	-0.00	-0.0	636.2	21.6	1.0
THERMOCOUPLE TEMPERATURES						
6.112	6.747	7.306	7.841	8.334	8.804	9.253
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
1.0821-002		4.027		6.5080-005		9.681

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28.70 1233 10						
60.76	78.59	94.86	110.23	124.13	137.70	150.77
-0.00	200.00	13.06				162.90
1746102	15.5000	-0.00	-0.0	636.4	22.0	1.0
THERMOCOUPLE TEMPERATURES						
8.258	9.409	10.417	11.347	12.196	13.000	13.764
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
2.7065-002		4.027		6.5290-005		14.491

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28.70 1345 11						
125.22	159.45	189.72	217.82	243.03	267.20	290.26
1.14	200.00	13.20				311.88
2836895	25.1800	-0.00	-0.0	636.4	22.0	1.0
THERMOCOUPLE TEMPERATURES						
12.245	14.283	16.049	17.674	19.150	20.548	21.880
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
7.1433-002		4.027		6.6010-005		23.154

Table 2 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSMH JUNE 1 1449 13							
19.62	27.96	36.43	44.82	52.56	60.50	68.49	76.00
0.77	200.00	13.34					
172614	15.3200	219.75	2.0	650.4	22.0	2.0	2.0
THERMOCOUPLE TEMPERATURES							
20.943	21.439	21.929	22.411	22.873	23.334	23.793	24.245
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
2.6444-002	19.827			6.6710-005			

THERMAL CONDUCTIVITY DATA FOR IRON OSMH JUNE 1,70 1626 14							
39.72	56.85	73.70	90.16	105.46	120.81	136.06	150.63
2.68	200.00	13.50					
252866	22.4400	220.10	2.0	650.0	22.1	2.0	2.0
THERMOCOUPLE TEMPERATURES							
22.122	23.132	24.113	25.071	25.900	26.800	27.772	28.646
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
5.6748-002	19.837			6.7490-005			

THERMAL CONDUCTIVITY DATA FOR IRON OSMH JUNE 2,70 1032 15							
83.34	117.70	150.73	182.64	212.69	242.59	272.40	301.47
12.16	200.00	14.02					
3758734	33.3400	224.46	2.0	648.6	21.7	2.0	2.0
THERMOCOUPLE TEMPERATURES							
24.789	26.819	28.766	30.652	32.453	34.236	36.014	37.771
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
1.2532-001	19.956			7.0110-005			

THERMAL CONDUCTIVITY DATA FOR IRON OSMH JUNE 2,70 16							
148.37	208.24	266.01	322.71	378.23	434.69	493.12	552.71
52.77	200.00	15.67					
5220315	46.2700	227.48	2.0	649.0	22.2	2.0	2.0
THERMOCOUPLE TEMPERATURES							
28.700	32.269	35.720	39.116	42.458	45.825	49.279	52.793
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
2.4154-001	20.037			7.8325-005			

Table 2 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2, 70 1509 17						
250.48	352.85	456.98	556.07	683.03	809.79	949.81 1102.32
262.39	200.00	22.62				
7055324	62.4600	232.28	2.0	648.2	23.0	2.0
THERMOCOUPLE TEMPERATURES						
34.913	41.067	47.276	53.688	60.463	67.656	75.447 83.791
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
4.4068-001		20.164				

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2, 70 1620 18						
250.50	352.90	456.94	565.92	682.97	809.69	949.83 1102.32
262.37	200.00	22.62				
7055354	62.4600	232.19	2.0	648.9	23.0	2.0
THERMOCOUPLE TEMPERATURES						
34.911	41.068	47.271	53.677	60.458	67.648	75.446 83.789
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
4.4068-001		20.162				

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25, 70 1403 2						
26.82	43.14	59.69	76.35	93.17	110.13	127.26 144.61
58.70	150.00	27.17				
2326217	20.6000	9287.54	2.0	635.4	21.9	3.0
THERMOCOUPLE TEMPERATURES						
77.419	78.315	79.221	80.129	81.046	81.967	82.899 83.837
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
4.7920-002		75.949				

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25, 70 1736 3						
46.76	79.53	113.08	147.13	181.82	217.02	253.02 289.64
128.77	150.00	30.14				
3267955	28.9300	9298.25	2.0	635.6	22.6	3.0
THERMOCOUPLE TEMPERATURES						
78.561	80.353	82.178	84.022	85.895	87.785	89.715 91.666
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE						
9.4542-002		75.998				

Table 2 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26.70 918 4							
96.02	162.85	232.40	304.07	378.19	454.24	533.07	613.92
305.82	150.00	37.39					
4570467	40.5000	9326.50	2.0	633.5	21.0	3.0	
THERMOCOUPLE TEMPERATURES							
81.377	84.998	88.737	92.557	96.478	100.468	104.576	108.755
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
1.8543-001		76.127		2.4929-004			

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26.70 1310 5							
172.59	299.68	435.11	577.24	726.56	881.50	1043.58	1210.93
688.22	150.00	51.70					
6143712	54.2900	9364.48	2.0	635.8	22.2	3.0	
THERMOCOUPLE TEMPERATURES							
85.633	92.492	99.634	107.025	114.690	122.544	130.669	138.961
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
3.3354-001		76.300		3.4465-004			

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26.70 1655 6							
330.28	586.70	867.84	1168.22	1487.29	1820.98	2171.69	2555.71
1594.28	150.00	85.71					
8329310	73.4400	9416.20	2.0	636.4	22.9	3.0	
THERMOCOUPLE TEMPERATURES							
94.341	107.735	122.073	137.065	152.681	168.720	185.318	202.309
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
6.1170-001		76.535		5.7139-004			

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 3 1600 19							
66.76	123.84	181.70	239.60	297.90	356.29	415.41	474.74
299.87	158.00	148.08					
3296055	29.0500	54417.35	2.0	631.8	22.1	4.0	
THERMOCOUPLE TEMPERATURES							
195.865	198.523	201.211	203.897	206.596	209.294	212.020	214.752
HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE							
9.5750-002		192.750		9.8723-004			

Table 2 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE J 1027 20
 137.08 254.38 373.98 494.34 616.16 739.78 863.54 989.30
 613.14 150.00 163.55
 4709392 41.4500 34445.90 2.0 631.6 21.0 4.0
 THERMOCOUPLE TEMPERATURES
 199.275 204.717 210.245 215.788 221.378 226.986 232.674 238.391
 HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE
 1.9520-001 132.887 1.0903-003

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4.70 1600 21
 245.61 470.82 702.44 937.44 1177.17 1420.17 1669.09 1921.62
 1148.57 150.00 191.69
 6485870 57.0400 34523.00 2.0 630.6 22.1 4.0
 THERMOCOUPLE TEMPERATURES
 204.678 215.070 225.687 236.395 247.262 258.222 269.403 280.710
 HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE
 3.6395-001 193.256 1.2779-003

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 5.70 1405 22
 71.22 135.32 200.40 265.50 331.01 396.64 463.24 530.07
 281.31 100.00 164.91
 3297690 29.0000 50978.00 2.0 630.6 21.9 5.0
 THERMOCOUPLE TEMPERATURES
 276.512 279.374 282.279 285.196 288.111 291.041 294.014 296.998
 HEATER POWER REFERENCE TEMPERATURE SPECIMEN RESISTANCE
 9.5633-002 273.316 1.6491-003

Thermocouple Positions 2.2202 4.7594 7.2989 9.8382
 (cm from floating sink) 12.379 14.919 17.458 19.998

Specimen diameters (cm) 0.36627 0.36632 0.36619 0.36609
 between thermocouples 0.36619 0.36606 0.36634
 starting from floating sink

Table 3. Basic semi-processed isothermal electrical resistivity data for OSRM iron-1265

ISOTHERMAL RESISTIVITY DATA FOR OSRM IRONMAY 28.70 915 7					
-0.00	636.40	21.50	-0.00	1.00	200.00
REFERENCE TEMPERATURE	SPECIMEN RESISTANCE	SPECIMEN RESISTANCE	SPECIMEN TEMPERATURE	SPECIMEN TEMPERATURE	SPECIMEN TEMPERATURE
4.027	6.4950-005	4.422	12.99	4.96	

ISOTHERMAL RESISTIVITY DATA FOR OSRM IROJUNE 1.70 1319 12					
219.37	649.00	22.00	2.00	2.00	200.00
REFERENCE TEMPERATURE	SPECIMEN RESISTANCE	SPECIMEN RESISTANCE	SPECIMEN TEMPERATURE	SPECIMEN TEMPERATURE	SPECIMEN TEMPERATURE
19.917	6.6160-005	19.853	13.23	0.63	

ISOTHERMAL RESISTIVITY DATA FOR IRON OSRM MAY 25.70 1147 1					
9273.15	634.70	20.90	2.00	3.00	100.00
REFERENCE TEMPERATURE	SPECIMEN RESISTANCE	SPECIMEN RESISTANCE	SPECIMEN TEMPERATURE	SPECIMEN TEMPERATURE	SPECIMEN TEMPERATURE
75.884	1.6282-004	76.128	16.28	4.42	

Table 4. Parameters in equations 1, 2, and 3 for OSRM iron-1265

COEFFICIENTS FOR		
THERMAL	ELECTRICAL	THERMPOWER
CONDUCTIVITY	RESISTIVITY	
-1.48463068+001	1.52995843-005	-4.42050903+002
6.93779265+001	-6.57221842-005	2.91385157+003
-1.13470636+002	1.28083500-004	-7.88597272+003
1.01420592+002	-1.50027718-004	1.14395105+004
-5.68004853+001	1.17942860-004	-9.71586106+003
2.10770015+001	-6.57740194-005	4.92662120+003
-5.27537674+000	2.67952461-005	-1.44644001+003
8.81839451-001	-8.08115141-006	2.26661972+002
-9.43950407-002	1.80581011-006	-1.47175223+001
5.85191930-003	-2.95519976-007	
-1.59785857-004	3.44469418-008	
	-2.70952664-009	
	1.28939040-010	
	-2.80388287-012	

Table 5. Thermal conductivity deviations for OSRM iron-1265.

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 950 8						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
5.156	0.313	3.28+001	3.31+001	-0.7		
5.457	0.289	3.56+001	3.52+001	1.2		
5.741	0.279	3.68+001	3.71+001	-0.6		
6.011	0.260	3.96+001	3.89+001	1.8		
6.269	0.256	4.01+001	4.05+001	-1.0		
6.518	0.242	4.25+001	4.22+001	0.8		
6.759	0.241	4.26+001	4.37+001	-2.8		

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 1045 9						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
6.430	0.635	4.11+001	4.16+001	-1.3		
7.027	0.559	4.66+001	4.55+001	2.5		
7.574	0.534	4.88+001	4.90+001	-0.4		
8.087	0.493	5.30+001	5.23+001	1.3		
8.569	0.470	5.55+001	5.54+001	0.1		
9.028	0.449	5.81+001	5.84+001	-0.5		
9.467	0.428	6.09+001	6.12+001	-0.6		

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 1233 10						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
8.833	1.151	5.67+001	5.72+001	-0.8		
9.913	1.008	6.47+001	6.41+001	0.9		
10.882	0.930	7.02+001	7.03+001	-0.2		
11.772	0.850	7.69+001	7.59+001	1.2		
12.598	0.804	8.12+001	8.11+001	0.1		
13.382	0.764	8.55+001	8.59+001	-0.5		
14.128	0.727	8.97+001	9.04+001	-0.8		

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 1345 11						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
13.264	2.038	8.45+001	8.52+001	-0.9		
15.166	1.766	9.75+001	9.66+001	0.9		
16.862	1.625	1.06+002	1.06+002	-0.4		
18.412	1.475	1.17+002	1.15+002	1.7		
19.849	1.398	1.23+002	1.22+002	0.6		
21.214	1.332	1.29+002	1.29+002	0.1		
22.517	1.274	1.35+002	1.35+002	-0.1		

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 1 1449 13						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
21.191	0.496	1.28+002	1.29+002	-0.6		
21.684	0.489	1.30+002	1.31+002	-1.0		
22.170	0.483	1.32+002	1.34+002	-1.3		
22.642	0.462	1.38+002	1.36+002	1.6		
23.104	0.460	1.39+002	1.38+002	0.4		
23.563	0.459	1.39+002	1.40+002	-0.7		
24.019	0.452	1.41+002	1.42+002	-0.6		

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 1 70 1626 14						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
22.627	1.010	1.35+002	1.36+002	-0.3		
23.623	0.981	1.39+002	1.40+002	-0.5		
24.592	0.958	1.43+002	1.44+002	-0.9		
25.525	0.909	1.51+002	1.48+002	1.9		
26.430	0.900	1.52+002	1.51+002	0.6		
27.326	0.892	1.54+002	1.54+002	-0.3		
28.209	0.874	1.56+002	1.57+002	-0.2		

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2, 70 1032 15						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
25.804	2.030	1.49+002	1.49+002	-0.0		
27.792	1.947	1.55+002	1.56+002	-0.3		
29.709	1.887	1.60+002	1.61+002	-0.5		
31.553	1.801	1.68+002	1.65+002	1.7		
33.345	1.783	1.69+002	1.68+002	0.7		
35.125	1.777	1.70+002	1.71+002	-0.3		
36.892	1.757	1.72+002	1.72+002	-0.2		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2, 70 16						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
30.485	3.569	1.63+002	1.63+002	0.2		
33.995	3.451	1.69+002	1.69+002	-0.4		
37.418	3.396	1.71+002	1.73+002	-0.6		
40.787	3.342	1.74+002	1.73+002	0.7		
44.141	3.366	1.73+002	1.72+002	0.6		
47.552	3.454	1.69+002	1.69+002	-0.3		
51.036	3.514	1.66+002	1.65+002	0.2		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2, 70 1509 17						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
37.990	6.154	1.73+002	1.73+002	-0.2		
44.172	6.209	1.71+002	1.72+002	-0.6		
50.482	6.412	1.66+002	1.66+002	-0.1		
57.076	6.775	1.57+002	1.57+002	0.0		
64.060	7.193	1.48+002	1.47+002	0.6		
71.552	7.791	1.36+002	1.37+002	-0.1		
79.619	8.344	1.27+002	1.27+002	0.1		

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2, 70 1620 18						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
37.989	6.156	1.73+002	1.73+002	-0.2		
44.170	6.204	1.71+002	1.72+002	-0.5		
50.474	6.406	1.66+002	1.66+002	-0.1		
57.067	6.780	1.57+002	1.57+002	-0.1		
64.053	7.191	1.48+002	1.47+002	0.6		
71.547	7.798	1.36+002	1.37+002	-0.2		
79.617	8.343	1.27+002	1.27+002	0.1		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25, 70 1403 2						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
77.867	0.896	1.29+002	1.29+002	-0.1		
78.768	0.906	1.27+002	1.28+002	-0.5		
79.675	0.908	1.27+002	1.27+002	0.1		
80.588	0.917	1.26+002	1.26+002	-0.0		
81.507	0.921	1.25+002	1.25+002	0.2		
82.433	0.932	1.24+002	1.24+002	-0.1		
83.368	0.938	1.23+002	1.23+002	-0.2		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25, 70 1736 3						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
79.457	1.791	1.27+002	1.27+002	-0.1		
81.265	1.826	1.25+002	1.25+002	-0.5		
83.100	1.844	1.24+002	1.24+002	0.0		
84.959	1.873	1.22+002	1.22+002	0.0		
86.840	1.890	1.21+002	1.20+002	0.4		
88.750	1.929	1.18+002	1.18+002	-0.2		
90.690	1.951	1.17+002	1.17+002	-0.1		

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26, 70 918 4						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
83.188	3.621	1.23+002	1.23+002	-0.1		
86.868	3.739	1.19+002	1.20+002	-0.5		
90.647	3.820	1.17+002	1.17+002	0.1		
94.518	3.921	1.14+002	1.14+002	0.1		
98.473	3.990	1.12+002	1.11+002	0.6		
102.522	4.108	1.09+002	1.09+002	-0.1		
106.665	4.178	1.07+002	1.07+002	0.1		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26, 70 1310 5						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
89.093	6.799	1.18+002	1.18+002	0.0		
96.063	7.142	1.13+002	1.13+002	-0.4		
103.329	7.391	1.09+002	1.09+002	0.2		
110.857	7.665	1.05+002	1.05+002	0.2		
118.617	7.854	1.02+002	1.02+002	0.6		
126.606	8.124	9.91+001	9.92+001	-0.2		
134.815	8.293	9.69+001	9.70+001	-0.1		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26, 70 1655 6						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
101.038	13.395	1.10+002	1.10+002	0.2		
114.904	14.338	1.03+002	1.03+002	-0.4		
129.569	14.991	9.84+001	9.84+001	-0.0		
144.873	15.616	9.46+001	9.48+001	-0.2		
160.701	16.039	9.20+001	9.18+001	0.1		
177.019	16.597	8.89+001	8.93+001	-0.4		
193.813	16.991	8.68+001	8.70+001	-0.3		

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 3 1600 19						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
197.194	2.658	8.68+001	8.66+001	0.3		
199.867	2.689	8.58+001	8.62+001	-0.5		
202.554	2.685	8.60+001	8.59+001	0.1		
205.246	2.699	8.56+001	8.56+001	0.0		
207.945	2.698	8.56+001	8.53+001	0.3		
210.657	2.727	8.47+001	8.50+001	-0.3		
213.386	2.731	8.45+001	8.47+001	-0.3		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4 1027 20						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
201.996	5.443	8.64+001	8.60+001	0.5		
207.481	5.528	8.51+001	8.54+001	-0.3		
213.017	5.542	8.49+001	8.48+001	0.2		
218.583	5.590	8.43+001	8.42+001	0.2		
224.182	5.608	8.39+001	8.36+001	0.3		
229.830	5.688	8.28+001	8.31+001	-0.4		
235.533	5.717	8.23+001	8.27+001	-0.5		
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4 70 1600 21						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
209.874	10.393	8.58+001	8.51+001	0.8		
220.379	10.617	8.40+001	8.40+001	-0.0		
231.041	10.708	8.33+001	8.30+001	0.3		
241.829	10.867	8.22+001	8.22+001	0.0		
252.742	10.961	8.14+001	8.14+001	0.0		
263.813	11.181	7.98+001	8.06+001	-0.9		
275.057	11.307	7.88+001	7.97+001	-1.1		

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRH JUNE 5, 70 1405 22						
MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION		
277.943	2.862	8.05+001	7.95+001	1.3		
280.826	2.906	7.93+001	7.92+001	0.1		
285.733	2.907	7.95+001	7.89+001	0.5		
286.648	2.925	7.89+001	7.86+001	0.4		
289.576	2.930	7.87+001	7.85+001	0.5		
292.528	2.973	7.76+001	7.80+001	-0.5		
295.506	2.984	7.72+001	7.76+001	-0.5		

Table 6. Electrical resistivity deviations for OSRM iron-1265.

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
5.987	1.880	6.498-005	6.498-005	0.00
8.026	3.569	6.508-005	6.508-005	-0.00
11.644	6.233	6.529-005	6.529-005	0.01
18.184	10.909	6.601-005	6.602-005	-0.02
22.625	3.302	6.671-005	6.669-005	0.02
25.476	6.524	6.749-005	6.749-005	-0.01
31.460	12.982	7.011-005	7.015-005	-0.05
40.774	24.093	7.833-005	7.826-005	0.08
57.851	48.878	1.131-004	1.131-004	-0.02
57.846	48.877	1.131-004	1.131-004	-0.01
80.601	6.418	1.811-004	1.811-004	0.02
85.009	13.104	2.009-004	2.008-004	0.05
94.698	27.377	2.493-004	2.493-004	0.01
111.341	53.268	3.447-004	3.448-004	-0.03
145.990	107.968	5.714-004	5.713-004	0.02
205.265	18.887	9.872-004	9.872-004	0.00
218.661	39.117	1.090-003	1.090-003	0.01
242.106	76.033	1.278-003	1.278-003	0.01
286.680	20.486	1.649-003	1.649-003	0.00
4.422	0.000	6.495-005	6.495-005	-0.00
19.853	0.000	6.616-005	6.616-005	0.01
76.128	0.000	1.628-004	1.628-004	0.00

Table 7. Thermovoltage deviations for OSRM iron-1265

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
6.880	5.000	-0.08	-0.18	0.10
9.681	6.112	-0.07	0.03	-0.10
14.491	8.258	-0.00	0.00	-0.00
23.154	12.245	1.14	1.05	0.09
24.245	20.943	0.77	0.89	-0.12
28.646	22.122	2.68	2.84	-0.16
37.771	24.789	12.16	12.22	-0.06
52.793	28.700	52.77	52.62	0.15
83.791	34.913	262.39	262.43	-0.04
83.789	34.911	262.37	262.41	-0.03
83.837	77.419	58.70	58.62	0.09
91.666	78.561	128.77	128.73	0.04
108.755	81.377	305.82	305.83	-0.01
138.961	85.693	688.22	688.20	0.02
202.309	94.341	1594.28	1594.28	-0.00
214.752	195.865	299.87	299.93	-0.05
238.391	199.275	613.14	613.13	0.01
280.710	204.678	1148.37	1148.36	0.01
296.998	276.512	281.31	281.33	-0.02

Table 8. Transport properties of OSRM iron-1265

Temp (K)	Thermal Conductivity (Wm ⁻¹ K ⁻¹)	Electrical Resistivity (n ohm m)	Lorenz ratio × 10 ⁸ (V ² /K ²)	Thermo- power (μV/K)
6	38.8	3.867	2.50	-0.06
7	45.3	3.870	2.50	0.02
8	51.8	3.851	2.49	0.04
9	58.2	3.845	2.49	0.04
10	64.7	3.852	2.49	0.04
12	77.4	3.873	2.50	0.08
14	89.7	3.887	2.49	0.15
16	101	3.896	2.47	0.24
18	113	3.905	2.45	0.35
20	123	3.920	2.42	0.46
25	146	3.988	2.33	0.78
30	162	4.098	2.21	1.20
35	171	4.264	2.08	1.75
40	173	4.501	1.95	2.44
45	171	4.836	1.84	3.23
50	167	5.279	1.76	4.09
55	160	5.847	1.70	5.01
60	153	6.542	1.67	5.94
65	145	7.367	1.65	6.88
70	139	8.322	1.65	7.80
75	132	9.379	1.66	8.68
80	127	10.56	1.67	9.52
85	122	11.88	1.70	10.31
90	117	13.27	1.73	11.05
95	114	14.76	1.77	11.74
100	110	16.32	1.80	12.37
110	105	19.69	1.88	13.47
120	101	23.30	1.97	14.37
130	98.3	27.07	2.05	15.10
140	95.8	30.97	2.12	15.67
150	93.8	34.97	2.19	16.10
160	92.0	39.10	2.25	16.41
170	90.3	43.23	2.30	16.63
180	88.9	47.47	2.34	16.76
190	87.5	51.78	2.38	16.82
200	86.2	56.13	2.42	16.81
220	84.0	65.16	2.49	16.64
240	82.3	74.45	2.55	16.31
260	80.8	84.19	2.62	15.83
280	79.3	94.29	2.67	15.23

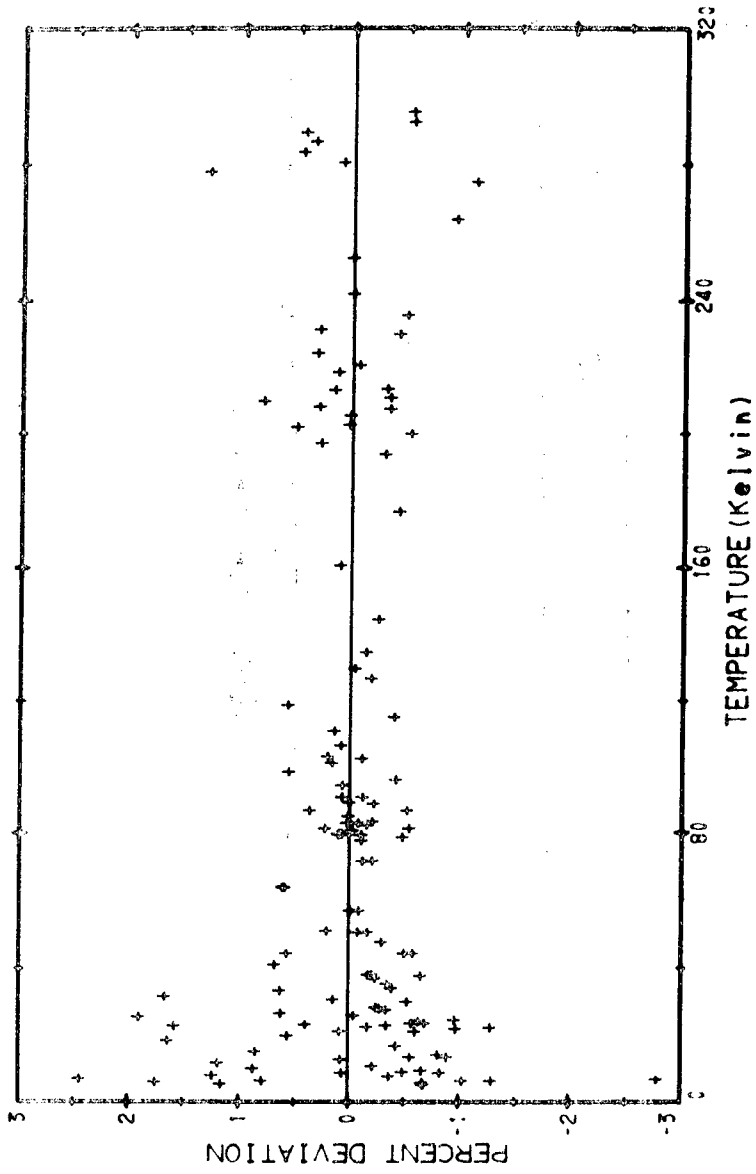


Figure 1. Thermal conductivity deviations for OSRM iron-1265

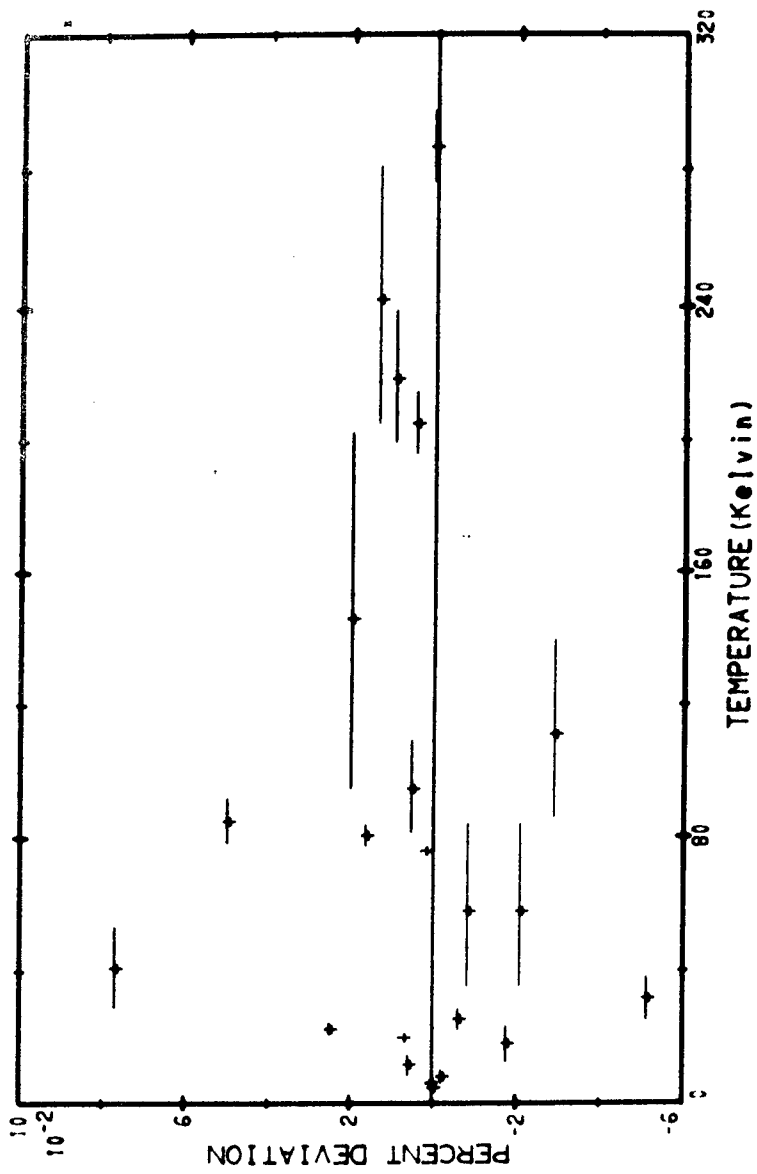


Figure 2. Electrical resistivity deviations for OSRM iron-1265

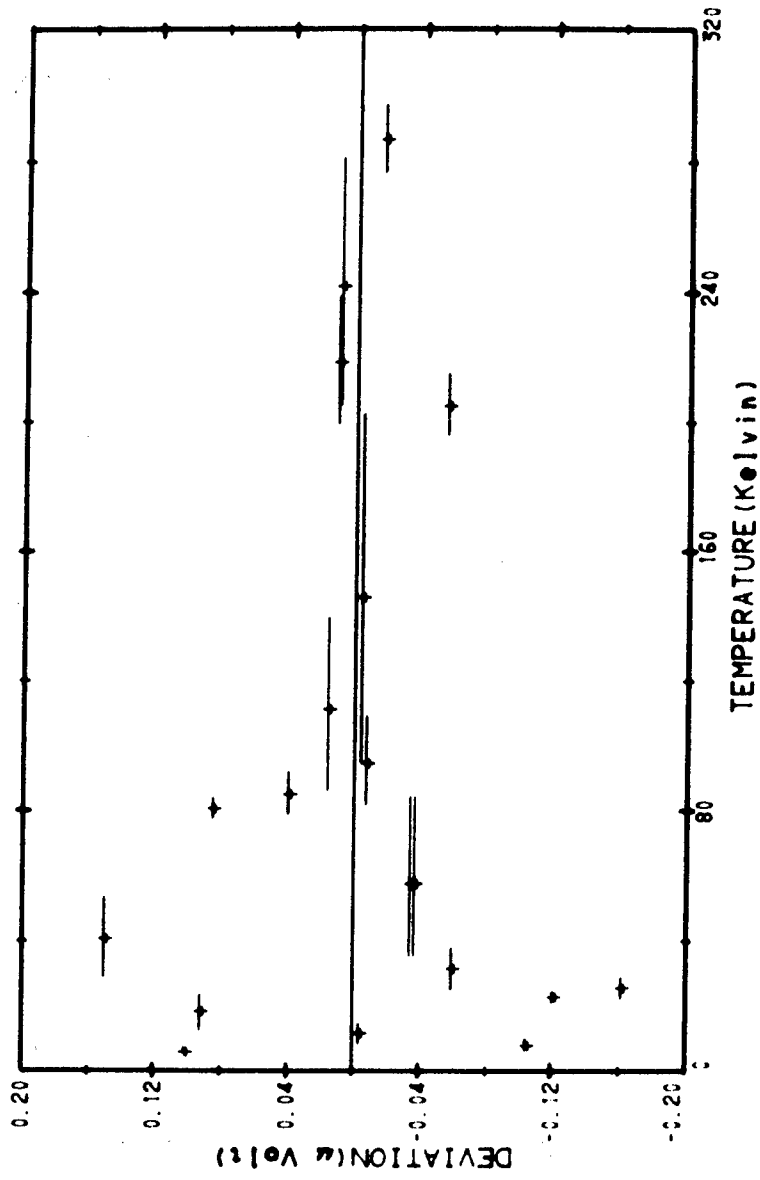


Figure 3. Thermovoltage deviations for OSRM iron-1265

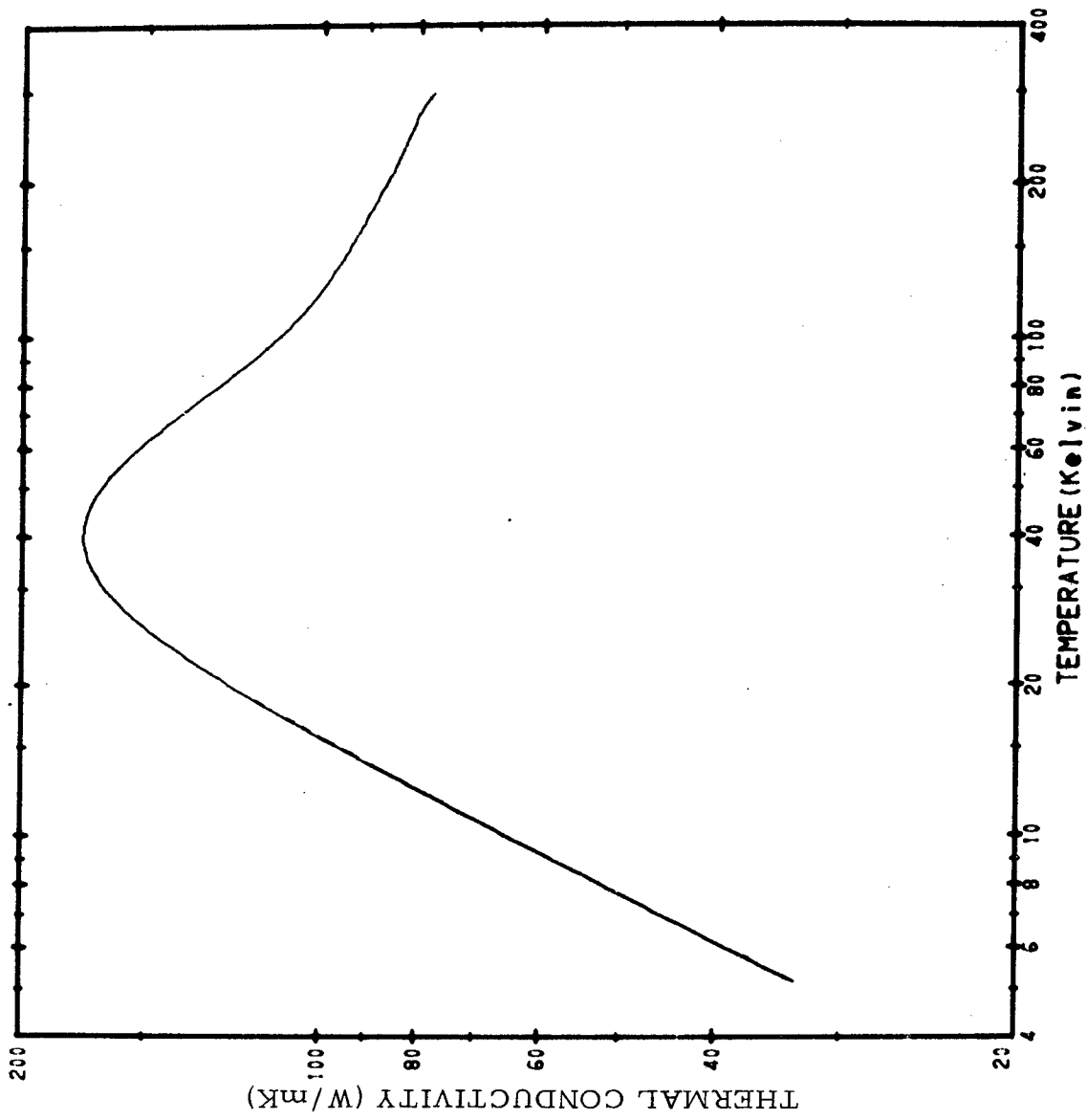


Figure 4. Thermal conductivity of OSRM iron-1265

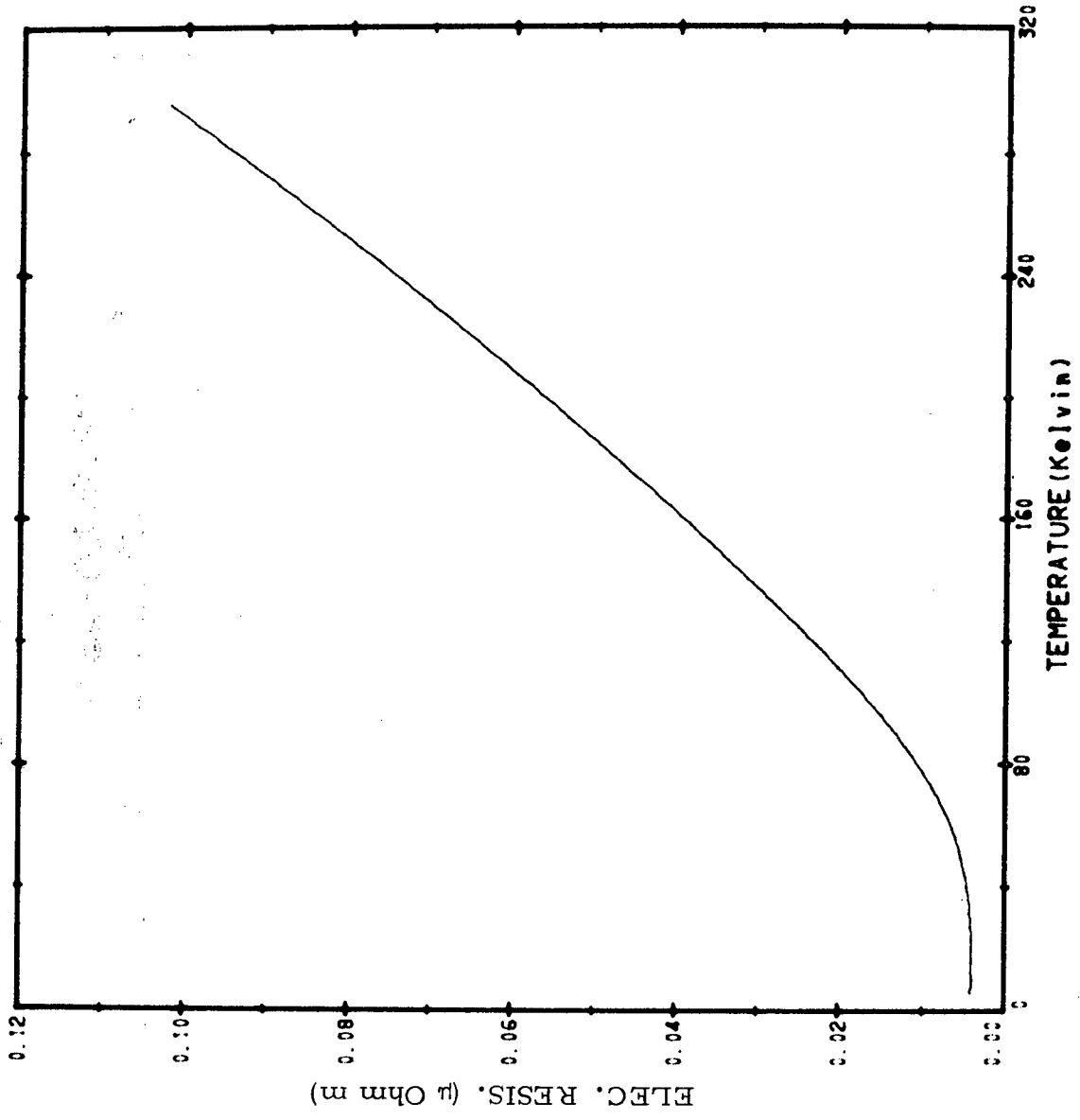


Figure 5. Electrical resistivity of OSRM iron-1265

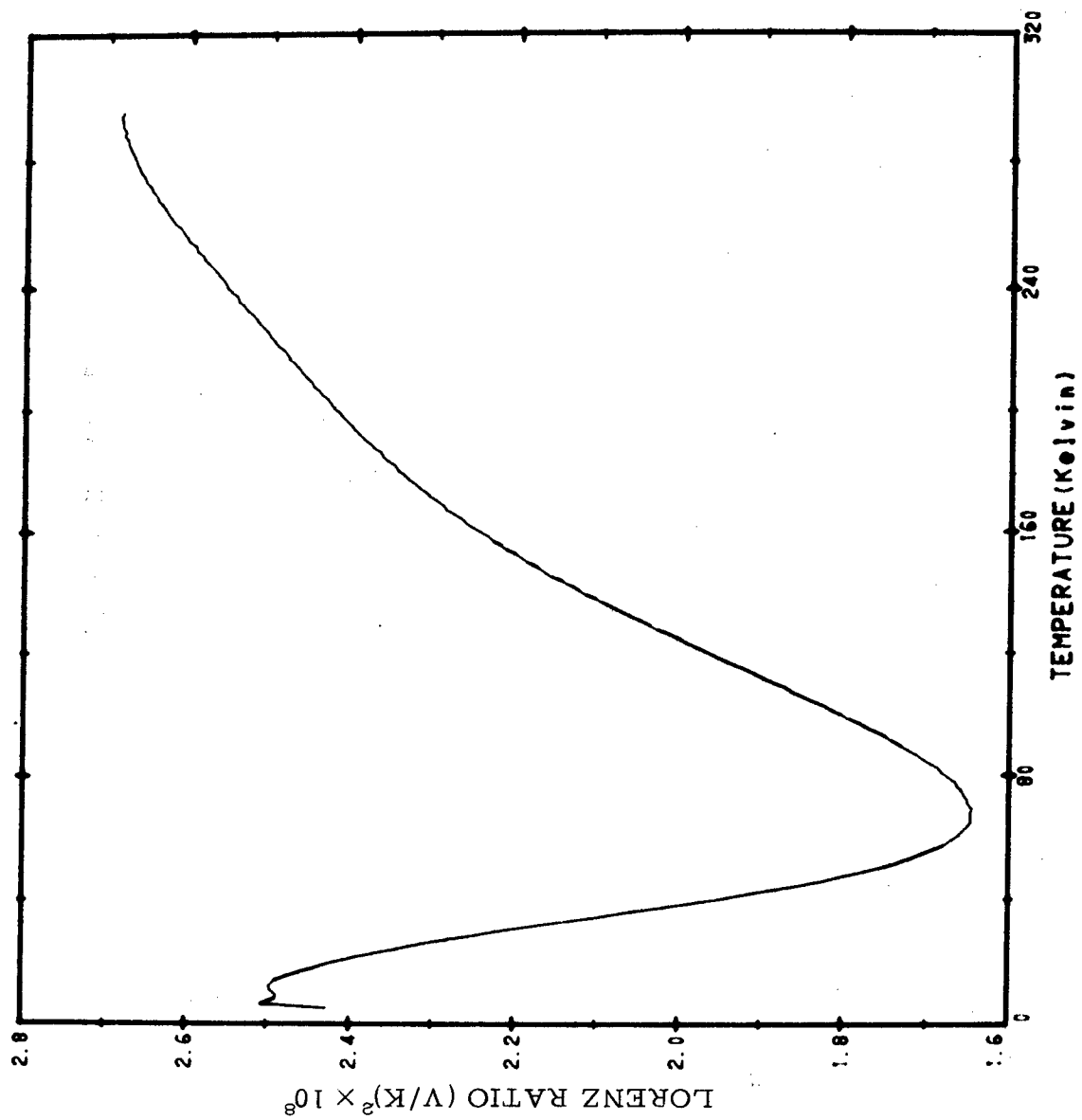


Figure 6. Lorenz ratio of OSRM iron-1265

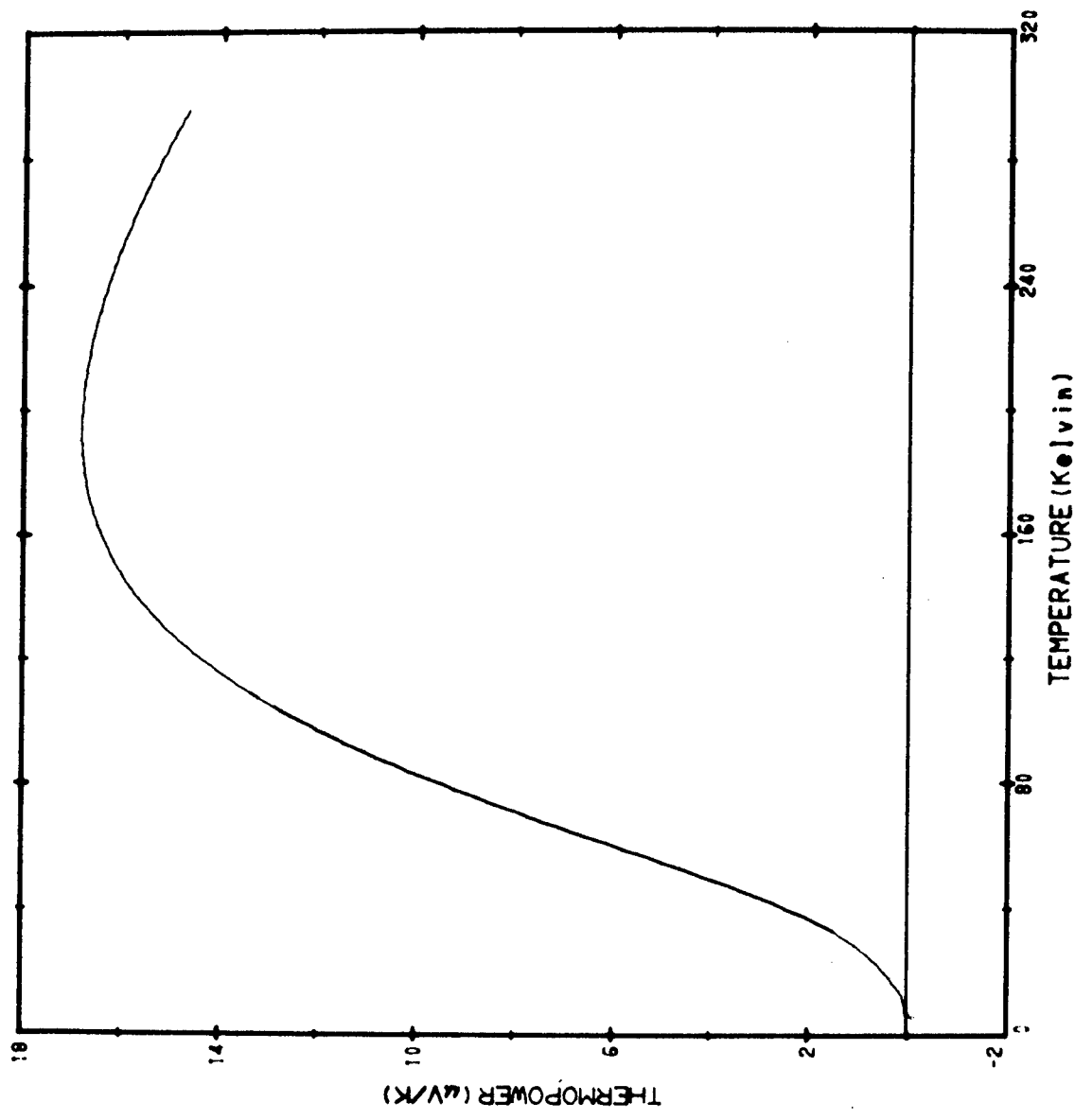


Figure 7. Thermopower of OSRM iron-1265