

# Selected Electrical Resistivity Values for the Platinum Group of Metals Part II: Rhodium and Iridium

## Improved values obtained for liquid phases of rhodium and iridium

**John W. Arblaster**

Wombourne, West Midlands, UK

Email: [jwarblaster@yahoo.co.uk](mailto:jwarblaster@yahoo.co.uk)

Electrical resistivity values for both the solid and liquid phases of the platinum group metals (pgms) rhodium and iridium are evaluated. In particular improved values are obtained for the liquid phases of these metals.

### 1. Introduction

A previous review on electrical resistivity was given in Part I for palladium and platinum (1).

The elements rhodium and iridium are both superconducting with transition temperatures of 325  $\mu$ K for rhodium (2) and  $0.1125 \pm 0.001$  K for iridium (3). Both metals have a face-centred cubic structure and their melting point are secondary fixed points on the International Temperature Scale of 1990 (ITS-90) at  $2236 \pm 3$  K and  $2719 \pm 6$  K respectively (4).

### 2. Rhodium

#### 2.1 Solid

As given in **Table I** the measurement of Powell and Tye (5) is assumed to be superseded by the later measurements of Powell *et al.* (8, 9) and

the measurement of White and Woods (6) by the later measurement of White and Woods (7). The measurement of Powell *et al.* (8) is not considered to be superseded by the later measurements of Powell *et al.* (9) since it is at a specific temperature whereas the later measurements are obtained from an interpolation. The selected value is an average of the last four determinations.

Values up to 273.15 K are based on the measurements of White and Woods (7) (20–295 K) after correction to the selected value at 273.15 K using the ratio 4.35/4.36. At 100 K and above the data was fitted to Equation (i) which has an overall accuracy as a standard deviation of  $\pm 0.02 \mu\Omega$  cm.

The measurements of White and Woods (7) are considered to exceed their earlier measurements (6) (15–295 K). Measurements of Powell and Tye (5) (86–282 K) vary from initially 2.5% high to 4.3% high at 97 K and 1.3% low at 214 K then converge towards the selected values whilst those of Kemp *et al.* (10) (4.2–292 K) above 50 K can be considered as trending from 2.6% high to 7.1% high. After correction for residual resistivity the value of Natarajan and Chari (11) at 4 K and  $0.014 \mu\Omega$  cm is notably higher than the value obtained by White and Woods (7) at  $0.0018 \mu\Omega$  cm at 20 K.

In the high temperature region the combined measurements of Sorokin *et al.* (12) (1250–2050 K) and of Filippov and Yurchak (13, 14) (1300–2000 K) showed a distinct change in slope at 1750 K

**Table I Electrical Resistivity of Rhodium at 273.15 K**

Authors	Ref.	$\rho_i$ , $\mu\Omega$ cm	Temperature of Data
Powell and Tye	5	4.34	Interpolated 213.8–281.6 K
White and Woods	6	4.38	At 273.15 K
White and Woods	7	4.36	At 273.15 K
Powell <i>et al.</i>	8	4.31	At 273.15 K. Corrected for $\rho_0$ 0.024 $\mu\Omega$ cm
Powell <i>et al.</i>	9	4.33	First sample. Interpolated 200–400 K. Corrected for $\rho_0$ 0.024 $\mu\Omega$ cm
		4.38	Second sample. Interpolated 200–400 K. Corrected for $\rho_0$ 0.019 $\mu\Omega$ cm
<b>Selected</b>		<b>4.35 <math>\pm</math> 0.04</b>	<b>At 273.15 K</b>

allowing a linear extrapolation to the melting point of 53.8  $\mu\Omega$  cm which is notably lower than the value of 60.7  $\mu\Omega$  cm determined by Hüpf *et al.* (15) (1950–2236 K in the solid region). The measurements of Milošević (16) (300–2200 K) are intermediate extrapolating to a value of 57.4  $\mu\Omega$  cm at the melting point. The values of Milošević compared to those of Sorokin *et al.* and Filippov and Yurchak trend from initially 5.3% low at 1250 K to 4.0% low at 1700 K and then to 5.5% low at 2050 K. The measurements of Hüpf *et al.* trend from 3.6% high to 5.6% high. Measurements of Jain *et al.* (17) (1180–1573 K) trend from 0.9% lower to 8.9% higher than the measurements of Milošević.

Because of these large discrepancies and in order to obtain a consistent set of values for solid rhodium it is noted for the cubic pgms that at the melting points the ratio of the resistivities of the liquid phase ( $\rho_L$ ) and of the solid phase ( $\rho_S$ ) can be considered in terms of the entropy of fusion ( $\Delta S_M$ ) by using a modified version of the Mott equation (18):  $\ln(\rho_L/\rho_S) = A\Delta S_M + B$  where  $A$  and  $B$  are constants. Using selected values of  $\rho_L/\rho_S$  of 1.738 for palladium (1), 1.610 for platinum (1) and 1.391 for iridium (see below) and values of  $\Delta S_M$  of 8.80 J mol<sup>-1</sup> K<sup>-1</sup> for palladium (19), 10.83 J mol<sup>-1</sup> K<sup>-1</sup> for platinum (20) and 15.20 J mol<sup>-1</sup> K<sup>-1</sup> for iridium (21) leads to the equation  $\ln(\rho_L/\rho_S) = 0.85387 - 3.4535 \times 10^{-2}\Delta S_M$  with the degree of correlation indicated by the fact that the standard deviation was only  $\pm 0.008$ . Substituting in the entropy value of  $\Delta S_M = 12.21$  J mol<sup>-1</sup> K<sup>-1</sup> for rhodium (22) then  $\rho_L/\rho_S = 1.541$  and based on the selected value of  $\rho_L = 89.2$   $\mu\Omega$  cm then  $\rho_S = 57.9$   $\mu\Omega$  cm which is very close to the extrapolated experimental value of Milošević which is therefore selected after taking into account possible systematic errors in the entropies of fusion and the liquid electrical resistivity measurements. However although the measurements

of Milošević were given preference it is noted that the equation given by Milošević extrapolates to a value at 273.15 K which is 13% higher than the selected value and in order to achieve compatibility only the measurements of Milošević at 1000 K and above could be considered. However these were used to produce Equation (ii) which is assumed to represent the electrical resistivity from 273.15 K to the melting point. The measurements of Binkele and Brunen (23) (273–1373 K) gave a value at 273.15 K which was 6.0% higher than the selected value and therefore these measurements could not be considered below 700 K but above this temperature bias only 0.5% low which, based on very large differences between the various sets of other measurements, is considered as confirming the selection procedure. Therefore above 100 K Equations (i) and (ii) were used to generate the selected values for the solid in **Table II** where values at 600 K and above were given to four significant figures only for interpolation purposes.

Three sets of measurements of resistivity ratios were corrected for thermal expansion using values selected by the present author (24) and then values above 273.15 K were compared with the selected curve (**Figure 1**). The measurements of Holborn (25) (81–773 K) were given as  $R_T/R_{273.15\text{ K}}$  and on this basis trended to 4.0% low at 773 K. Mimeault and Hansen (26) (100–700 K) gave measurements as the ratio  $R_T/R_{295}$  and after correcting to  $R_T/R_{273.15\text{ K}}$  trended to 12.5% low whilst the measurements of García and Löffler (27) (295–1000 K) which were also corrected from  $R_T/R_{295}$  to  $R_T/R_{273.15\text{ K}}$  trended to 13.5% low. For comparison purposes as given in **Figure 2** the resistivity ratios are reconsidered as being electrical resistivity values. At the melting point the measurement of Savvatimskii (28) is 6.2% high and that of Martynyuk and Tsapkov (29) is 2.7% high. The electrical resistivity measurements of Glazkov (30) (800–2000 K) are given

**Table II Intrinsic Electrical Resistivity of Rhodium**

Temperature, K	$\rho_i$ , $\mu\Omega$ cm	Temperature, K	$\rho_i$ , $\mu\Omega$ cm	Temperature, K	$\rho_i$ , $\mu\Omega$ cm
<b>Solid</b>					
20	0.0018	180	2.52	700	13.74
25	0.0049	190	2.72	800	16.22
30	0.011	200	2.92	900	18.77
40	0.043	210	3.12	1000	21.39
50	0.10	220	3.32	1100	24.08
60	0.20	230	3.51	1200	26.81
70	0.34	240	3.71	1300	29.59
80	0.51	250	3.90	1400	32.41
90	0.69	260	4.10	1500	35.27
100	0.88	270	4.29	1600	38.17
110	1.09	273.15	4.35	1700	41.10
120	1.30	280	4.48	1800	44.07
130	1.51	290	4.68	1900	47.07
140	1.71	300	4.87	2000	50.10
150	1.92	400	6.91	2100	53.18
160	2.12	500	9.08	2200	56.30
170	2.32	600	11.36	2236	57.44
<b>Liquid</b>					
2236	89.2	2500	93.6	2900	100.3
2250	89.4	2600	95.3	3000	102.0
2300	90.2	2700	97.0	3100	103.7
2400	91.9	2800	98.6	3150	104.5

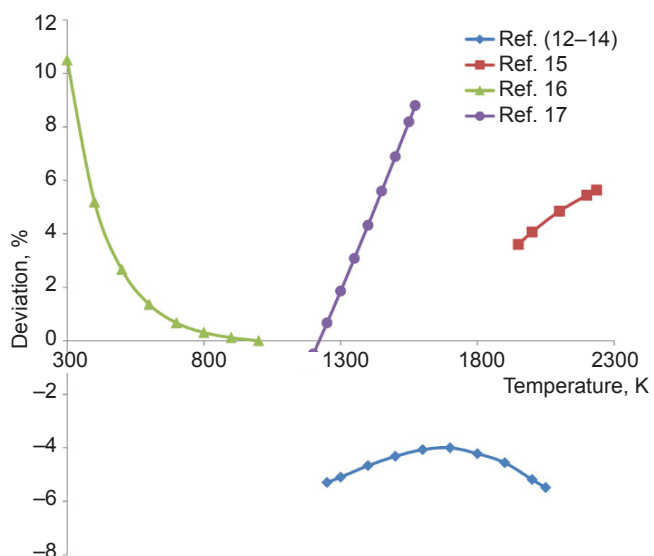


Fig. 1. Solid rhodium – percentage deviations from selected curve

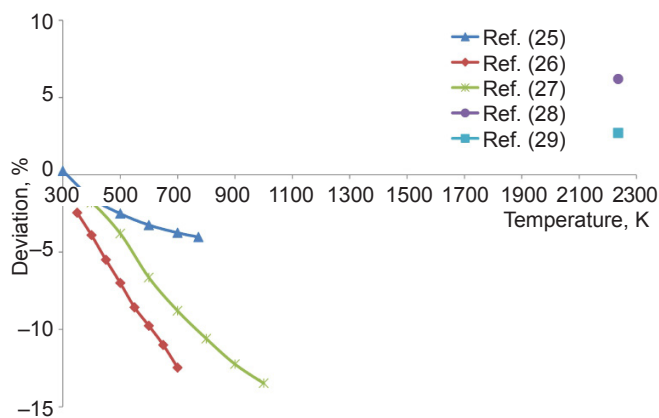


Fig. 2. Solid rhodium – percentage deviations from selected curve

only as a temperature coefficient of electrical resistivity which over the given temperature range decreases from 0.021 to 0.019  $\mu\Omega \text{ cm K}^{-1}$ , differing from the present evaluation which suggests a rise from 0.025 to 0.031  $\mu\Omega \text{ cm K}^{-1}$  over the same temperature range.

## 2.2 Liquid

Measured electrical resistivity values for rhodium at the melting point are given in **Table III**. In the liquid region electrical resistivity measurements of Hüpf *et al.* (15) (2236–3150 K) were accepted and are given by Equation (iii) and are also included in **Table II**.

## 3. Iridium

### 3.1 Solid

As given in **Table IV** the measurement of Powell and Tye (5) is assumed to be superseded by the later measurements of Powell *et al.* (8, 9) and the measurements of White and Woods (6) by the later measurement of White and Woods (7). The measurement of Powell *et al.* (8) is not considered to be superseded by the later measurements of

Powell *et al.* (9) since it is at a specific temperature whereas the later measurements are obtained from an interpolation. The selected value is an average of the last three determinations.

Values up to 273.15 K are based on the measurements of White and Woods (7) (20–295 K) after correction to the selected value at 273.15 K using the ratio 4.67/4.65. At 100 K and above, but less than 220 K, the data was fitted to Equation (iv) which has an overall accuracy as a standard deviation of  $\pm 0.01 \mu\Omega \text{ cm}$ .

The measurements of White and Woods (7) are considered as superseding their earlier measurements (6) (15–295 K). Measurements of Volkenshtein *et al.* (32) (0.4–70 K) are only shown graphically whilst measurements of Volkenshtein *et al.* (33) (4.2–300 K) are also shown graphically except at 25 K and below. These are given in the form of an equation which appears to lead to electrical resistivity values about half those of White and Woods (7). Measurements of Powell and Tye (5) (83–289 K) are initially 2.8% high drifting to 5.6% high at 90 K to 0.6% high at 191 K and then to an average of 1.6% high at 278 K and above.

**Table III Differences Between the Solid and Liquid Electrical Resistivity of Rhodium at the Melting Point**

Authors	Reference	$\rho_s$ , $\mu\Omega \text{ cm}$	$\rho_L$ , $\mu\Omega \text{ cm}$	$\rho_L/\rho_s$
Savvatimskii	28	61.0	85.5	1.402
Martynyuk and Tsapkov	29	59.0	92.5	1.568
Hüpf <i>et al.</i>	15	60.7	89.2	1.470
Present assessment	–	57.44	89.2	1.553

**Table IV Electrical Resistivity of Iridium at 273.15 K**

Authors	Reference	$\rho_i$ , $\mu\Omega \text{ cm}$	Temperature of Data
Powell and Tye	5	4.75	Extrapolated 277.5–289.3 K
Wimber and Halvorson	31	5.29	Extrapolated from equation 295–2275 K
García and Löffler	27	8.47	Extrapolated from 295–850 K
White and Woods	6	4.63	At 273.15 K
White and Woods	7	4.65	At 273.15 K
Powell <i>et al.</i>	8	4.65	At 273.15 K. Corrected for $\rho_0$ 0.055 $\mu\Omega \text{ cm}$
Powell <i>et al.</i>	9	4.72	Interpolated 200–400 K. Corrected for $\rho_0$ 0.056 $\mu\Omega \text{ cm}$
<b>Selected</b>		<b>4.67 <math>\pm</math> 0.05</b>	<b>At 273.15 K</b>

In the high-temperature region measurements of Trukhanova and Filippov (34) (1300–2500 K) and of Filippov and Yurchak (13, 14) (1500–2500 K) over the full range at 100 K intervals, Pottlacher (35) (2000–2719 K in the solid range) at 50 K intervals from 2000 to 2700 K and Wimber and Halvorson (31) (293–2300 K) at 100 K intervals from 700 to 1900 K, after correcting the latter for thermal expansion using values selected by the present author (36), were combined with the selected value at 273.15 K and fitted to Equation (v) with an overall accuracy as a standard deviation of  $\pm 0.33 \mu\Omega \text{ cm}$ . Therefore above 100 K Equations (iv) and (v) were used to generate a selected

value for the solid in **Table V** where values at 600 K and above were given to four significant figures only for interpolation purposes. Deviations of the input values from this equation are shown in **Figure 3** except for the measurements of Wimber and Halvorson at 300 K and 400 K which are respectively 10.2% and 7.3% higher than the selected values.

Measurements of Binkele and Brunen (23) (273–1373 K) combined from four runs trend from initially 16% high to 1.4% high whilst measurements of Gathers *et al.* (37) (2000–2720 K in the solid range) trend from 2.7% high to 6.4% high and those of L'vov *et al.* (38) (100–1700 K) above 273.15 K scatter 5.8%

**Table V Intrinsic Electrical Resistivity of Iridium**

Temperature, K	$\rho_i, \mu\Omega \text{ cm}$	Temperature, K	$\rho_i, \mu\Omega \text{ cm}$	Temperature, K	$\rho_i, \mu\Omega \text{ cm}$
<b>Solid</b>					
15	0.0013	190	3.01	1000	21.19
20	0.0050	200	3.22	1100	23.76
25	0.015	210	3.42	1200	26.38
30	0.032	220	3.62	1300	29.06
40	0.10	230	3.82	1400	31.77
50	0.20	240	4.02	1500	34.53
60	0.35	250	4.21	1600	37.32
70	0.53	260	4.41	1700	40.14
80	0.72	270	4.61	1800	42.98
90	0.90	273.15	4.67	1900	45.84
100	1.11	280	4.80	2000	48.71
110	1.33	290	5.00	2100	51.59
120	1.55	300	5.20	2200	54.46
130	1.76	400	7.23	2300	57.33
140	1.97	500	9.36	2400	60.20
150	2.18	600	11.57	2500	63.05
160	2.39	700	13.87	2600	65.88
170	2.60	800	16.24	2700	68.69
180	2.81	900	18.68	2719	69.22
<b>Liquid</b>					
2719	96.3	3000	100.0	3400	105.2
2750	96.7	3100	101.3	3500	106.6
2800	97.3	3200	102.6	3550	107.2
2900	98.7	3300	103.9	–	–

low to 4.6% high. At the melting point the value of electrical resistivity determined by Lebedev *et al.* (39) is 1.6% high whilst that determined by Martynyuk and Tsapkov (29) is 4.8% low.

Values determined as resistivity ratios were corrected for thermal expansion (36) and from  $R_T/R_{295\text{ K}}$  to  $R_T/R_{273.15\text{ K}}$ . Measurements of Mimeault and Hansen (26) (100–700 K) on this basis trend to 18% low above 273.15 K whilst the measurements of García and Löffler (27) (295–1100 K) trend to 30% low. Measurements of Gugnin *et al.* (40) (473–1973 K) were only shown in the form of a small graph. Deviations of these measurements from Equation (v) above 300 K are shown in **Figure 4**

where values of Mimeault and Hansen and of García and Löffler were reconsidered as electrical resistivity values based on the selected value at 273.15 K.

### 3.2 Liquid

Electrical resistivity values for iridium at the melting point are given in **Table VI**. The variation of electrical resistivity with temperature as given by Pottlacher (35) (2719–3550 K) are accepted and are given as Equation (vi) and included in **Table V**. Over the common temperature range of 2719 to 3550 K the measurements of Gathers *et al.* (37) (2719–4250 K in the liquid range) trend from 3.8% high to 1.3% high.

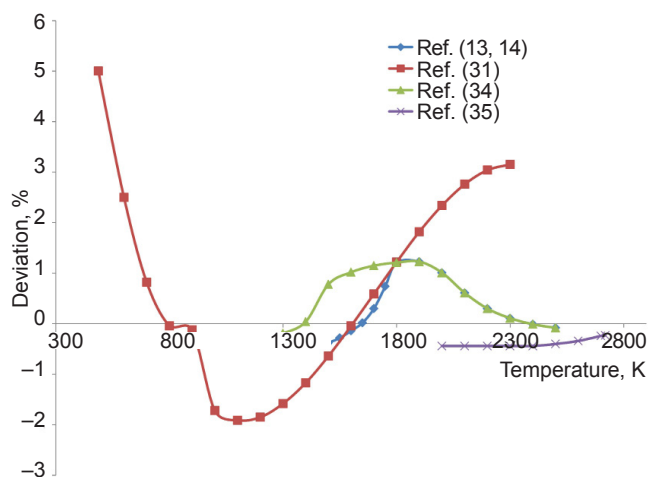


Fig. 3. Solid iridium – percentage deviations from selected curve

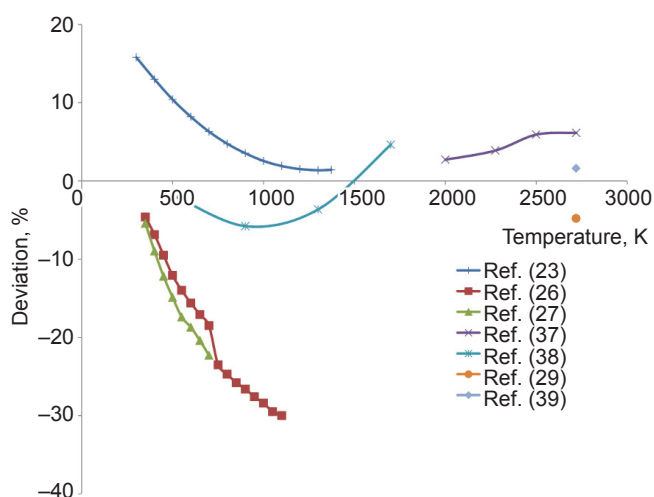


Fig. 4. Solid iridium – percentage deviations from selected curve

**Table VI Differences Between the Solid and Liquid Electrical Resistivity of Iridium at the Melting Point**

Authors	Reference	$\rho_s$ , $\mu\Omega\text{ cm}$	$\rho_L$ , $\mu\Omega\text{ cm}$	$\rho_L/\rho_s$
Lebedev <i>et al.</i>	38	70.3	92.0	1.309
Martynyuk and Tsapkov	28	65.9	85.5	1.297
Gathers <i>et al.</i>	36	73.7	100.0	1.357
Pottlacher	34	69.1	96.3	1.394
Present assessment	–	69.22	96.3	1.391

**Low Temperature Intrinsic Resistivity of Solid Rhodium (100 to 273.15 K)**

$$\rho_i (\mu\Omega \text{ cm}) = 2.37925 \times 10^{-2} T - 1.49605 \times 10^{-5} T^2 + 1.66098 \times 10^{-8} T^3 - 1.37121 \quad (\text{i})$$

**High Temperature Intrinsic Resistivity of Solid Rhodium (273.15 to 2236 K)**

$$\rho_i (\mu\Omega \text{ cm}) = 1.45031 \times 10^{-2} T + 1.00331 \times 10^{-5} T^2 - 3.35384 \times 10^{-9} T^3 + 5.05588 \times 10^{-13} T^4 - 0.294564 \quad (\text{ii})$$

**Intrinsic Resistivity of Liquid Rhodium (2236 to 3150 K)**

$$\rho_i (\mu\Omega \text{ cm}) = 1.680 \times 10^{-2} T + 51.6 \quad (\text{iii})$$

**Low Temperature Intrinsic Resistivity of Solid Iridium (100 to 273.15 K)**

$$\rho_i (\mu\Omega \text{ cm}) = 2.47088 \times 10^{-2} T - 1.58538 \times 10^{-5} T^2 + 1.58062 \times 10^{-8} T^3 - 1.21847 \quad (\text{iv})$$

**High Temperature Intrinsic Resistivity of Solid Iridium (273.15 to 2719 K)**

$$\rho_i (\mu\Omega \text{ cm}) = 1.66688 \times 10^{-2} T + 5.70656 \times 10^{-6} T^2 - 8.95612 \times 10^{-10} T^3 - 0.290595 \quad (\text{v})$$

**Intrinsic Resistivity of Liquid Iridium (2719 to 3550 K)**

$$\rho_i (\mu\Omega \text{ cm}) = 1.316 \times 10^{-2} T + 60.5 \quad (\text{vi})$$

**References**

1. J. W. Arblaster, *Johnson Matthey Technol. Rev.*, 2015, **59**, (3), 174
2. C. Buchal, F. Pobell, R. M. Mueller, M. Kubota and J.R. Owers-Bradley, *Phys. Rev. Lett.*, 1983, **50**, (1–3), 64
3. B. W. Roberts, *J. Phys. Chem. Ref. Data*, 1976, **5**, (3), 581
4. R. E. Bedford, G. Bonnier, H. Maas and F. Pavese, *Metrologia*, 1996, **33**, (2), 133
5. R. W. Powell and R. P. Tye, 'Thermal Conductivity Measurements Down to Minus 190 Degrees: Iridium and Rhodium', *Comptes Rendue du IX e Congrès International du Froid*, Paris, France, 31st August to 7th September, 1955, "Proceedings of the 9th International Congress of Refrigeration", Vol. 1, Institut International du Froid, France, 1956, p. 2083
6. G. K. White and S. B. Woods, *Can. J. Phys.*, 1957, **35**, (3), 248
7. G. K. White and S. B. Woods, *Phil. Trans. R. Soc. Lond. A*, 1959, **251**, (995), 273
8. R. W. Powell, R. P. Tye and M. J. Woodman, *Platinum Metals Rev.*, 1962, **6**, (4), 138
9. R. W. Powell, R. P. Tye and M. J. Woodman, *J. Less Common Met.*, 1967, **12**, (1), 1
10. W. R. G. Kemp, P. G. Klemens and R. J. Tainsh, *Ann. Phys.*, 1959, **460**, (1–2), 35
11. N. S. Natarajan and M. S. R. Chari, 'Thermal Conductivity of Rhodium at Helium Temperatures and in Magnetic Fields', Ninth International Thermal Conductivity Conference, Iowa State University, USA, 6th–8th October, 1969, "Ninth Conference on Thermal Conductivity", ed. H. R. Shanks, CONF-691002, US Atomic Energy Committee, USA, 1970, p.208
12. A. G. Sorokin, L. N. Trukhanova and L. P. Filippov, *Teplofiz. Vys. Temp.*, 1969, **7**, (2), 372; translated into English in *High Temp.*, 1969, **7**, (2), 342
13. L. P. Filippov and R. P. Yurchak, *Inzh. Fiz. Zh.*, 1971, **21**, (3), 561; translated into English in *J. Eng. Phys.*, 1971, **21**, (3), 1209
14. L. P. Filippov, *Int. J. Heat Mass Transfer*, 1973, **16**, (5), 865
15. T. Hüpf, C. Cagran, B. Wilthan and G. Pottlacher, *J. Phys.: Condens. Matter*, 2009, **21**, (12), 125701
16. N. Milošević, *Int. J. Mater. Res.*, 2014, **105**, (6), 571
17. S. C. Jain, B. B. Sharma and B. K. Reddy, *J. Phys. D:*

- Appl. Phys.*, 1972, **5**, (1), 155
18. N. F. Mott, *Proc. R. Soc. Lond. A*, 1934, **146**, (857), 465
19. J. W. Arblaster, *Calphad*, 1995, **19**, (3), 327
20. J. W. Arblaster, *Platinum Metals Rev.*, 2005, **49**, (3), 141
21. J. W. Arblaster, *Calphad*, 1995, **19**, (3), 365
22. J. W. Arblaster, *Calphad*, 1995, **19**, (3), 357
23. L. Binkele and M. Brunen, "Thermal Conductivity, Electrical Resistivity and Lorentz Function Data for Metallic Elements in the Range 273 to 1500 K", Forschungszentrum Jülich, Institut für Werkstoffe der Energietechnik, Zentralbibliothek, Germany, 1994
24. J. W. Arblaster, *Platinum Metals Rev.*, 1997, **41**, (4), 184
25. L. Holborn, *Ann. Phys.*, 1919, **364**, (10), 145
26. V. J. Mimeault and R.S. Hansen, *J. Chem. Phys.*, 1966, **45**, (6), 2240
27. E. Y. Garcia and D. G. Löffler, *J. Chem. Eng. Data*, 1985, **30**, (3), 304
28. A. I. Savvatimskii, *Teplofiz. Vys. Temp.*, 1973, **11**, (6), 1182; translated into English in *High Temp.*, 1973, **11**, (6), 1057
29. M. M. Martynyuk and V. I. Tsapkov, *Fiz. Metal. Metalloved.*, 1974, **37**, (1), 49; translated into English in *Phys. Met. Metallogr.*, 1974, **37**, (1), 40
30. S. Yu. Glazkov, *Teplofiz. Vys. Temp.*, 1988, **26**, (3), 501; translated into English in *High Temp.*, 1988, **26**, (3), 367
31. R. T. Wimber and J. J. Halvorson, *J. Mater.*, 1972, **7**, (4), 564
32. N. V. Volkenshtein, V. A. Novoselov and V. E. Startsev, *Zh. Eksperim. Teor. Fiz.*, 1971, **60**, (3), 1078; translated into English in *Sov. Phys. JETP*, 1971, **33**, (3), 584
33. N. V. Volkenshtein, V. A. Novoselov and V. E. Startsev, *Fiz. Metal. Metalloved.*, 1971, **31**, (2), 427; translated into English in *Phys. Met. Metallogr.*, 1971, **31**, (2), 212
34. L. N. Trukhanova and L. P. Filippov, *Teplofiz. Vys. Temp.*, 1970, **8**, (4), 919; translated into English in *High Temp.*, 1970, **8**, (4), 868
35. G. Pottlacher, "High Temperature Thermophysical Properties of 22 Pure Metals", Edition Keiper, Graz, Austria, 2010
36. J. W. Arblaster, *Platinum Metals Rev.*, 2010, **54**, (2), 93
37. G. R. Gathers, J. W. Shaner, R. S. Hixson and D. A. Young, *High Temp.-High Pressure*, 1979, **11**, (6), 653
38. S. N. L'vov, P. I. Mal'ko and V. F. Nemchenko, *Fiz. Metal. Metalloved.*, 1971, **31**, (1), 108; translated into English in *Phys. Met. Metallogr.*, 1971, **31**, (1), 107
39. S. V. Lebedev, A. I. Savvatimskii and Yu. B. Smirnov, *Zh. Tekh. Fiz.*, 1972, **42**, (8), 1752; translated into English in *Sov. Phys. Tech. Phys.*, 1973, **17**, (8), 1400
40. A. A. Gugnin, S. N. L'vov, P. I. Mal'ko, V. F. Nemchenko and I. P. Starodubov, *Parosh. Metall.*, 1972, **1**, (109), 65; translated into English in *Sov. Powder Metall. Met. Ceram.*, 1972, **11**, (1), 51

## The Author



John W. Arblaster is interested in the history of science and the evaluation of the thermodynamic and crystallographic properties of the elements. Now retired, he previously worked as a metallurgical chemist in a number of commercial laboratories and was involved in the analysis of a wide range of ferrous and non-ferrous alloys.