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Selected Electrical Resistivity Values for the Platinum Group of Metals Part I: Palladium and Platinum

Improved values obtained for liquid phases of palladium and platinum

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Electrical resistivity values for both the solid and liquid phases of the platinum group metals (pgms) palladium and platinum are evaluated. In particular improved values are obtained for the liquid phases of these metals. Previous reviews on electrical resistivity which included evaluations for the pgms included those of Meaden (1), Bass (2), Savitskii *et al.* (3) and Binkele and Brunen (4) as well as individual reviews by Matula (5) on palladium and White (6) on platinum.

1. Introduction

Electrical resistivity (ρ) is defined in terms of the International System of Units (SI units) as:

$$\rho = R\,A\,/\,l \qquad \text{(i)}$$

where
R is the electrical resistance of a uniform specimen of material in ohms (Ω)
A is the cross-sectional area of the specimen in square metres (m^2)
l is the length of the specimen in metres (m)

The units of ρ are therefore Ω m although practically the most useful units are μΩ cm.

The measured electrical resistivity (ρ) usually consists of a temperature dependent intrinsic resistivity, ρ_i, which is due to the pure metal and is caused by the scattering of the charge carriers (electrons or holes) by phonons (quantised vibrations of the lattice) and by their collisions with each other, and a residual resistivity (ρ_0) due to impurities which also scatter the carriers and increase the resistivity. The quantity ρ_0 is considered to be a summation of the effects of different impurities and is also considered to be temperature independent. The two contributions to the total resistivity are combined according to Matthiessen's Rule: $\rho = \rho_0 + \rho_i$ and because ρ_0 may vary from sample to sample then attempts are made to evaluate values of ρ_i which should be universal for a specific metal.

1.1 Correction for Thermal Expansion Effects

In order to obtain a reference value to which all other measurements are adjusted the electrical resistivity is evaluated at 273.15 K (0ºC).

In the low temperature region below about 30 K the resistivity can be represented by $\rho = \rho_0 + A\,T^2 + B\,T^5$ where the temperature dependent terms represent the intrinsic resistivity, whilst up to room temperature the experimental values are generally given in such a form that interpolation can be achieved by using simple polynomials rather than using the complicated Bloch-Grüneisen formula (7–9). In the definition of resistivity as $\rho = R\,A\,/\,l$ then *A* and *l* are usually measured at room temperature and therefore at different temperatures both A and l have to be corrected for thermal expansion effects. It is found below room temperature that for the level of accuracy given for ρ, thermal expansion corrections are generally negligible but at higher temperature the measurements have to be corrected, especially if they are based entirely on the room temperature values for A and l which are usually measured at 293.15 K, the accepted reference temperature for length change measurements:

$$\rho\,(\text{corrected}) = \rho\,(\text{uncorrected})\,[(A_T / A_{293.15}) \times (l_{293.15} / l_T)] \quad \text{(ii)}$$

$$= \rho\,(\text{uncorrected})\,[1 + (l_T - l_{293.15}) / l_{293.15}] \quad \text{(iii)}$$

where Equation (iii) can be considered to be a close approximation of Equation (ii). However since 273.15 K is the actual reference temperature then corrected values of ρ(T) should be further corrected for thermal expansion from 293.15 K to 273.15 K. Since this correction is usually negligible at the level of accuracy given then it is not applied.

In the case of rapid pulse heating to high temperatures, because of inertia l generally is unaltered and it is A that changes. If D is the diameter of the wire then:

$$\rho\,(\text{T}) = \rho\,(\text{measured})\,(D_T^2 / D_{293.15}^2) = \rho\,(\text{measured})\,(V_T / V_{293.15}) \quad \text{(iv)}$$

where V_T is the volume of the sample at temperature T and $V_{293.15}$ is the volume at 293.15 K. These are essentially D_T^2 and $D_{293.15}^2$ respectively since l is assumed to be unaltered.

2. Palladium

Palladium has a face-centred cubic structure and the melting point is a secondary fixed point on the International Temperature Scale of 1990 (ITS-90) at 1828.0 ± 0.1 K (10).

2.1 Solid

Electrical resistivity values for solid palladium at 273.15 K are given in **Table I**. The selected value is an average of the last three determinations. The ρ_0 correction to the measurement of Laubitz and Matsumura (14) was suggested by Matula (5) who also appears to have selected this value as the reference value.

From 71 data sets for solid palladium Matula (5) selected only the measurements of Schriempf (17) (1.6 K–10.6 K), White and Woods (13) (10 K–295 K) and Laubitz and Matsumura (14) (90 K–1300 K). However it is considered that the values of White and Woods have been superseded by the later high precision measurements of Williams and Weaver (15) (0 K–300 K) and Khellar and Vuillemin (16) (17 K–300 K), with the latter given only in the form of an equation which was evaluated at 17 K and then at 10 K intervals from 20 K to 270 K. The measurements of Williams and Weaver were interpolated above 100 K so as to also obtain a full evaluation at 10 K intervals from 20 K to 270 K. The measurements of Schriempf and of Williams and Weaver agree satisfactorily and were averaged to 10 K with the measurements of Williams and Weaver being extended to 16 K. The measurements of the latter and of Khellar and Vuillemin do not agree below 35 K. However the equation of Khellar and Vuillemin showed peculiar behaviour below this temperature with derived values being 6% higher than those of Williams and Weaver at 17 K but 31% lower at 20 K. Therefore the latter measurements were given preference up to 35 K. At this temperature and above values from the two sets of measurements were averaged. Overall agreement is to within 0.5% between 60 K and 180 K and to within 0.1% above 180 K. The selected values of Matula below 273.15 K are based on a combination of the measurements of White and Woods and of Laubitz and Matsumura and on average the intrinsic values show a bias of 0.02 μΩ cm above the more recently selected values. Other measurements in the low temperature region were discussed by Matula.

In the high temperature region Matula (5) selected only the measurements of Laubitz and Matsumura (14) (90 K–1300 K). After correction for ρ_0 = 0.020 μΩ cm the values were calculated at 50 K intervals from 350 to 1300 K. In the present evaluation these measurements were combined with the more recent measurements of Khellaf *et al.* (18) (295 K–1700 K) which were given in the form of an equation which was also evaluated at 50 K intervals but over the range 350 K to 1750 K. After correction of both sets of measurements for thermal expansion using the values selected by the present author (19) they were fitted to Equation (v) which has an overall accuracy as a standard deviation of ± 0.13 μΩ cm. The two sets of measurements show a maximum disagreement of 1.0% at 1300 K. The equation was extrapolated to the melting point and selected values are given in **Table II**.

Measurements of Milošević and Babić (20) (250 K–1800 K) were independently corrected for thermal expansion. Their equation differs from the selected equation sinusoidally by trending from initially 0.3% high to 1.7% high at 400 K to 0.9% low at 1400 K

Table I Electrical Resistivity of Palladium at 273.15 K

Authors	Ref.	ρ_i, μΩ cm	Temperature of data
Powell *et al.*	11	9.79	At 273.15 K. Corrected for ρ_0 0.144 μΩ m
Powell *et al.*	12	9.75	Interpolated 200 – 400 K. Corrected for ρ_0 0.143 μΩ m
White and Woods	13	9.70	At 273.15 K. Average of three samples
Laubitz and Matsumura	14	9.760	Interpolated 250–300 K. Corrected for ρ_0 0.020 μΩ m
Williams and Weaver	15	9.751	At 273.15 K. Corrected for ρ_0 0.007 μΩ m
Khellar and Vuillemin	16	9.765	Calculated. Fit 17–300 K
Selected		**9.76 ± 0.01**	**At 273.15 K**

Table II Intrinsic Electrical Resistivity of Palladium

Temperature, K	ρ_i, μΩ cm	Temperature, K	ρ_i, μΩ cm	Temperature, K	ρ_i, μΩ cm
Solid					
5	0.0008	140	4.36	400	14.47
10	0.0038	150	4.79	500	17.92
15	0.011	160	5.21	600	21.14
20	0.028	170	5.63	700	24.15
25	0.061	180	6.04	800	26.96
30	0.113	190	6.45	900	29.59
35	0.189	200	6.86	1000	32.03
40	0.294	210	7.26	1100	34.30
45	0.420	220	7.66	1200	36.42
50	0.566	230	8.06	1300	38.39
60	0.908	240	8.46	1400	40.23
70	1.29	250	8.85	1500	41.95
80	1.71	260	9.25	1600	43.55
90	2.14	270	9.64	1700	45.05
100	2.59	273.15	9.76	1800	46.46
110	3.04	280	10.02	1828	46.84
120	3.48	290	10.41		
130	3.92	300	10.79		
Liquid					
1828	81.4	2200	82.2	2700	83.3
1850	81.5	2300	82.4	2800	83.5
1900	81.6	2400	82.6	2900	83.7
2000	81.8	2500	82.8		
2100	82.0	2600	83.1		

to 0.4% high at 1800 K. **Figure 1** shows the deviations of the selected values of Matula (which are considered as incorporating the measurements of Laubitz and Matsumura) and the experimental values of Khellaf *et al.* and Milošević and Babić from the fitted curve. Measurements of Binkele and Brunen (4) (273–1423 K) which were also independently corrected for thermal expansion, showed systematic biases of 1.3% high for runs 1 and 2 and 1.7% high for run 3.

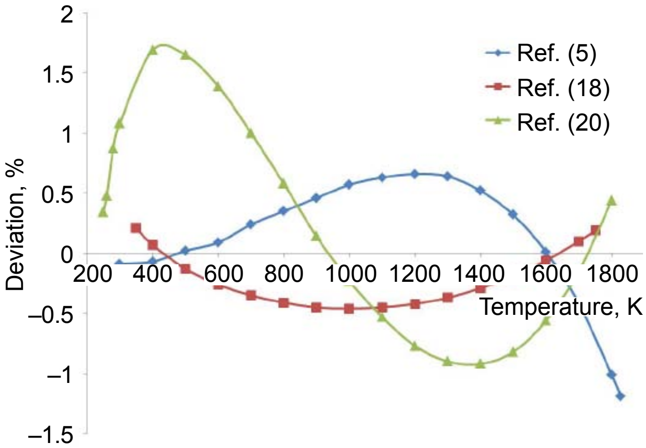

Fig. 1. Solid palladium – percentage deviations from selected curve

Also in the high temperature region there are a number of other measurements which were published after the review of Matula. After correction for thermal expansion (19) the electrical resistivity measurements of Miiller and Cezairliyan (21) (1400 K–1800 K) trend from 4.0% to 6.9% high whilst the measurement of Pottlacher (22) at the melting point is 5.9% high. Resistivity ratio measurements of García and Löffler (23) (295 K–1100 K) were corrected from R_T/R_{295} to $R_T/R_{273.15}$ and were also corrected for thermal expansion. On this basis the differences reached a maximum of 4.1% high at 450 K but then showed some scatter varying between 1.0% low at 800 K and 1.6% high at 1100 K. **Figure 2** shows the deviations of these three sets of measurements from the fitted curve where the resistivity ratios of García and Löffler were converted to electrical resistivity values for comparison purposes.

2.2 Liquid

Electrical resistivity values for palladium at the melting point are given in **Table III**. In the liquid state neither Dupree *et al.* (24) (1832 K–1924 K) nor Güntherodt *et al.* (25) (1864 K–2019 K) obtained evidence for any variation of resistivity with temperature. Although Seydel and Fischer (26) (1825 K–3000 K) did obtain evidence of such a variation, the values of Pottlacher (22) (1828 K–2900 K) were selected and fitted to

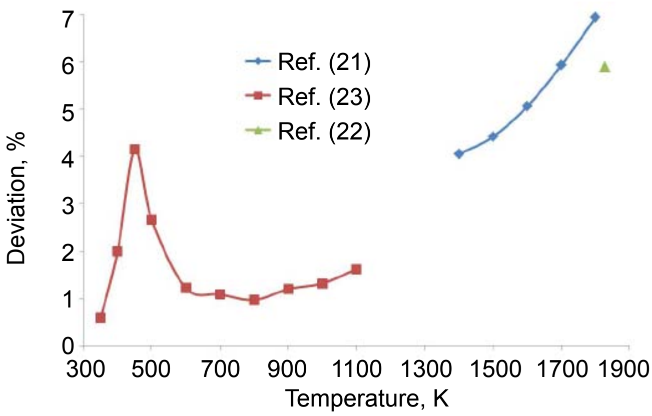

Fig. 2. Solid palladium – percentage deviations from selected curve

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

Authors	Reference	ρ_S, μΩ cm	ρ_L, μΩ cm	ρ_L/ρ_S	Notes
Dupree *et al.*	24	(48.8)	83.0	1.700	(a)
Güntherodt *et al.*	25	47.3	78.8	1.666	
Seydel and Fischer	26	50.2	79.1	1.576	
Khellaf *et al.*	18	(45.2)	77.3	1.710	(b)
Pottlacher	22	49.6	81.4	1.641	
Present assessment	–	46.84	81.4	1.738	

Notes to Table III

(a) Solid value based on $(\rho L - \rho S)/\rho S = 0.70 \pm 0.05$

(b) Solid value based on $\rho L/\rho S = 1.71$

Equation (vi) with selected values for the electrical resistivity of the liquid and are also given in **Table II**.

3. Platinum

Platinum has a face-centred cubic structure and the melting point is a secondary fixed point on ITS-90 at 2041.3 ± 0.4 K (10).

3.1 Solid

The resistance ratio of platinum, $W_T = R_T/R_{273.15}$, forms the basis of the International Temperature Scale which White (6) extended to 1300 K and calculated values of intrinsic resistivity using the fixed reference value of 9.82 ± 0.01 μΩ cm at 273.15 K. Above 1300 K White combined the selected values to this temperature with the electrical resistivity measurements of Righini and Rosso (27) (1000 K–2000 K), Laubitz and van der Meer (28) (300 K–1500 K), and Flynn and O'Hagan (29) (273 K–1373 K) and the resistance ratios of Roeser (30) (73 K–1773 K) and Kraftmakher (31) (1000 K–2000 K) together with resistivity measurements given by Martin *et al.* (32) (300 K–1200 K). White fitted all selected values from 100 K to 2000 K to Equation (vii) which was extrapolated to the melting point. Differences between values derived from this equation and the tabulated values of White as given in **Table IV** do not exceed 0.01 μΩ cm. An abridged version of the values for the solid phase as given in **Table IV** was originally given in *Platinum Metals Review* by Corti (33).

For comparison between these measurements and the selected values as given in **Figure 3**, the resistivity ratios of Roeser (30) and Kraftmakher (31) were converted to electrical resistivity values and all

Table IV Intrinsic Electrical Resistivity of Platinum

Temperature, K	ρ_i, μΩ cm	Temperature, K	ρ_i, μΩ cm	Temperature, K	ρ_i, μΩ cm
Solid					
10	0.0026	150	4.89	500	18.45
15	0.0119	160	5.30	600	22.07
20	0.0367	170	5.70	700	25.59
25	0.0855	180	6.11	800	29.00
30	0.163	190	6.52	900	32.29
35	0.270	200	6.92	1000	35.47
40	0.403	210	7.32	1100	38.54
45	0.560	220	7.72	1200	41.50
50	0.734	230	8.12	1300	44.35
60	1.12	240	8.51	1400	47.09
70	1.53	250	8.91	1500	49.74
80	1.95	260	9.30	1600	52.34
90	2.38	270	9.70	1700	54.93
100	2.80	273.15	9.82	1800	57.51
110	3.23	280	10.09	1900	60.11
120	3.65	290	10.48	2000	62.76
130	4.06	300	10.87	2041.3	63.87
140	4.48	400	14.71		
Liquid					
2041.3	102.8	2300	105.3	2700	109.1
2050	102.9	2400	106.2	2800	110.1
2100	103.4	2500	107.2	2900	111.1
2200	104.3	2600	108.2		

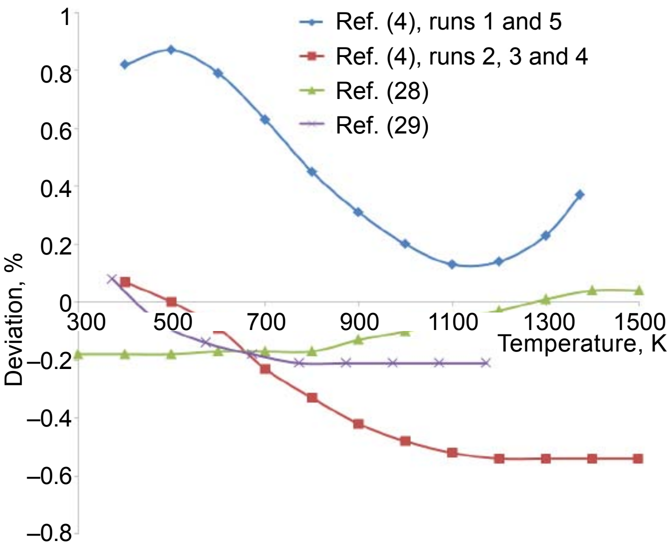

Fig. 3. Solid platinum – percentage deviations from selected curve

measurements except those of Flynn and O'Hagan (29) were corrected for thermal expansion using values selected by the present author (34). In addition the measurements of Martin *et al.* (32) were corrected to correspond to the selected electrical resistivity value at 273.15 K. Because of their larger deviations values of Righini and Rosso (27) are compared with the selected values in **Figure 4**.

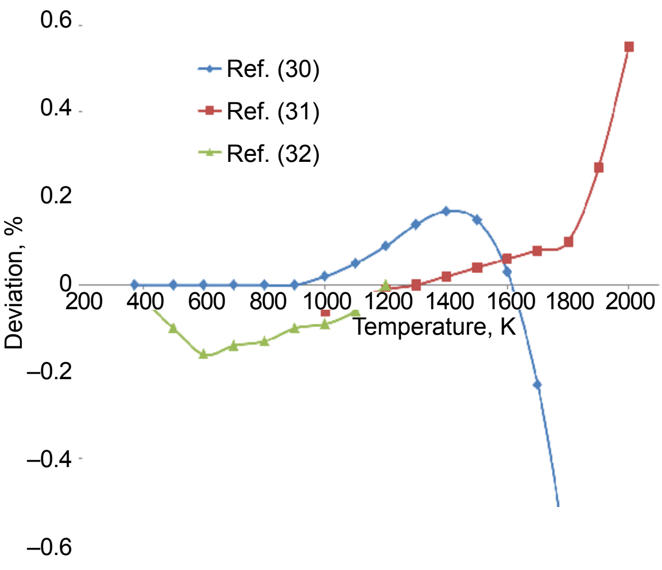

Fig. 4. Solid platinum – percentage deviations from selected curve

In the case of additional electrical resistivity measurements of Birkele and Brunen (4) (273–1497 K), combined runs 1 and 5 trend from initially 0.8% high to 0.1% high at 1200 K to 0.4% high at 1373 K whilst combined runs 2, 3 and 4 trend to an average of 0.5% low above 1000 K. These trends are also shown in **Figure 3**.

Electrical resistivity measurements of Pottlacher (22) (473 K–1573 K and 1740 K–2042 K in the solid range) are initially 1% higher then trend to an average of 3% higher between 900 and 1573 K before trending to 1.2% higher and then to 0.5% higher between 1740 K and the melting point. These differences are also shown in **Figure 5**.

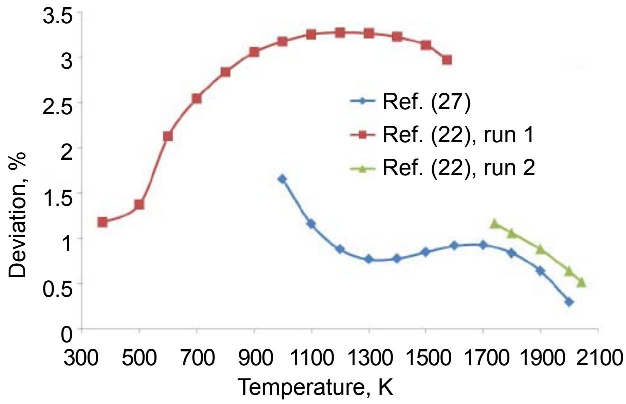

Fig. 5. Solid platinum – percentage deviations from selected curve

3.2 Liquid

Electrical resistivity values of platinum at the melting point are given in **Table V**. In the liquid state electrical resistivity measurements of Pottlacher (22) (2042 K–2900 K) were selected as Equation (viii) since in the overlap region they are closely confirmed by measurements of Gathers *et al.* (36) (2100 K–7300 K) obtained at a pressure of 0.3 GPa which trend from 0.5% low at 2100 K to 1.0% high at 2900 K. Measurements of Hixson and Winkler (37) (2042 K–5100 K) are initially 7% low at the melting point and trend 1% low to 1% high between 2100 K and 2900 K but above 3000 K, in direct comparison with the measurements of Gathers *et al.*, the trend is to an average of 2% low. Selected values for the electrical resistivity of liquid platinum from the melting point to 2900 K are also given in **Table IV**.

Table V Differences Between the Solid and Liquid Electrical Resistivity of Platinum at the Melting Point

Authors	Reference	ρ_S, µΩ cm	ρ_L, µΩ cm	ρ_L/ρ_S
Martynyuk and Tsapkov	35	62.1	92.6	1.491
Pottlacher	22	64.2	102.8	1.601
Present assessment	–	63.87	102.8	1.610

High Temperature Intrinsic Resistivity of Solid Palladium (273.15 to 1828 K)

$$\rho_i\ (\mu\Omega\ \text{cm}) = 4.58639 \times 10^{-2}\,T - 1.39098 \times 10^{-5}\,T^2 + 1.84118 \times 10^{-9}\,T^3 - 1.76742 \quad \text{(v)}$$

Intrinsic Resistivity of Liquid Palladium (1828 to 2900 K)

$$\rho_i\ (\mu\Omega\ \text{cm}) = 2.058 \times 10^{-3}\,T + 77.7 \quad \text{(vi)}$$

Intrinsic Resistivity of Solid Platinum (100 to 2041.3 K)

$$\begin{aligned}\rho_i\ (\mu\Omega\ \text{cm}) = {} & 4.681197 \times 10^{-2}\,T - 3.258075 \times 10^{-5}\,T^2 + 8.554023 \times 10^{-8}\,T^3 \\ & - 1.594242 \times 10^{-10}\,T^4 + 1.837342 \times 10^{-13}\,T^5 - 1.316886 \times 10^{-16}\,T^6 \\ & + 5.678222 \times 10^{-20}\,T^7 - 1.340980 \times 10^{-23}\,T^8 + 1.329896 \times 10^{-27}\,T^9 \\ & - 1.621733 \end{aligned} \quad \text{(vii)}$$

Intrinsic Resistivity of Liquid Platinum (2041.3 to 2900 K)

$$\rho_i\ (\mu\Omega\ \text{cm}) = 9.604 \times 10^{-3}\,T + 83.2 \quad \text{(viii)}$$

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