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Crystallographic Properties of Ruthenium

Assessment of properties from absolute zero to 2606 K

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The crystallographic properties of ruthenium at temperatures from absolute zero to the melting point at 2606 K are assessed following a review of the literature published between 1935 and to date. Selected values of the thermal expansion coefficients and measurements of length changes due to thermal expansion have been used to calculate the variation with temperature of the lattice parameters, interatomic distances, atomic and molar volumes and densities. The data is presented in the form of Figures, Equations and Tables.

This is the sixth in a series of papers in this Journal on the crystallographic properties of the platinum group metals (pgms), following two papers on platinum (1, 2) and one each on rhodium (3), iridium (4) and palladium (5). Ruthenium exists in a hexagonal close-packed (hcp) structure (Pearson symbol *hP2*) up to the melting point which is a secondary fixed point on ITS-90 at 2606 ± 10 K (6).

The thermal expansion is represented by five sets of lattice parameter measurements, those of Owen and Roberts (7, 8) (from 323 K to 873 K), Hall and Crangle (9) (from 799 K to 1557 K), Ross and Hume-Rothery (10) (from 1793 K to 2453 K), Schröder *et al.* (11) (from 84 K to 1982 K) and Finkel' *et al.* (12) (from 80 K to 300 K) and one set of dilatometric measurements, those of Shirasu and Minato (13) (from 323 K to 1300 K). The measurements of Hall and Crangle, Ross and Hume-Rothery and Finkel' *et al.* were only shown graphically with actual data points as length change values being given by Touloukian *et al.* (14). Because there is a certain degree of incompatibility between the high-temperature measurements, and those obtained at low-temperature by Finkel' *et al.*, the high- and low-temperature data were initially treated separately. Available thermal expansion data covers the range from 293.15 K to 2453 K with estimated values below the lower limit whilst in the high-temperature region the derived equations are extrapolated to the melting point.

Thermal Expansion

High-Temperature Region

Length change values derived from the measurements of Owen and Roberts (7, 8) and Ross and Hume-Rothery (10) agree satisfactorily and were combined to give Equations (i) and (ii) to represent the thermal expansion from 293.15 K to the melting point. On the basis ± $100\delta L/L_{293.15\text{ K}}$ Equation (i) for the *a*-axis has an accuracy of ± 0.009 and Equation (ii) for the *c*-axis an accuracy of ± 0.025. Crystallographic properties derived from Equations (i) and (ii) are given in **Tables I** and **II**.

On the basis of the expression:

$$100 \times (\delta L/L_{293.15\text{ K (experimental)}} - \delta L/L_{293.15\text{ K (calculated)}})$$

where $\delta L/L_{293.15\text{ K (experimental)}}$ is the experimental length change relative to 293.15 K and $\delta L/L_{293.15\text{ K (calculated)}}$ is the selected length change value, then length change values derived from the measurements of Hall and Crangle (9) deviate continuously from selected values and both axes are 0.14 low at the experimental limit 1557 K. Above room temperature the *a*-axis values of Schröder *et al.* (11) initially trend to be 0.080 low at 1300 K before increasing to 0.089 high at 1982 K. The *c*-axis values behave similarly, initially trending to 0.072 low at 1100 K before increasing sharply to 0.35 high at 1982 K. The dilatometric measurements of Shirasu and Minato (13) trend to 0.10 low. The deviations of these three sets of values are shown in **Figure 1**.

Low-Temperature Region

The lattice parameter measurements of Finkel' *et al.* (12), given as length change values by Touloukian *et al.* (14), were fitted to cubic Equations (v) and (vi) for the *a*- and c-axes respectively. Derived thermal expansion coefficients at 293.15 K of 6.5 × 10^{-6} K^{-1} for the *a*-axis and 11.5 × 10^{-6} K^{-1} for the *c*-axis are notably higher than those derived from

Table I

High-Temperature Crystallographic Properties of Ruthenium

Temperature, K	Thermal expansion coefficient, α_a, 10^{-6} K^{-1}	Thermal expansion coefficient, α_c, 10^{-6} K^{-1}	Thermal expansion coefficient, α_{avr}, 10^{-6} K^{-1}	Length change, $\delta a/a_{293.15\text{ K}}$ × 100, %	Length change, $\delta c/c_{293.15\text{ K}}$ × 100, %	Length change, $\delta avr/avr_{293.15\text{ K}}$ × 100^a, %
293.15	5.77	8.80	6.78	0	0	0
300	5.79	8.83	6.80	0.004	0.006	0.005
400	6.09	9.29	7.16	0.063	0.097	0.074
500	6.40	9.77	7.52	0.126	0.192	0.148
600	6.72	10.25	7.90	0.191	0.292	0.225
700	7.05	10.76	8.28	0.260	0.398	0.306
800	7.39	11.27	8.68	0.333	0.509	0.391
900	7.73	11.80	9.09	0.409	0.625	0.481
1000	8.09	12.34	9.51	0.488	0.746	0.574
1100	8.46	12.90	9.94	0.571	0.873	0.672
1200	8.83	13.47	10.38	0.658	1.006	0.774
1300	9.22	14.05	10.83	0.749	1.145	0.881
1400	9.61	14.65	11.29	0.844	1.291	0.993
1500	10.02	15.26	11.76	0.943	1.442	1.110
1600	10.43	15.88	12.24	1.046	1.600	1.231
1700	10.85	16.51	12.74	1.154	1.765	1.358
1800	11.28	17.16	13.24	1.266	1.936	1.489

(Continued)

Table I (Continued)

Temperature, K	Thermal expansion coefficient, α_a, 10^{-6} K^{-1}	Thermal expansion coefficient, α_c, 10^{-6} K^{-1}	Thermal expansion coefficient, α_{avr}, 10^{-6} K^{-1}	Length change, $\delta a/a_{293.15\,K} \times 100$, %	Length change, $\delta c/c_{293.15\,K} \times 100$, %	Length change, $\delta avr/avr_{293.15\,K} \times 100$[a], %
1900	11.71	17.82	13.75	1.382	2.115	1.627
2000	12.16	18.49	14.27	1.503	2.300	1.769
2100	12.61	19.17	14.80	1.629	2.493	1.917
2200	13.08	19.86	15.34	1.760	2.693	2.071
2300	13.55	20.56	15.89	1.895	2.901	2.231
2400	14.03	21.28	16.44	2.036	3.117	2.396
2500	14.51	22.00	17.01	2.182	3.340	2.568
2600	15.01	22.74	17.58	2.333	3.571	2.746
2606	15.04	22.78	17.62	2.342	3.586	2.756

[a] *avr = average*

Table II

Further High-Temperature Crystallographic Properties of Ruthenium

Temperature, K	Lattice parameter, a, nm[a]	Lattice parameter, c, nm	c/a ratio	Interatomic distance, $d1$, nm	Atomic volume, 10^{-3} nm^3	Molar volume, 10^{-6} m^3 mol^{-1}	Density, kg m^{-3}
293.15	0.27058	0.42816	1.5824	0.26502	13.574	8.174	12364
300	0.27059	0.42819	1.5824	0.26503	13.576	8.175	12363
400	0.27075	0.42857	1.5829	0.26524	13.604	8.193	12337
500	0.27092	0.42898	1.5834	0.26547	13.634	8.211	12310
600	0.27110	0.42941	1.5840	0.26570	13.666	8.230	12281
700	0.27128	0.42986	1.5845	0.26595	13.699	8.250	12251
800	0.27148	0.43034	1.5851	0.26620	13.734	8.271	12220
900	0.27169	0.43083	1.5858	0.26647	13.770	8.293	12188
1000	0.27190	0.43135	1.5864	0.26676	13.809	8.316	12154
1100	0.27213	0.43190	1.5871	0.26706	13.849	8.340	12118
1200	0.27236	0.43247	1.5878	0.26737	13.891	8.366	12082
1300	0.27261	0.43306	1.5886	0.26769	13.936	8.392	12043
1400	0.27286	0.43369	1.5894	0.26803	13.982	8.420	12003
1500	0.27313	0.43434	1.5902	0.26838	14.030	8.449	11962
1600	0.27341	0.43501	1.5911	0.26875	14.081	8.480	11919
1700	0.27370	0.43572	1.5919	0.26913	14.134	8.512	11874
1800	0.27401	0.43645	1.5929	0.26953	14.189	8.545	11828

(Continued)

Table II (Continued)

Temperature, K	Lattice parameter, *a*, nm[a]	Lattice parameter, c, nm	*c/a* ratio	Interatomic distance, *d*1, nm	Atomic volume, 10^{-3} nm^3	Molar volume, 10^{-6} m^3 mol^{-1}	Density, kg m^{-3}
1900	0.27432	0.43722	1.5938	0.26995	14.247	8.580	11780
2000	0.27465	0.43801	1.5948	0.27038	14.307	8.616	11731
2100	0.27499	0.43883	1.5958	0.27083	14.369	8.653	11680
2200	0.27534	0.43969	1.5969	0.27130	14.434	8.692	11627
2300	0.27571	0.44058	1.5980	0.27178	14.502	8.733	11573
2400	0.27609	0.44150	1.5911	0.27229	14.572	8.776	11517
2500	0.27648	0.44246	1.6003	0.27281	14.646	8.820	11459
2600	0.27689	0.44345	1.6015	0.27335	14.722	8.866	11400
2606	0.27692	0.44351	1.6016	0.27338	14.727	8.869	11396

[a] $a = d2$

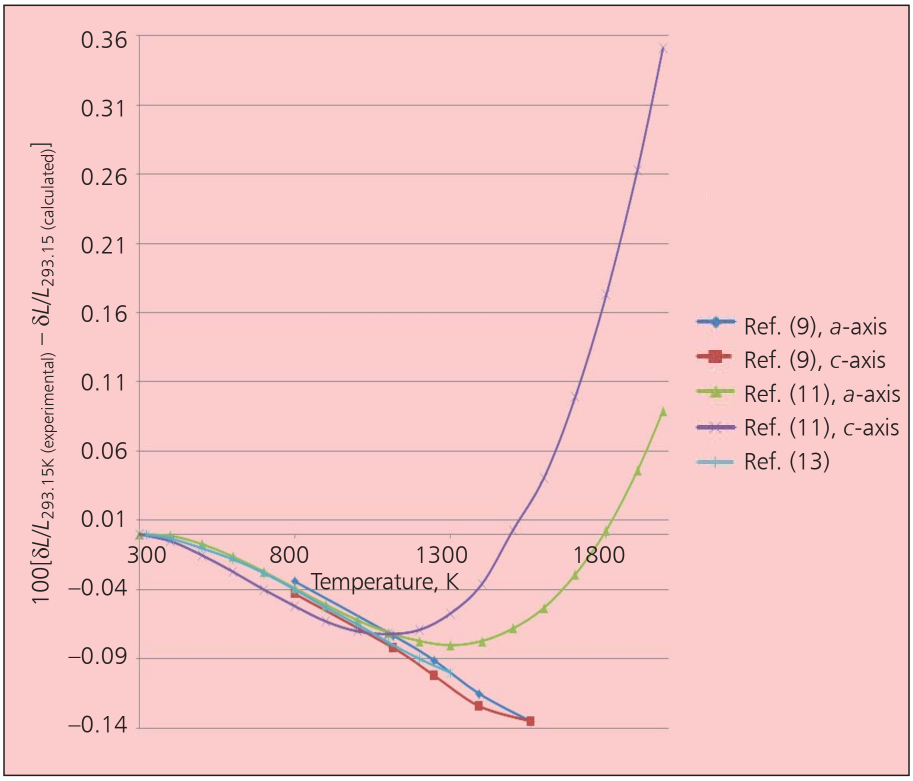

Fig. 1. The difference between length change values derived from the measurements of Hall and Crangle (9), Schröder et al. (11) and Shirasu and Minato (13)

Equations (i) and (ii) as given in **Tables II** and **III** and indicate the degree of incompatibility between the high- and low-temperature data. Various manipulations of subsets of the low-temperature measurements to try and reconcile the differences proved to be unsatisfactory and the measurements of Finkel' *et al.* were rejected. Therefore in order to extrapolate below room temperature Equations (i) and (ii) were differentiated and derived values of the thermal expansion coefficient relative to 293.15 K, α^*, were converted to thermodynamic thermal expansion, α, using $\alpha = \alpha^*/(1 + \delta L/L_{293.15\ \mathrm{K}})$. The α values obtained

Table III

Low-Temperature Crystallographic Properties of Ruthenium

Temperature, K	Lattice parameter, *a*, nm[a]	Lattice parameter, c, nm	c/*a* ratio	Interatomic distance, *d*1, nm	Atomic volume, 10^{-3} nm^3	Molar volume, 10^{-6} m^3 mol^{-1}	Density, kg m^{-3}
0[b]	*0.27028*	*0.42742*	*1.5814*	*0.26462*	*13.520*	*8.142*	*12414*
10	*0.27028*	*0.42742*	*1.5814*	*0.26462*	*13.520*	*8.142*	*12414*
20	*0.27028*	*0.42743*	*1.5814*	*0.26462*	*13.520*	*8.142*	*12414*
30	*0.27028*	*0.42743*	*1.5814*	*0.26462*	*13.520*	*8.142*	*12414*
40	*0.27028*	*0.42743*	*1.5814*	*0.26462*	*13.520*	*8.142*	*12413*
50	*0.27028*	*0.42744*	*1.5815*	*0.26462*	*13.521*	*8.142*	*12413*
60	*0.27028*	*0.42745*	*1.5815*	*0.26463*	*13.521*	*8.143*	*12412*
70	*0.27029*	*0.42746*	*1.5815*	*0.26464*	*13.522*	*8.143*	*12411*
80	*0.27030*	*0.42748*	*1.5815*	*0.26465*	*13.524*	*8.144*	*12410*
90	*0.27031*	*0.42750*	*1.5815*	*0.26466*	*13.525*	*8.145*	*12409*
100	*0.27031*	*0.42752*	*1.5816*	*0.26467*	*13.527*	*8.146*	*12407*
110	*0.27033*	*0.42755*	*1.5816*	*0.26468*	*13.529*	*8.147*	*12406*
120	*0.27034*	*0.42757*	*1.5816*	*0.26470*	*13.531*	*8.148*	*12404*
130	*0.27035*	*0.42760*	*1.5817*	*0.26471*	*13.533*	*8.150*	*12402*
140	*0.27036*	*0.42763*	*1.5817*	*0.26473*	*13.535*	*8.151*	*12400*
150	*0.27037*	*0.42766*	*1.5817*	*0.26475*	*13.537*	*8.152*	*12398*
160	*0.27039*	*0.42769*	*1.5818*	*0.26476*	*13.539*	*8.154*	*12396*
170	*0.27040*	*0.42772*	*1.5818*	*0.26478*	*13.542*	*8.155*	*12394*
180	*0.27041*	*0.42776*	*1.5819*	*0.26480*	*13.544*	*8.156*	*12391*
190	*0.27043*	*0.42779*	*1.5819*	*0.26482*	*13.547*	*8.158*	*12389*
200	*0.27044*	*0.42782*	*1.5820*	*0.26484*	*13.549*	*8.159*	*12387*
210	*0.27045*	*0.42786*	*1.5820*	*0.26485*	*13.552*	*8.161*	*12385*
220	*0.27046*	*0.42789*	*1.5820*	*0.26487*	*13.554*	*8.162*	*12382*
230	*0.27048*	*0.42793*	*1.5821*	*0.26489*	*13.557*	*8.164*	*12380*
240	*0.27050*	*0.42796*	*1.5821*	*0.26491*	*13.559*	*8.166*	*12377*
250	*0.27051*	*0.42800*	*1.5822*	*0.26493*	*13.562*	*8.167*	*12375*
260	*0.27053*	*0.42804*	*1.5822*	*0.26495*	*13.565*	*8.169*	*12373*
270	*0.27054*	*0.42807*	*1.5823*	*0.26497*	*13.567*	*8.170*	*12370*
280	*0.27056*	*0.42811*	*1.5823*	*0.26499*	*13.570*	*8.172*	*12368*
290	*0.27058*	*0.42815*	*1.5824*	*0.26501*	*13.573*	*8.174*	*12365*
293.15	0.27058	0.42816	1.5824	0.26502	13.574	8.174	12364

[a] *a = d2*

[b] *Since all values below 293.15 K are estimated they are given in italics*

at 293.15 K and over the range 300 K to 800 K at 50 K intervals were then fitted to Equations (iii) and (iv) where the values of the specific heat used, C_p, are given by Equation (vii). Equations (iii) and (iv) were then extrapolated below the room temperature region using specific heat values given in the Appendix in order to represent the thermal expansion to absolute zero, although *a*-axis thermal expansion coefficients above 240 K were slightly adjusted in order to give a smooth continuity with the high-temperature selected values. Crystallographic properties derived from Equations (iii) and (iv) are given in **Tables III** and **IV**.

There is the possibility of significant uncertainty in this procedure but it is noted that in comparison, using the same procedure as for the high-temperature data, the measurements of Finkel' *et al.* (12) show a maximum deviation of only 0.006 low at 80 K for the *a*-axis and then converge towards the selected values. For the *c*-axis, there is initially agreement with the selected values and a maximum deviation of only 0.010 low at 220 K. These small differences would actually suggest agreement between the high- and low-temperature data; however, the fitting procedure is so sensitive that these differences represent incompatibility. The low-temperature measurements of Schröder *et al.* (11) are initially 0.027 low at 84 K for the *a*-axis and then converge towards the selected values, whilst for the *c*-axis the value is initially 0.026 low but there is agreement to better than 0.001 above 210 K.

Normally, as an alternative method of calculation, Equations (iii) and (iv) would be fitted to a series of

Table IV

Further Low-Temperature Crystallographic Properties of Ruthenium

Temperature, K	Thermal expansion coefficient, α_a, 10^{-6} K^{-1}	Thermal expansion coefficient, α_c, 10^{-6} K^{-1}	Thermal expansion coefficient, α_{avr}, 10^{-6} K^{-1}	Length change, $\delta a/a_{293.15\,K}$ × 100, %	Length change, $\delta c/c_{293.15\,K}$ × 100, %	Length change, $\delta avr/avr_{293.15\,K}$ × 100, %
0[a]	0	0	0	–0.113	–0.172	–0.132
10	0.04	0.06	0.05	–0.113	–0.172	–0.132
20	0.09	0.16	0.12	–0.113	–0.172	–0.132
30	0.32	0.48	0.37	–0.112	–0.171	–0.132
40	0.70	1.07	0.83	–0.112	–0.171	–0.131
50	1.25	1.91	1.47	–0.111	–0.169	–0.130
60	1.85	2.82	2.17	–0.109	–0.167	–0.129
70	2.39	3.66	2.56	–0.107	–0.163	–0.126
80	2.88	4.40	3.39	–0.105	–0.159	–0.123
90	3.30	5.04	3.88	–0.102	–0.155	–0.119
100	3.66	5.58	4.30	–0.098	–0.149	–0.115
110	3.95	6.03	4.65	–0.094	–0.144	–0.111
120	4.20	6.42	4.94	–0.090	–0.137	–0.106
130	4.42	6.74	5.19	–0.086	–0.131	–0.101
140	4.60	7.02	5.40	–0.081	–0.124	–0.096
150	4.75	7.25	5.58	–0.077	–0.117	–0.090
160	4.88	7.44	5.73	–0.072	–0.109	–0.084
170	4.98	7.61	5.86	–0.067	–0.102	–0.079
180	5.08	7.76	5.97	–0.062	–0.094	–0.073
190	5.17	7.89	6.07	–0.057	–0.086	–0.067
200	5.25	8.01	6.17	–0.052	–0.079	–0.061

(Continued)

Table IV (Continued)

Temperature, K	Thermal expansion coefficient, α_a, 10^{-6} K^{-1}	Thermal expansion coefficient, α_c, 10^{-6} K^{-1}	Thermal expansion coefficient, α_{avr}, 10^{-6} K^{-1}	Length change, $\delta a/a_{293.15\,K}$ × 100, %	Length change, $\delta c/c_{293.15\,K}$ × 100, %	Length change, $\delta avr/avr_{293.15\,K}$ × 100, %
210	*5.32*	*8.12*	*6.25*	*–0.046*	*–0.070*	*–0.054*
220	*5.38*	*8.22*	*6.33*	*–0.041*	*–0.062*	*–0.048*
230	*5.45*	*8.31*	*6.40*	*–0.036*	*–0.054*	*–0.042*
240	*5.50*	*8.40*	*6.47*	*–0.030*	*–0.046*	*–0.035*
250	*5.58*	*8.48*	*6.55*	*–0.024*	*–0.037*	*–0.029*
260	*5.63*	*8.56*	*6.61*	*–0.019*	*–0.029*	*–0.022*
270	*5.68*	*8.63*	*6.66*	*–0.013*	*–0.020*	*–0.016*
280	*5.71*	*8.70*	*6.71*	*–0.008*	*–0.011*	*–0.009*
290	*5.75*	*8.77*	*6.76*	*–0.002*	*–0.003*	*–0.002*
293.15	*5.77*	*8.80*	*6.78*	*0*	*0*	*0*

[a] *Since all values below 293.15 K are estimated they are given in italics*

spline fitted equations; however as there are two axes this could involve a significant number of equations and therefore the much simpler procedure has been adopted of substituting values of C_p from the **Appendix** into the equations.

The Lattice Parameter at 293.15 K

The values of the lattice parameters, a and c, given in **Table V** represent a combination of those values selected by Donohue (15) and more recent measurements. Values originally given in kX units were converted to nanometres using the 2010 International Council for Science: Committee on Data for Science and Technology (CODATA) Fundamental Constants (16, 17) conversion factor for CuKα_1, which is 0.100207697 ± 0.000000028 whilst values given in angstroms (Å) were converted using the default ratio 0.100207697/1.00202 where the latter value represents the old conversion factor from kX units to Å. Lattice parameter values were corrected to 293.15 K using the values of the thermal expansion coefficient selected in the present review. Density values given in **Tables II** and **III** were calculated using the currently accepted atomic weight of 101.07 ± 0.02 (18) and an Avogadro

Table V

Lattice Parameter Values at 293.15 K[a]

Authors (Year)	Reference	Original temperature, K	Original units	Lattice parameter, a, corrected to 293.15 K, nm	Lattice parameter, c, corrected to 293.15 K, nm	Notes
Owen *et al.* (1935)	(18)	291	kX	0.27044	0.42818	(a)
Owen and Roberts (1936)	(7)	291	kX	0.27042	0.42819	(a)
Owen and Roberts (1937)	(8)	293	kX	0.27040	0.42819	(a)

(Continued)

Table V (Continued)

Authors (Year)	Reference	Original temperature, K	Original units	Lattice parameter, *a*, corrected to 293.15 K, nm	Lattice parameter, c, corrected to 293.15 K, nm	Notes
Ross and Hume-Rothery	(10)	303	Å	0.27042	0.42799	(a), (b)
Finkel' *et al.* (1971)	(12)	293	Å	0.27062	0.42815	(a), (b)
Hellawell and Hume-Rothery (1954)	(19)	298	kX	0.27058	0.42817	
Swanson *et al.* (1955)	(20)	300	Å	0.27059	0.42819	
Hall and Crangle (1957)	(9)	rt[b]	Å	0.27058	0.42805	
Anderson and Hume-Rothery (1960)	(21)	293	kX	0.27058	0.42814	
Černohorský (1960)	(22)	295	Å	0.27059	0.42812	
Savitskii *et al.* (1962)	(23)	rt	kX	0.27059	0.42819	
Schröder *et al.* (1972)	(11)	284	Å	0.27056	0.42826	

[a] *Selected values for the present paper are: a = 0.27058 ± 0.00002 and 0.42816 ± 0.00007*

[b] *rt = room temperature*

Notes to Table V

(a) For information only – not included in the average

(b) Lattice parameter values given by Touloukian *et al*. (14)

constant (N_A) of $(6.02214129 \pm 0.00000027) \times 10^{23}$ mol^{-1} (16, 17). From the lattice parameter values at 293.15 K selected in **Table V** as: a = 0.27058 ± 0.00002 nm and c = 0.42816 ± 0.00007 nm, the derived selected density is 12364 ± 3 kg m^{-3} and the molar volume is $(8.1743 \pm 0.0018) \times 10^{-6}$ m^3 mol^{-1}. In **Tables II** and **III** the interatomic distance $d1 = (a^2/3 + c^2/4)^{½}$ and $d2 = a$. The atomic volume is $(\sqrt{3}\ a^2\ c)/4$ and the molar volume is calculated as $N_A\ (\sqrt{3}\ a^2\ c)/4$ which is equivalent to atomic weight divided by density. Thermal expansion is $\alpha_{avr} = (2\ \alpha_a + \alpha_c)/3$ and length change is $\delta avr/avr_{293.15\ K} = (2\ \delta a/a_{293.15\ K} + \delta c/c_{293.15\ K})/3$ (avr = average).

Summary

Because there is disagreement between the high- and low-temperature measurements for ruthenium, satisfactory thermal expansion data is only available above 293.15 K with a novel approach being used to extrapolate below this temperature to derive values which must be considered to be tentative. Clearly further measurements are required for this element.

High-Temperature Thermal Expansion Equations for Ruthenium (293.15 K to 2606 K)

$$\delta a/a_{293.15} = -1.56642 \times 10^{-3} + 4.93471 \times 10^{-6}\, T + 1.34455 \times 10^{-9}\, T^{2} + 1.69158 \times 10^{-13}\, T^{3} \qquad \text{(i)}$$

$$\delta c/c_{293.15} = -2.39045 \times 10^{-3} + 7.52727 \times 10^{-6}\, T + 2.06251 \times 10^{-9}\, T^{2} + 2.61425 \times 10^{-13}\, T^{3} \qquad \text{(ii)}$$

Low-Temperature Thermal Expansion Equations for Ruthenium (0 K to 293.15 K)

$$\alpha_a\ (\mathrm{K}^{-1}) = C_p\,(1.92207 \times 10^{-7} + 8.09046 \times 10^{-11}\, T + 7.16082 \times 10^{-6} / T) \qquad \text{(iii)}$$

$$\alpha_c\ (\mathrm{K}^{-1}) = C_p\,(2.93088 \times 10^{-7} + 1.24609 \times 10^{-10}\, T + 1.09421 \times 10^{-5} / T) \qquad \text{(iv)}$$

Thermal Expansion Equations Representing the Measurements of Finkel' *et al.* (12)

$$\delta a/a_{293.15} = -1.40337 \times 10^{-3} + 3.25082 \times 10^{-6}\, T + 4.63332 \times 10^{-9}\, T^{2} + 2.07266 \times 10^{-12}\, T^{3} \qquad \text{(v)}$$

$$\delta c/c_{293.15} = -1.87652 \times 10^{-3} + 3.44170 \times 10^{-6}\, T + 2.91501 \times 10^{-9}\, T^{2} + 2.44946 \times 10^{-11}\, T^{3} \qquad \text{(vi)}$$

High-Temperature Specific Heat Equation (298.15 K to 2606 K)

$$C_p\ (\mathrm{J\ mol^{-1}\ K^{-1}}) = 23.1728 + 7.28378 \times 10^{-3}\, T - 2.703021 \times 10^{-6}\, T^{2} + 1.50844 \times 10^{-9}\, T^{3} - 97572.6/T^{2} \qquad \text{(vii)}$$

Appendix: Specific Heat Values for Ruthenium

Because of the large number of spline fitted equations that would be required to conform to Equations (iii) and (iv), a simpler approach is used for the non-cubic metals in that specific heat values are directly applied to these equations. However this would require that the Table of low-temperature specific heat values originally given by the present author (24) has to be more comprehensive and the revised Table is given as **Table VI**. The high-temperature specific heat values corresponding to the above reference is given as Equation (vii) and is derived by differentiating the selected enthalpy equation.

Table VI

Low-Temperature Specific Heat Values for Ruthenium

Temperature, K	Specific heat, J mol^{-1} K	Temperature, K	Specific heat, J mol^{-1} K	Temperature, K	Specific heat, J mol^{-1} K
10	0.0438	50	3.682	130	17.130
15	0.0955	60	5.838	140	18.050
20	0.186	70	7.991	150	18.837
25	0.359	80	10.000	160	19.509
30	0.731	90	11.839	170	20.093
35	1.233	100	13.455	180	20.607
40	1.877	110	14.854	190	21.066
45	2.707	120	16.071	200	21.480

(Continued)

Table VI (Continued)

Temperature, K	Specific heat, J mol^{-1} K	Temperature, K	Specific heat, J mol^{-1} K	Temperature, K	Specific heat, J mol^{-1} K
210	21.857	250	23.047	290	23.889
220	22.200	260	23.277	293.15	23.950
230	22.514	270	23.490	298.15	24.046
240	22.796	280	23.693	300	24.071

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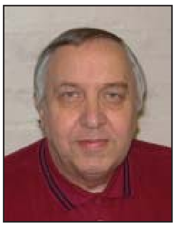

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