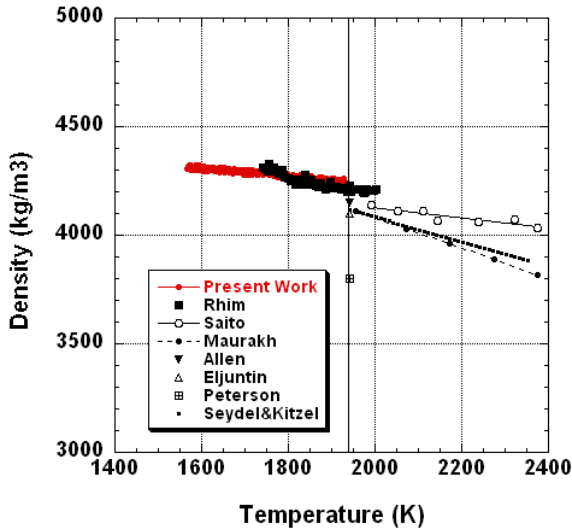


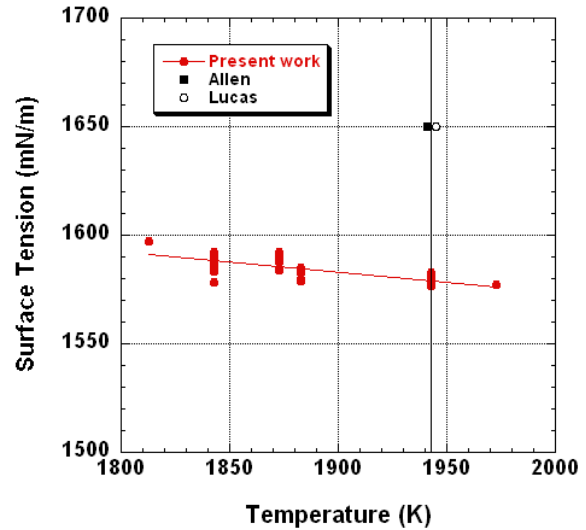
# Ti (Titanium)

Ti is very evaporative, and it was difficult to measure viscosity and surface tension.

## Density graph



## Surface tension graph



- T. Ishikawa and P.-F. Paradis, *Journal of Electronic Materials* 34 (2005), 1526-1532.

• **Reference:**

P.-F. Paradis, W. -K. Rhim, *J. Chem. Thermodynamisc*, 32 (2000), 123-133.  
 T. Saito, Y. Shiraishi, and Y. Sakuma, *Trans ISIJ* 9 (1969), 118-126.  
 M. A. Maurakh, *Trans. Indian Inst. Metals*, 14(1964), 209-225.  
 B. C. Allen, *Trans AIME*, 227 (1963), 1175.  
 Eljutin and Maurakh, *Izv. A. N., OTN*, 4 (1956), 129.  
 A. W. Peterson, H. Kadesky, P. H. Keck, and E. Scharz, *J. Appl. Phys.*, 29(1958), 213U .  
 Seydel and W. Kitzel, *J. Phys. F: Metal Phys.*, 9 (1979), L153-160.

- P. -F. Paradis, T. Ishikawa and S. Yoda, *Int. J. Thermophys.*, 23(2002), 825-842.

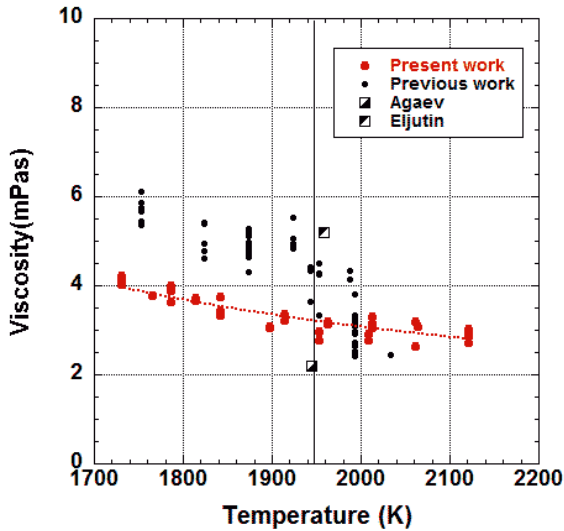
• **Reference:**

B. C. Allen, *Trans. AIME*, 227 (1963), 1175. L. D. Lucas, *Tech l'Ing.*, 7, Form. M67 (1984)

## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

new



- **Data taken by improved measurement method(Present Works)** new

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

- **Reference(Previous work) :**  
 P. -F. Paradis, T. Ishikawa and S. Yoda, Int. J. Thermophys., 23(2002), 825-842 .

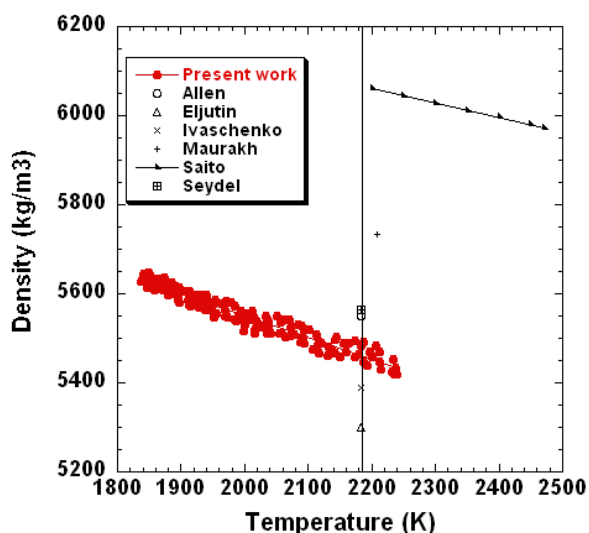
**Reference:**

A. D. Agaev, V. I. Kostikov, and V. N. Bobkovski, Izv. Akad. Nauk. SSSR Metall. 43 (1980). V. P. Eljutin, M. A. Maurakh, and I. A. Penkov, Izv. Vuz. Chem. Met. (1965), 128.

# V (Vanadium)

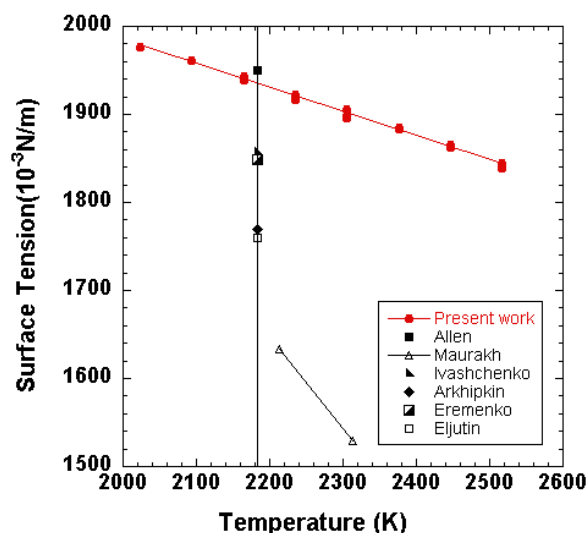
Due to its high vapor pressure, it was very difficult to measure viscosity and surface tension. By improving electrode design, these properties were successfully measured.

## Density graph



- P.-F. Paradis, T. Ishikawa, T. Aoyama, S. Yoda, *J. Chem. Thermodyn.*, 34 (2002), 1929-1942.
- **Reference:**  
B. C. Allen, *Trans AIME*, 227 (1963), 1175.  
Eljutin, Kostikov and Penkov, *Poroshk. Met.*, 9 (1970), 46  
Yu. N. Ivaschenko, and P. C. Marchenuk, *Teplov. Vys. Temp.*, 11 (1973), 1285-1287  
Maurakh, *Trans. Indian Inst. Met.* 14 (1964), 209  
S. Saito, Y. Shiraishi, and Y. Sakuma, *Trans ISIJ* 9 (1969), 118 U. Seydel and W. Kitzel, *J. Phys. F: Metal Phys.*, 9 (1979), L153.

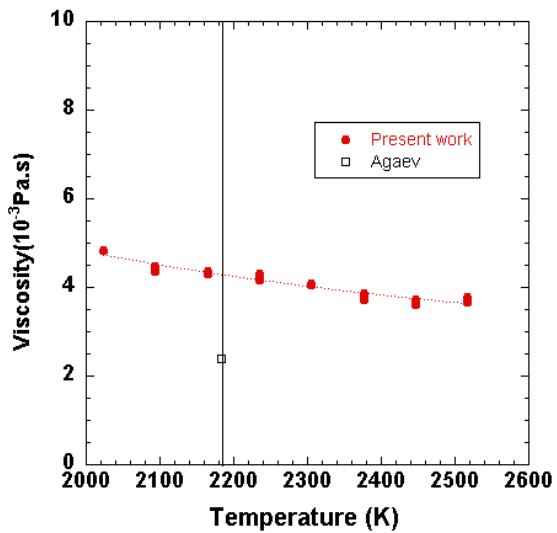
## Surface tension graph



- J. T. Okada, T. Ishikawa, Y. Watanabe, P.-F. Paradis, *J. Chem. Thermodyn.*, 42 (2010), 856-859.
- **Reference:**  
B. C. Allen, *Trans AIME*, 227 (1963), 1175.  
Maurakh, *Trans. Indian Inst. Met.* 14 (1964), 209  
Yu. N. Ivaschenko, and P. C. Marchenuk, *Teplov. Vys. Temp.*, 11 (1973), 1285-1287  
V. I. Arkhipkin, A. D. Agaev, G. A. Grogorev and V. I. Kostikov, *Ind. Lab. (USSR)*, 39 (1973), 1340.  
V. N. Eremenko, Yu. N. Ivashchenko, and P. S. Martsenyuk, *High Temp.* 22 (1984), 567.  
Eljutin, Kostikov and Penkov, *Poroshk. Met.*, 9 (1970), 46

## Viscosity graph

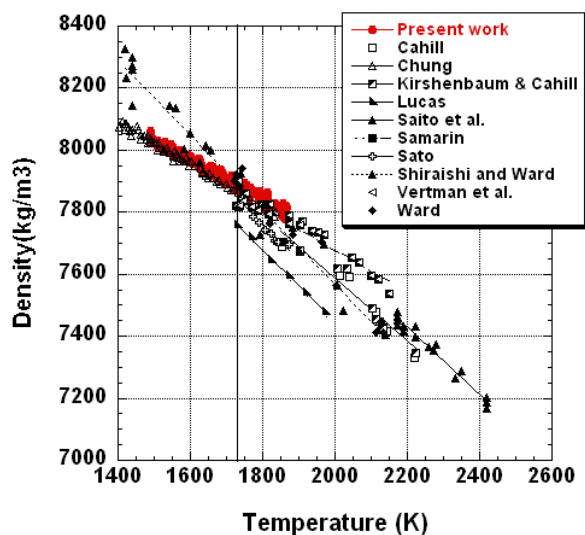
Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



- J. T. Okada, T. Ishikawa, Y. Watanabe, P.-F. Paradis, J. Chem. Thermodyn., 42 (2010), 856-859.
- **Reference:** A. D. Agaev, V. I. Kostikov, and V. N. Bobkovski, Izv. Akad. Nauk. SSSR Metall. 43 (1980).

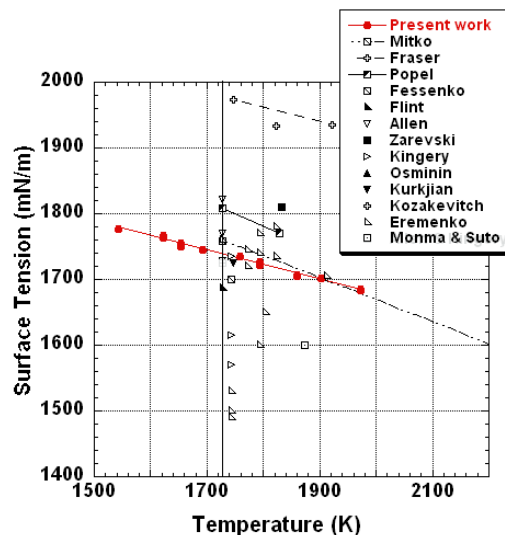
# Ni(Nickel)

## Density graph



- T. Ishikawa, P. -F. Paradis, Y. Saita, J. Japan Inst. Metals. 68 (9) (2004), 781-786.
- **Reference:**  
 S. K. Chung, D. B. Thiessen, and W. -K. Rhim, Rev. Sci. Instrum., 67 (1996), 3175-3181.  
 A. D. Kirshenbaum and J. A. Cahill, Trans, Quartely of A.S.M. Geld and Vertman, Fiz. Met. i. Met, 10 (1960), 793  
 Lucas, Mem. Sci. Rev. Met., 61 (1964), 97.  
 Saito and Sakuma, J. Jpn. Inst. Met., 31(1967), 1140.  
 S. Y. Shiraishi and R. G. Ward: Can. Metall. Quart., 3 (1964), 117

## Surface tension graph

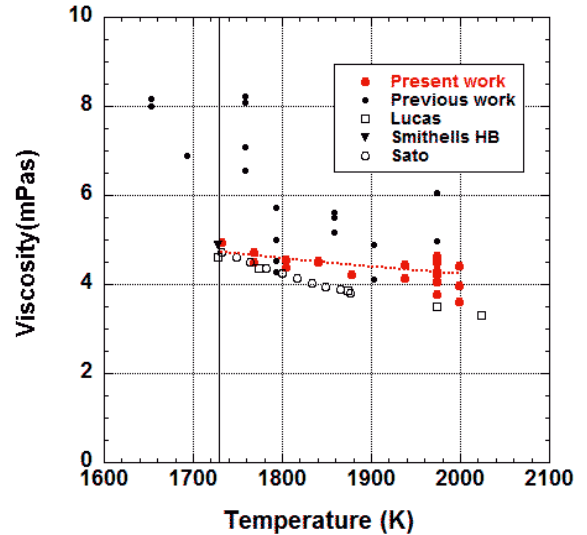


- T. Ishikawa, P. -F. Paradis, Y. Saita, J. Japan Inst. Metals. 68 (9) (2004), 781-786.
- **Reference:**  
 Mitko, Dubini, Timofejev, and Tshagodajev, Izv. Vyss. Uch. Sav., Tsvetn. Met., 3, 84 (1978).  
 Fraser, Liu, Hamielec, and Murarka, Met. Trans., 2, 817 (1971).  
 Popel, Shergin, and Zarevski, Zh. Fiz. Khim., 43, 2365 (1969).  
 V.V. Fesenko and M. I. Vasiliu, Poroshkov. Met. Akad. Nauk Ukr. SSR, 1 (1961), 25.  
 Flint, J. Nucl. Mat., 16, 260 (1965).  
 B.C. Allen, Trans. AIME 227, 1175 (1963).  
 Zarevski and Popel, Fiz. Met. i Met., 13, 451 (1962).  
 Kingery and Humenik, J. Phys. Chem., 57, 359 (1953).  
 Osminin, Zh. Fiz. Khim., 42, 2610 (1969).  
 Kurkjian and Kingery, J. Phys. Chem., 60, 961 (1956).  
 P. Kozakevitch and G. Urbain, J. iron Steel Inst., 186 (1957), 167.  
 V. N. Eremenko and V. I. Nizhenko, in Poverkh. Yav. Rasp. Prots. Poro. Met.",

97-109 (1963),  
 Naukova Dumka. Monma and Suto, J.  
 Inst. Met., 1, 69 (1960).

## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken  
 by improved measurement method  
 with 120 Hz position control  
 frequency) **new**



- **Data taken by improved measurement method(Present Works)** **new**

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

- **Reference(Previous work) :**

T. Ishikawa, P. -F. Paradis, Y. Saita, J. Japan Inst. Metals. 68 (9) (2004), 781-786.

**Reference:**

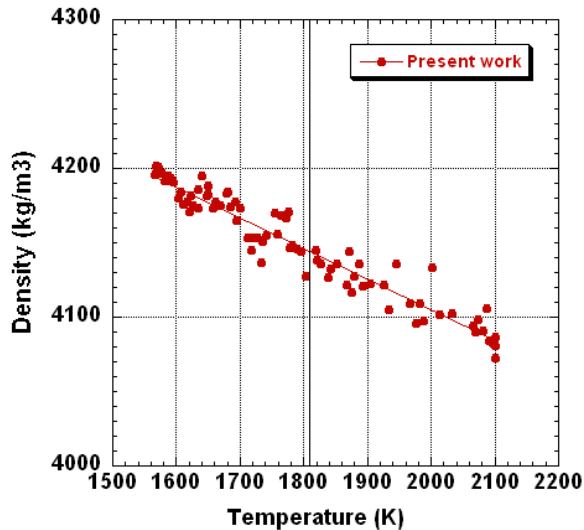
L. D. Lucas, C. R. Acad. Sci. 260 (1965), 499.

E. A. Brandes and G. B. Brook, Smithells Metals Reference Book, 7th edition (Butterworth-Heinemann, 1992), 14-7.

Y. Sato, K. Sugisawa, D. Aoki, F. Nozoe and T. Yamamura, Proc. The 23rd Japan Symposium on thermophysical properties, 2002, Tokyo, 27-29.

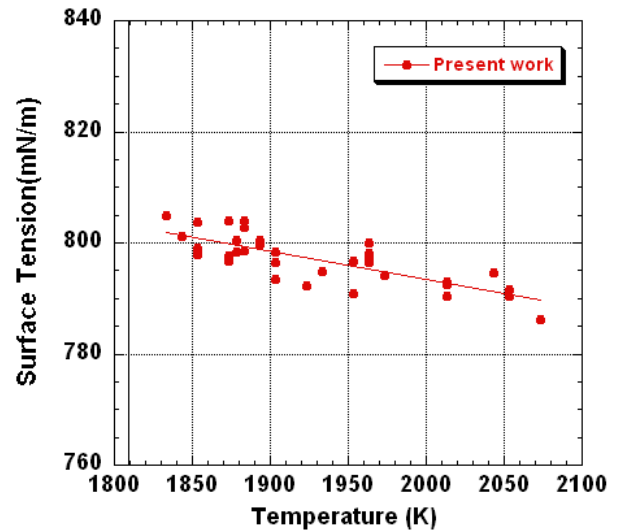
# Y(Yttrium)

## Density graph



- P. -F. Paradis, T. Ishikawa, N. Koike, *Microg. Sci. Tech.* 21 (2009), 113-118.
- **Reference:**  
Fogel, A.A., Sidorova, T.A., Chuprikov, G.E., Mezdrogina, M.M.: Determining the surface tension of yttrium alloys by levitation melting. *Izv. Akad. Nauk SSSR, Metal.*, Vol. 1, p. 50 (1975)  
V. I. Kononenko, A. L. Sukhman, S. L. Gruverman, and V. V. Torokin, *Phys. Stat. Solid.*, 84A, (1983), 423.  
S. V. Stankus and A. S. Basin, in *Fazovie perekhodi v chistikh metallakh i binarnikh splavakh*, Izd. Nauka (Sibirskoe otdelenie), Novosibirsk, 1980, 72.

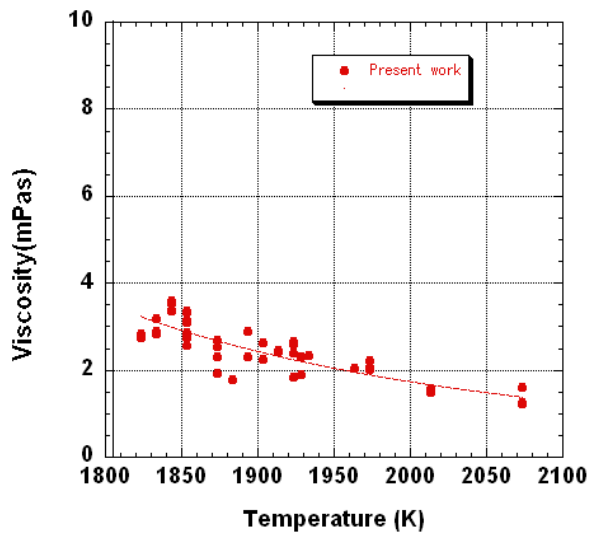
## Surface tension graph



- P. -F. Paradis, T. Ishikawa, N. Koike, *Microg. Sci. Tech.* 21 (2009), 113-118.
- **Reference:**  
Fogel, A.A., Sidorova, T.A., Chuprikov, G.E., Mezdrogina, M.M.: Determining the surface tension of yttrium alloys by levitation melting. *Izv. Akad. Nauk SSSR, Metal.*, Vol. 1, p. 50 (1975)  
Sukhman, A.L., Kononenko, V.I., Gruverman, S.L. and Torokiv, V.V., *Poverkhnostnye svoistva rasplavov (Surface properties of melts)* (in Russian), 107, Nauka Dumka, 1982. V. I. Kononenko, A. L. Sukhman, S. L. Gruverman, and V. V. Torokin, *Phys. Stat. Solid.*, 84A, (1983), 423.

## Viscosity graph

Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



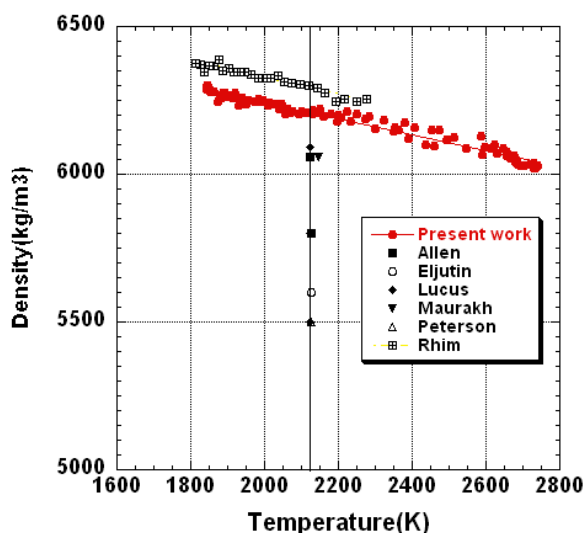
- P. -F. Paradis, T. Ishikawa, N. Koike, *Microg. Sci. Tech.* 21 (2009), 113-118.
- Reference: N/A



# Zr(Zirconium)

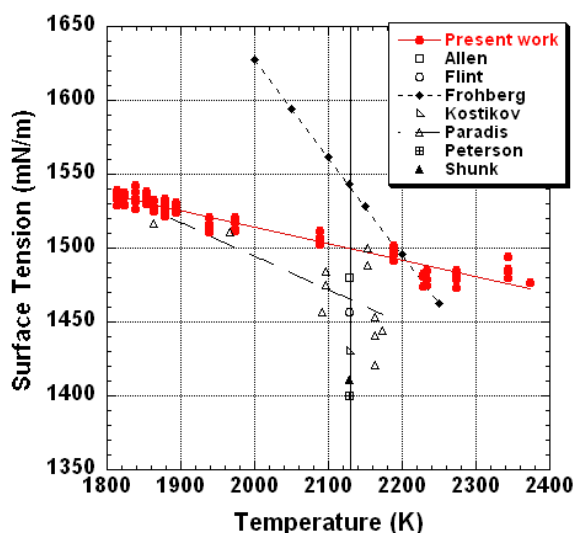
Zirconium is a “friendly” sample for electrostatic levitation because of its moderate melting temperature and low vapor pressure, and it is used for facility check out.

## Density graph



- T. Ishikawa, P. -F. Paradis, T. Itami, and S. Yoda, *Measurement Science and Technology*, 16 (2005), 443-451.
- **Reference:**  
 B. C. Allen, *Trans AIME*, 227 (1963), 1175.  
 V. P. Eljutin, V. I. Kostikov, and I. A. Penkov, *Poroshk. Met.*, 9 (1970), 46-51  
 L. D. Lucas, *Tech l'Ing.*, 7, Form. M65 (1984)  
 Maurakh, *Trans. Indian Inst. Met.* 14 (1964), 209  
 A. W. Peterson, H. Kedesdy, P. H. Keck, E. Schwarz, *J. Appl. Phys.* 29 (1958), 213.  
 P. -F. Paradis and W. K. Rhim, *J. Mater. Res.*, 14 (1999), 3713-3719

## Surface tension graph

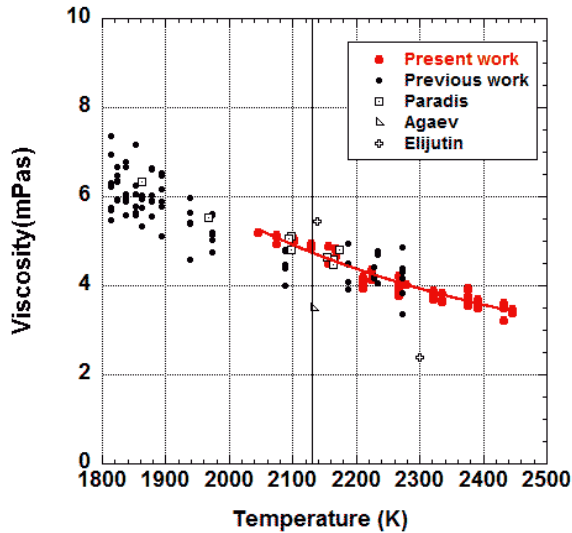


- P. -F. Paradis, T. Ishikawa and S. Yoda, *Int. J. Thermophys.*, 23(2002), 825-842.
- **Reference:**  
 B. C. Allen, *Trans. AIME*, 227 (1963), 1175. Flint, *J. Nucl. Mat.*, 16 (1965), 260.  
 I. Egry, A. Diefenbach, W. Dreier, and J. Piller, *Int. J. of Thermophysics*, 22 (2001), 569-578.  
 Kostikov, Grigorjev, Arkhipkin, and Agaev, *Izv. Vyss. Uch. Sav. Chern. Met.*, 3 (1972), 25.  
 P. -F. Paradis and W. K. Rhim, *J. Mater. Res.*, 14 (1999), 3713-3719  
 A. W. Peterson, H. Kadesky, P. H. Keck, and E. Scharz, *J. Appl. Phys.*, 29(1958), 213-216.  
 Shunk and Burr, *Trans. AIME*, 55 (1962), 786.

## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

◀new



- **Data taken by improved measurement method(Present Works) ◀new**

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

- **Reference(Previous work) :**

P. -F. Paradis, T. Ishikawa and S. Yoda, Int. J. Thermophys., 23(2002), 825-842.

**Reference:** P. -F. Paradis and W. K. Rhim, J. Mater. Res., 14 (1999), 3713-3719

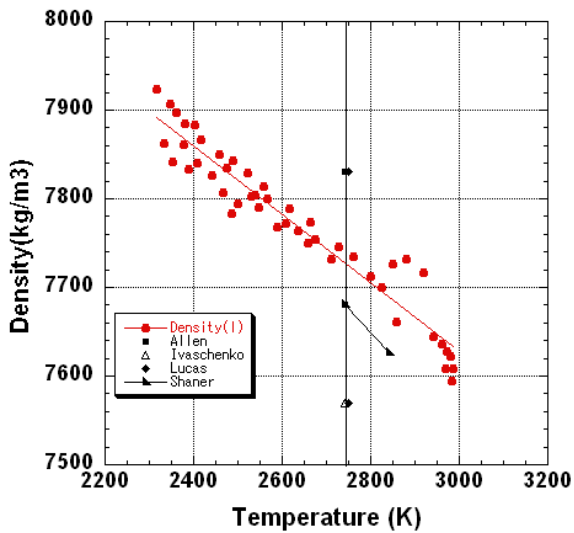
A. D. Agaev, V. I. Kostikov, and V. N. Bobkovski, Izv. Akad. Nauk. SSSR Metall. 43 (1980).

V. P. Eljutin, M. A. Maurakh, and V. D. Turov, Izv. Vyssh. Ucheb. Zaved. Chern. Met. 8 (1965), 110

# Nb(Niobium)

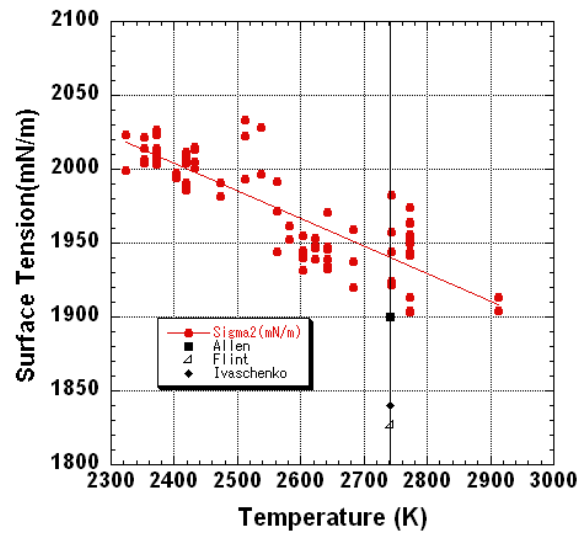
Niobium was the first target to be melt in our electrostatic levitation furnace in JAXA. Density of molten Nb was measured in 2000, and surface tension and viscosity were measured in 2002.

## Density graph



- T. Ishikawa, P. F. Paradis, T. Itami, and S. Yoda, Measurement Science and Technology, 16 (2005), 443-451.
- **Reference:**  
B. C. Allen, Trans AIME, 227 (1963), 1175.  
Yu. N. Ivaschenko, and P. C. Marchenuk, Teplov. Vys. Temp., 11 (1973), 1285-1287  
L. D. Lucas, Tech I'Ing., 7, Form. M65 (1984)  
J. W. Shaner, G. P. Gathers, and C. Minichino, High Temp. High Press., 8(1976), 425

## Surface tension graph

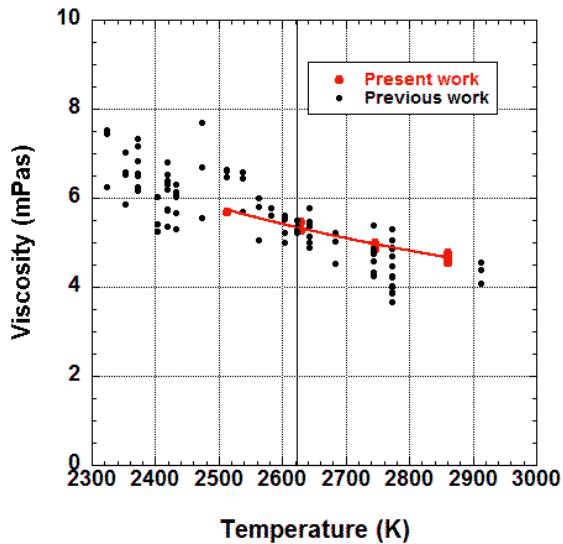


- P. F. Paradis, T. Ishikawa and S. Yoda, Int. J. Thermophys., 23(2002), 825-842.
- **Reference:**  
B. C. Allen, Trans. AIME, 227 (1963), 1175. Flint, J. Nucl. Mat., 16 (1965), 260.  
Yu. N. Ivashchenko and P. S. Martsenyuk, High Temp., 11 (1973), 1146.

## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

new



- **Data taken by improved measurement method(Present Works)** new

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

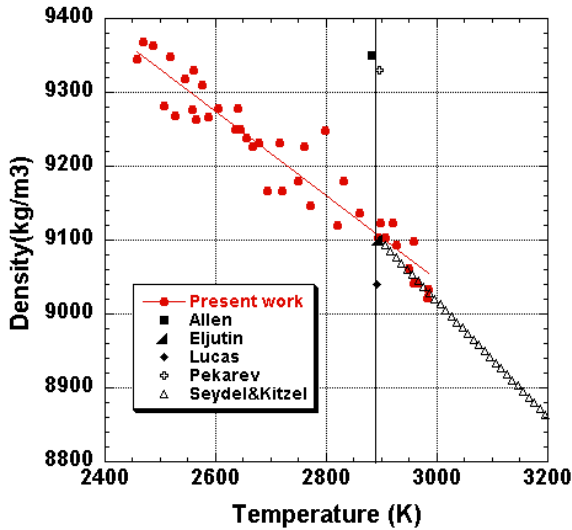
- **Reference(Previous work) :**

P. -F. Paradis, T. Ishikawa and S. Yoda, Int. J. Thermophys., 23(2002), 825-842.

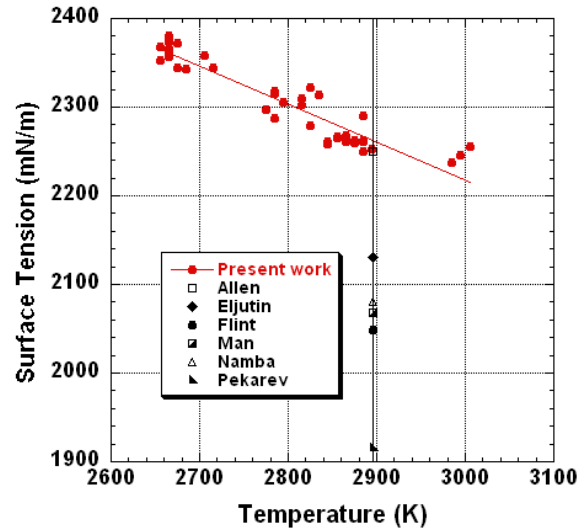
# Mo(Molybdenum)

Due to its high melting temperature, Mo can't be molten with CO2 lasers (200 W) and a YAG laser (500 W, shooting through the top electrode) was added.

## Density graph



## Surface tension graph



- P. -F. Paradis, T. Ishikawa, S. Yoda, *Int. J. Thermophys.* 23(2002), 555-569.

- **Reference:**  
G.Lang, "Density of liquid elements", in *CRC Handbook of Chemistry and Physics*, 72nd edition, edited by D. R. Lide, (CRC Press, Boca Raton, 1991-1992), 4-124.  
T. Itami, "Condensed Matter – Liquid Transition Metals and Alloys", in *Condensed Matter Disordered Solids*, edited by S. K. Srivastava and N. H. March (World Scientific, Singapore, 1995), 123-250.

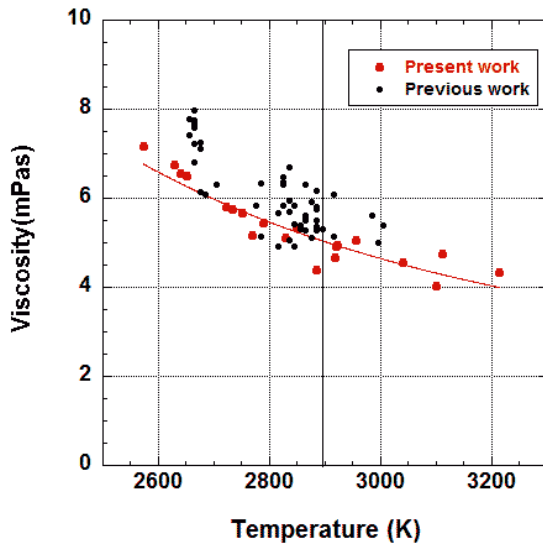
- P.-F. Paradis, T. Ishikawa, and N. Koike, *International Journal of Refractory Metals and Hard Materials* 25 (2007), 95-100.

- **Reference:**  
B. C. Allen, *Trans. AIME*, 227 (1963), 1175.  
V. P. Eljutin, V. I. Kostikov, and I. A. Penkov, *Poroshk. Met.*, 9 (1970), 46-51  
Flint, *J. Nucl. Mat.*, 16 (1965), 260.  
(2000), 793-804.  
S. Namba and T. Isobe, *Sci. Pap. Inst. Phys. Chem. Res.*, Tokyo, 57 (1963), 5154.  
Pekarev, *Izv. Vyss. Uch. Sav.*, *Tsvetn. Met.*, 6 (1963), 111

## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

new



- **Data taken by improved measurement method(Present Works)** new

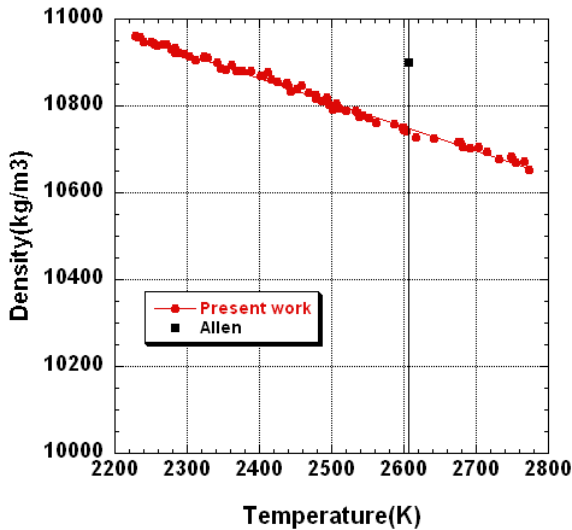
T. Ishikawa, P.-F Paradis, J. Okada, M. V. Kumar, Y. Watanabe, "Viscosity of molten Mo, Ta, Os, Re, and W measured by electrostatic levitation", J. Chem. Thermodynamics 65 (2013), 1-6.

- **Reference(Previous work) :**

P.-F. Paradis, T. Ishikawa, and N. Koike, International Journal of Refractory Metals and Hard Materials 25 (2007), 95-100

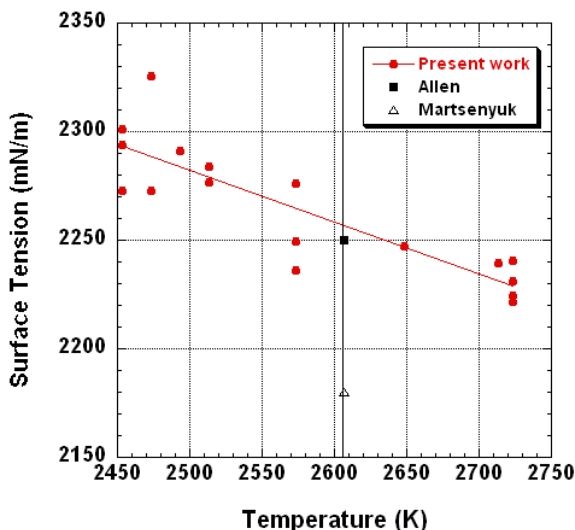
# Ru(Ruthenium)

## Density graph



- P. -F. Paradis, T. Ishikawa, and S. Yoda, J of Materials Research, 19 (2004), 590-594.
- Reference:  
B. C. Allen, Trans AIME, 227 (1963), 1175.

## Surface tension graph

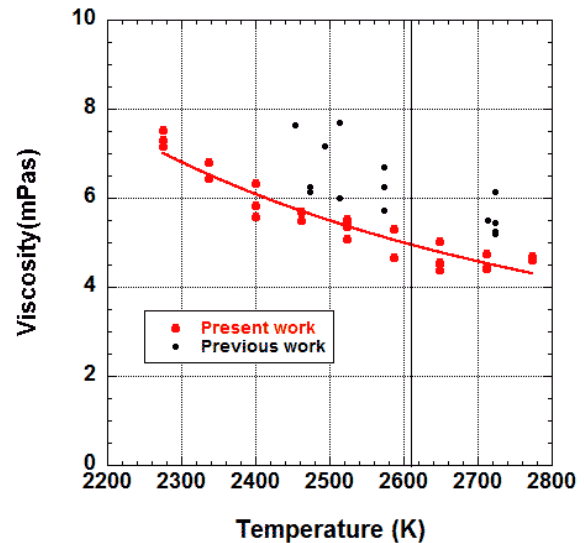


- P. -F. Paradis, T. Ishikawa, and S. Yoda, J of Materials Research, 19 (2004), 590-594.
- Reference:  
B. C. Allen, Trans AIME, 227 (1963), 1175. P. S. Martsenyuk and Yu. N. Ivashchenko, Adgez. Rasp. Paika Mater., 20 (1988), 15.

## Viscosity graph

Viscosity data has been updated. (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

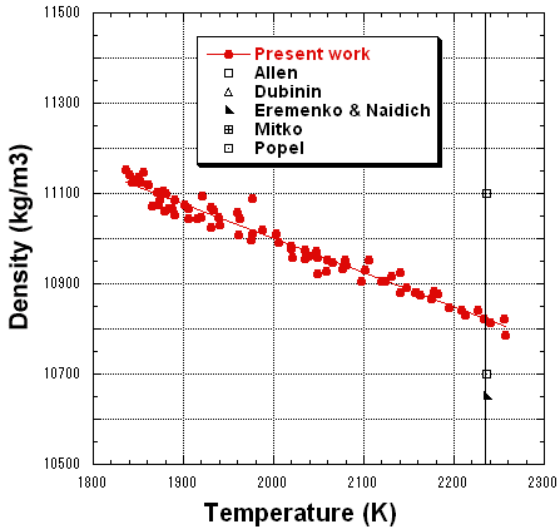
**new**



- Data taken by improved measurement method (Present Works) **new**  
T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305
- Reference (Previous work):  
P. -F. Paradis, T. Ishikawa, and S. Yoda, J of Materials Research, 19 (2004), 590-594.

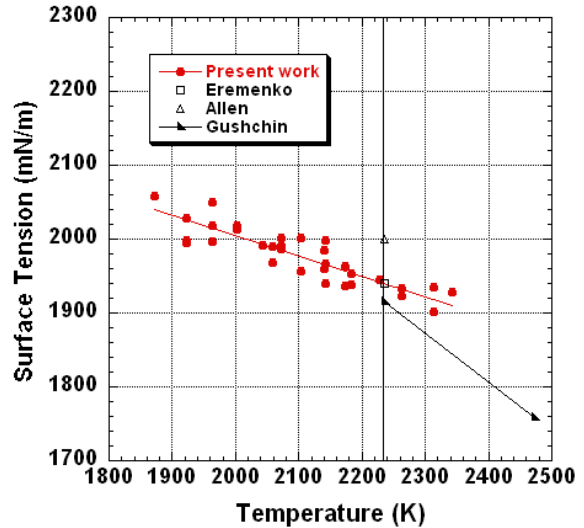
# Rh(Rhodium)

## Density graph



- P. -F. Paradis, T. Ishikawa, and S. Yoda, *Int. J. of Thermophys.*, 24 (2003), 1121-1136.
- **Reference:**  
 B. C. Allen, *Trans AIME*, 227 (1963), 1175.  
 Dubinin, Vlasov, Timofejev, Safonov, and Chegodajev, *Izv. Vtss. Uchebn. Saved.*, *Tsvetn. Met.*, 4 (1975), 160.  
 Eremenko and Naidich, *Izv. A. N. OTN*, 6 (1961), 100  
 Mitko, Dubinin, Timofejev, and Chegodajev, *Izv. Vyss. Uchebn. Saved.*, *Tsvetn. Met.*, 3 (1978), 84  
 S. I. Popel, B. V. Tsareveskii, and N. K. Dzhemilev, *Fiz. Met. Metall. SSSR*, 18 (1964), 468.

## Surface tension graph



- P. -F. Paradis, T. Ishikawa, and S. Yoda, *Int. J. of Thermophys.*, 24 (2003), 1121-1136.
- **Reference:**  
 V. N. Eremenko and Yu. V. Naidich, *Izv. Akad. Nauk. SSR, O. T. N. Met. Topliva*, 6 (1961), 100  
 B. C. Allen, *Trans. AIME*, 227 (1963), 1175.  
 S. G. Gushchin, N. A. Vatolin, E. L. Dubinin, and A. I. Timofeev, *Ogneupory* 12 (1977), 49.

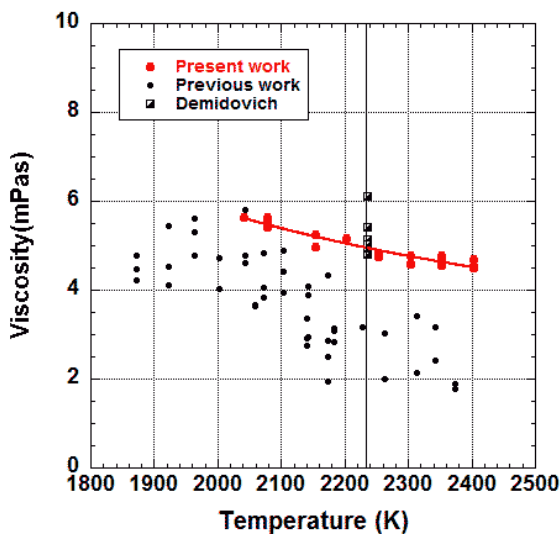


## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

**new**

Since the first viscosity measurement had been affected by sample position control, viscosity data was taken with an improved measurement method.



- **Data taken by improved measurement method(Present Works)** **new**

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

- **Reference(Previous work) :**  
 P. -F. Paradis, T. Ishikawa, and S. Yoda, Int. J. of Thermophys., 24 (2003), 1121-1136.

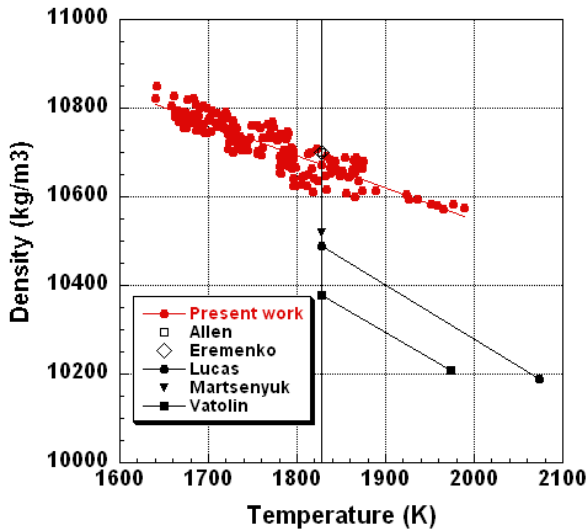
**Reference:**

O. V. Demidovich, A. A. Zhuchenko, E. L. Dubinin, N. A. Vatolin and A. I. Timofeev, Izv. Akad. Nauk. SSSR Met. 1 (1979), 73

-

# Pd(Palladium)

## Density graph



- P.-F. Paradis, T. Ishikawa, Y. Saita, and S. Yoda, *Int. J of Thermophys.* 25(2004), 1905-1912.
- **Reference:**  
 B.C. Allen, *Trans. AIME* 227: 1175 (1963)  
 V.N. Eremenko and E.J. Naidich, *Izv. Akad. Nauk. O.T.N.* 6: 100 (1961)  
 L.-D. Lucas, *C.R. Acad. Sci. (Fr)* 253: 2526 (1961).  
 P.S. Martsenyuk and Yu.V. Ivaschenko, *Ukr. Khim. Zhur. (SU)* 40: 431 (1974)  
 B. A. Vatolin, P.V. Esin, A. K. Ukhov, and E.L. Dubinin, *Trudy Inst. Met. Sverdlovsk* 18: 73 (1969)

## Surface tension graph

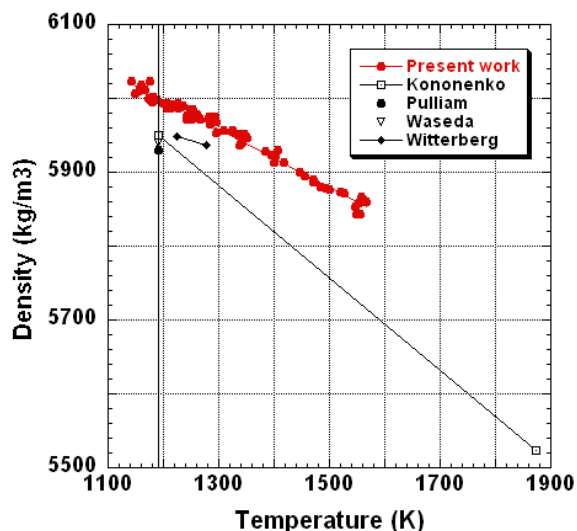
To Be Measured

## Viscosity graph

To Be Measured

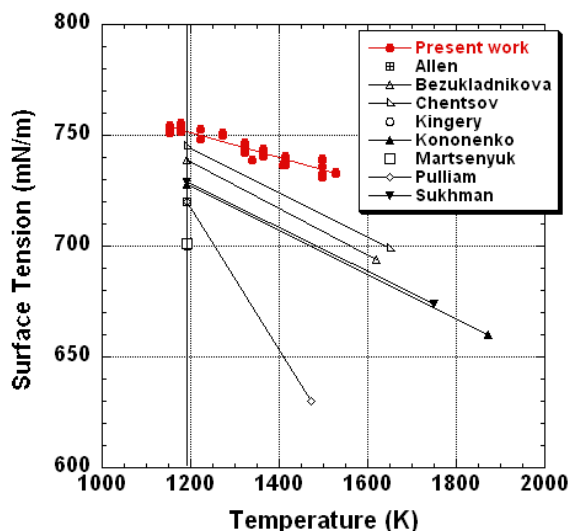
# La(Lanthanum)

## Density graph



- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.
- **Reference:**  
 V.I.Kononenko, A. L. Sukhman, S. L. Gruverman, V. V. Torokin, Phys. Stat. sol. (a)84,423 (1984)  
 Pulliam, G.R. and Fitzsimmons, E.S., Report US Atom. Energy Comm, Ames Lab. Rep. No.ISC-659-1955, 1955.  
 Y. Waseda and S. Tamaki, Phil. Mag., 36, 1, 1977.  
 L.J. Wittenberg, D. Ofte, et W. G. Rohr, Proceedings of the third rare earth conference 1963 vol. II 1964 Gordon and Breach, 257.

## Surface tension graph

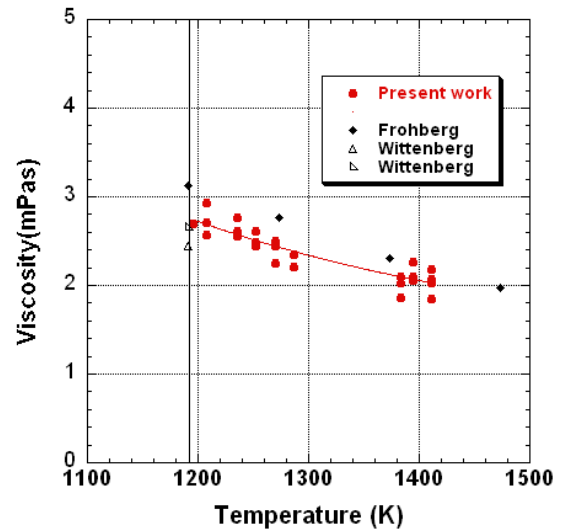


- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.
- **Reference:**  
 B. C. Allen, "Surface Tension of Liquid Metals", in Liquid Metals Chemistry and Physics, edited by S. Z. Beer, (Merzel Dekker, New York, 1972), 186-188.  
 Bezukladnikova, L.L., Kononenko, V.I. and Torokin, V.V., Teplofiz. Vys. Temp., 27, 478, 1989.  
 Chentsov, V.P., Dissertation Inst. Tekh. Metallurgiya UNTs, Akad. Nauk. SSSR, Sverdlovsk, 1972.  
 Kingery, W.D., Amer. Ceram. Soc. Bull., 35, 108, 1956.  
 V.I.Kononenko, A. L. Sukhman, S. L. Gruverman, V. V. Torokin, Phys. Stat. sol. (a)84,423 (1984)  
 P. S. Martsenyuk and Yu. N. Ivaschenko, Adgez. Rasp. Paika Mater., 1984, 12, 19.  
 Pulliam, G.R. and Fitzsimmons, E.S., "Reactions of Cerium and Lanthanum with ceramic oxides", Report US Atom. Energy Comm, Ames Lab. Rep. No.ISC-659-1955, 1955.  
 Sukhman, A.L., Kononenko, V.I., Gruverman, S.L. and Torokiv, V.V., Poverkhnostnye svoistva rasplavov

(Surface properties of melts) (in Russian), 107, Nauka Dumka, 1982

## Viscosity graph

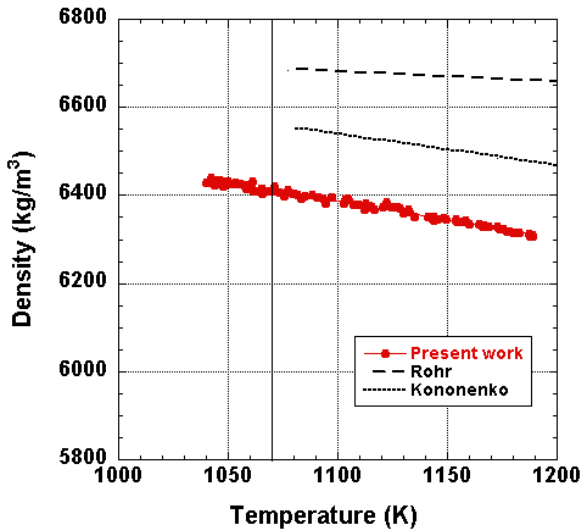
Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.
- **Reference:**  
 Frohberg, M. and Cakici, T., Z. Metallkunde, 69, 296, 1978. Wittenberg, L.J., Ofte, D. and Rohr, W.G., "Rare Earth Research", Vol II ed. K.S. Vorres, Gordon and Breach, p. 257, 1964. L. J. Wittenberg, R. Dewitt, in the Properties of liquid metals (ed. by S. Takeuchi), p.555. Taylor and Francis, London, (1973)

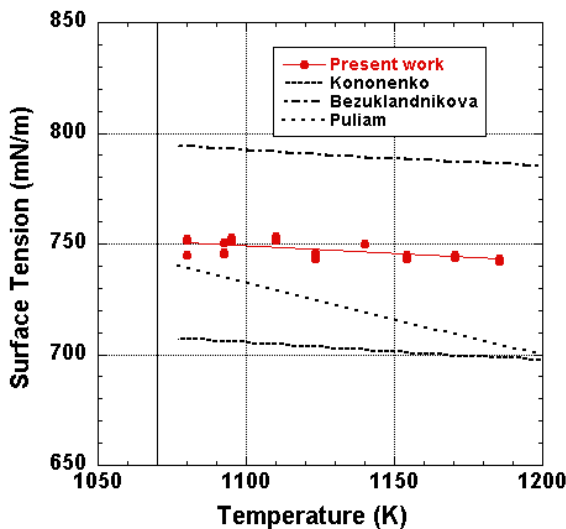
# Ce(Cerium)

## Density graph



- J. Li, T. Ishikawa, J. T. Okada, Y. Watanabe, J. Yu, S. Yoda, Z. Yuan, Journal of Materials Research 24 (2009), 2449
- Reference:**  
W. G. Rohr, Journal of less common metals, 10 (1966), 389  
Kononenko, Phys. stat. Sol. (a) 84, 423 (1984)

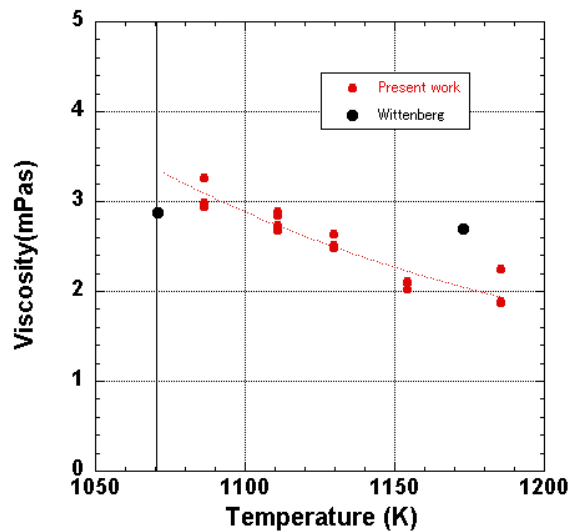
## Surface tension graph



- J. Li, T. Ishikawa, J. T. Okada, Y. Watanabe, J. Yu, S. Yoda, Z. Yuan, Journal of Materials Research 24 (2009), 2449
- Reference:**  
Kononenko, Phys. stat. Sol. (a) 84, 423 (1984)  
L.L. Bezuklandnikova, V. I. Kononenko, V. V. Torokin, Teplofiz. Vys. Temp 1989, 27, (3), 478  
G. R. Pulliam and E. S. Fitzsimmons, Ames lab. Rep. , No. ISC-659, 1955

## Viscosity graph

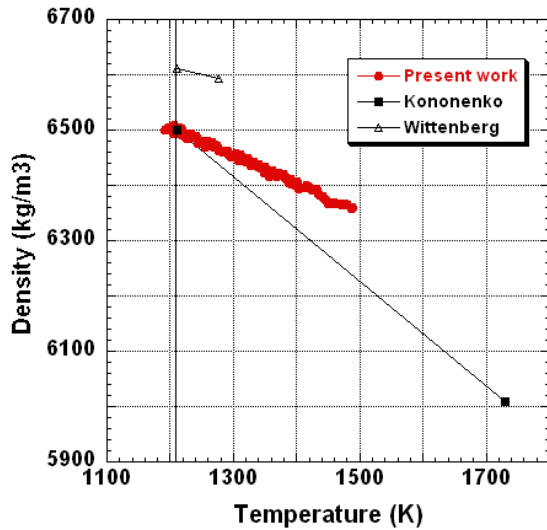
Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



- J. Li, T. Ishikawa, J. T. Okada, Y. Watanabe, J. Yu, S. Yoda, Z. Yuan, Journal of Materials Research 24 (2009), 2449
- Reference:**  
L.G. Wittenberg, R. DeWitt, in the properties of liquid metals (ed. By Tacheuchi), p.555, Taylor and Francis, London (1973)

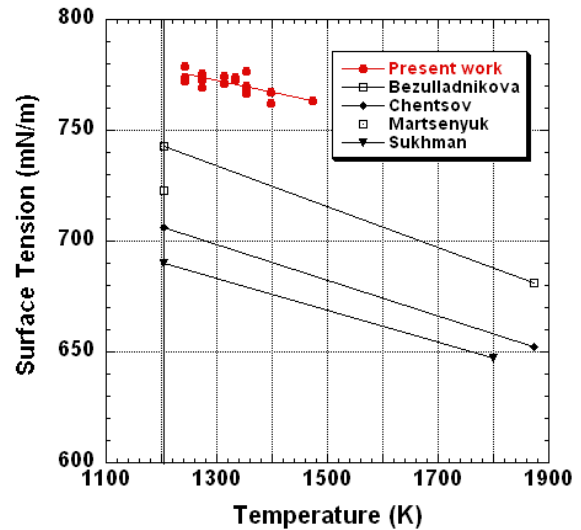
# Pr(Praseodymium)

## Density graph



- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.
- **Reference:**  
V. I. Kononenko, A. L. Sukhman, S. L. Gruverman, and V. V. Torokin, Phys. Stat. Solid., 84A, (1983), 423.  
Wittenberg. Ofte, Rohr, Proc. 3rd Rare Earth Conf. 1963, Vol2, (1964)

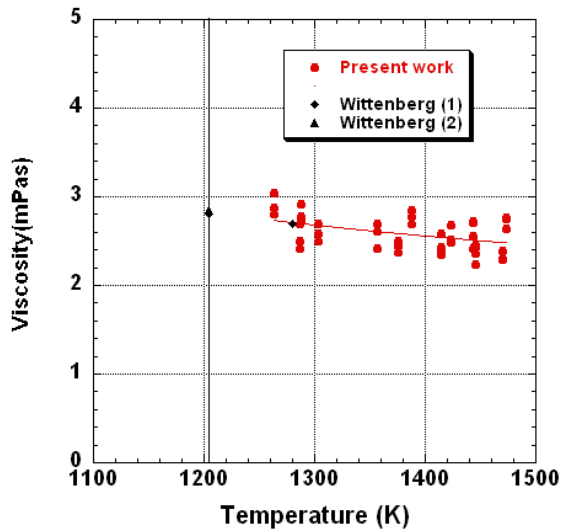
## Surface tension graph



- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.
- **Reference:**  
Bezukladnikova, L.L., Kononenko, V.I. and Torokin, V.V., Teplofiz. Vys. Temp., 27, 478, 1989.  
Chentsov, V.P., Dissertation Inst. Tekh. Metallurgiya UNTs, Akad. Nauk. SSSR, Sverdlovsk, 1972  
Martsenyuk, P.S. and Ivashchenko, Y.N., Adgez. Rasp. Paika Mater., 19, 12, 1984.  
Sukhman, A.L., Kononenko, V.I., Gruverman, S.L. and Torokiv, V.V., Poverkhnostnye svoistva rasplavov (Surface properties of melts) (in Russian), 107, Nauka Dumka, 1982.

## Viscosity graph

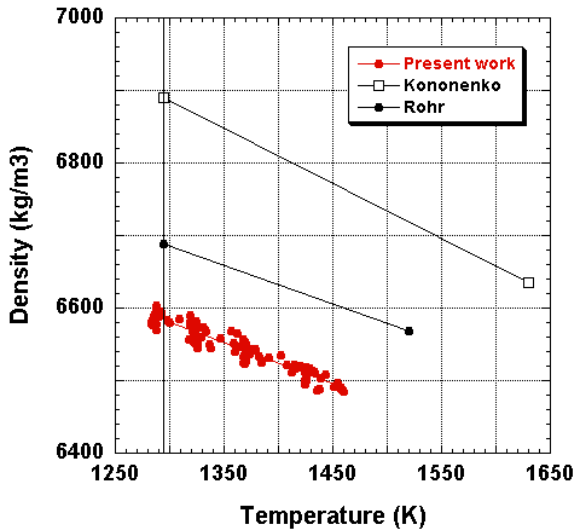
Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.
- **Reference:**  
Wittenberg, L.J., Ofte, D. and Rohr, W.G., "Rare Earth Research", Vol II ed. K.S. Vorres, Gordon and Breach, p. 257, 1964.  
Wittenberg, L.J. and DeWitt, R., "The properties of Liquid Metals", (ed. S. Takeuchi), p. 555, Taylor and Francis, 1973.

# Nd(Neodymium)

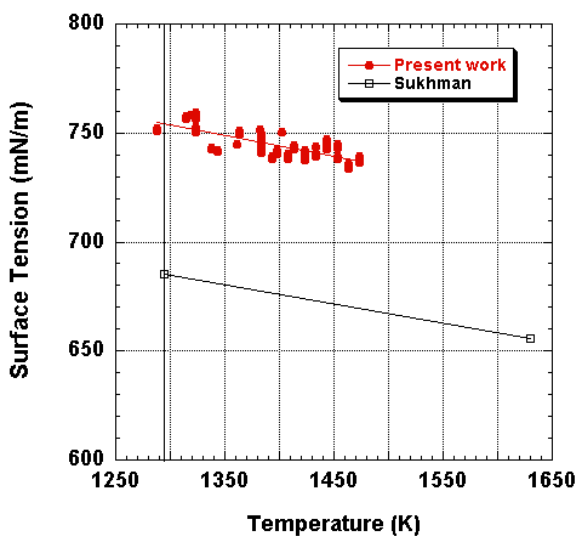
## Density graph



- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.

- **Reference:**  
 V. I. Kononenko, A. L. Sukhman, S. L. Gruverman, and V. V. Torokin, Phys. Stat. Solid., 84A, (1983), 423.  
 W.G. Rohr, J. Less Common Metals, 10, 389, 1966.

## Surface tension graph

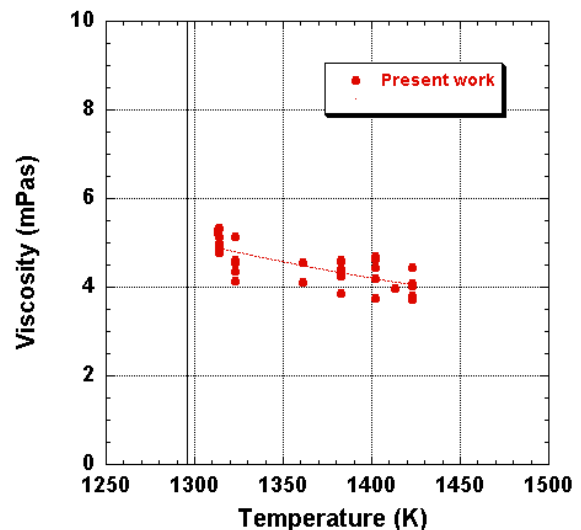


- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.

- **Reference:**  
 Sukhman, A.L., Kononenko, V.I., Gruverman, S.L. and Torokiv, V.V., Poverkhnostnye svoistva rasplavov (Surface properties of melts) (in Russian), 107 Nauka Dumka, 1982.

## Viscosity graph

Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



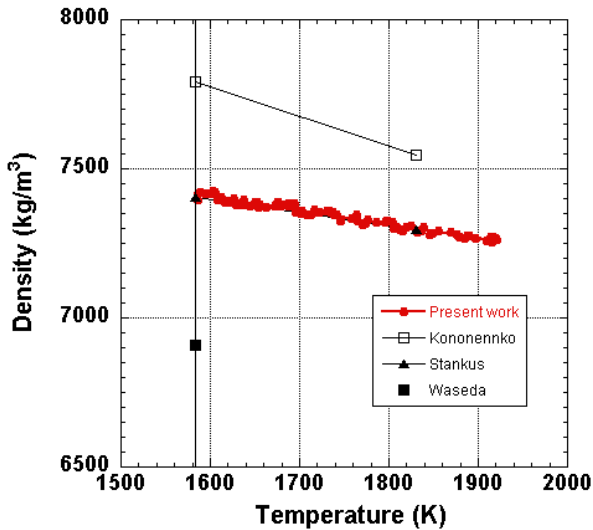
- P.-F. Paradis, T. Ishikawa, N. Koike, and Y. Watanabe, J of Jpn Soc. of Microgravity Appl. 25 (2008), 407-412.

- **Reference:** N/A



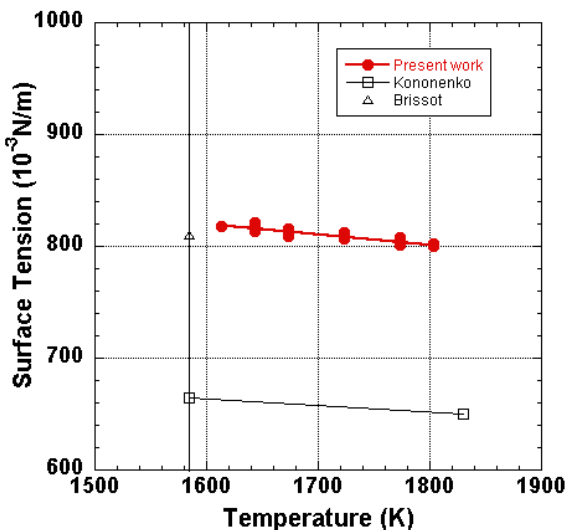
# Gd(Gadolinium)

## Density graph



- T. Ishikawa, J. T. Okada, P.-F. Paradis, Y. Watanabe, Int. J. Thermophys. 31 (2010), 388
- **Reference:**  
Kononenko, Phys. stat. Sol. (a) 84, 423 (1984)  
S. V. Stankus, A. S. Basin, M. A. Revenko, Teplofiz. viskikh Temp 19, 293, 1981  
Y. Waseda S. Tamaki, Phil. Mag. 36, 1, 1977.

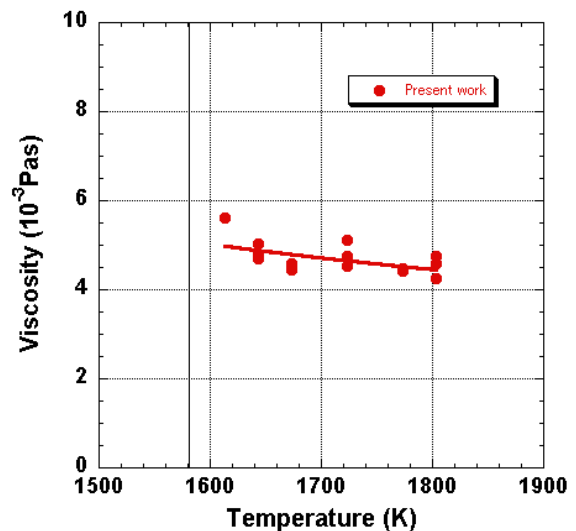
## Surface tension graph



- T. Ishikawa, J. T. Okada, P.-F. Paradis, Y. Watanabe, Int. J. Thermophys. 31 (2010), 388
- **Reference:**  
Kononenko, Phys. stat. Sol. (a) 84, 423 (1984)  
J. J. Brissot, and R. Martres, J. Appl. Phys. 36 (10), 3360 (1965)

## Viscosity graph

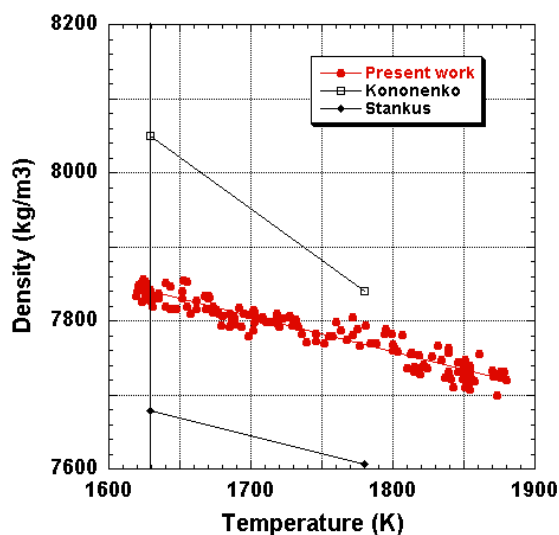
Viscosity data has been taken by improved measurement method with 120 Hz position control frequency.



- T. Ishikawa, J. T. Okada, P.-F. Paradis, Y. Watanabe, Int. J. Thermophys. 31 (2010), 388
- **Reference:** N/A

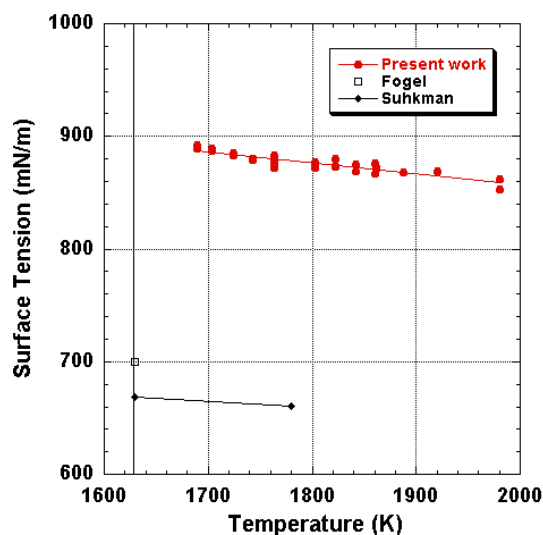
# Tb(Terbium)

## Density graph



- P.-F. Paradis, T. Ishikawa, N. Koike, Y. Watanabe, *Journal of Rare Earths* 25 (2007), 665.
- **Reference:**  
V. I. Kononenko, A. L. Sukhman, S. L. Gruverman, and V. V. Torokin, *Phys. Stat. Solid.*, 84A, (1983), 423.  
S. V. Stankus, A. S. Basin, *Tezisi. VII vsesoyuznoi konf. Teplofizicheskie svoistvaveschestv, chap.2*, Inst. Teplofiz. Sov., AN SSSR (in Russian), Novosibirsk (1982), 80.

## Surface tension graph



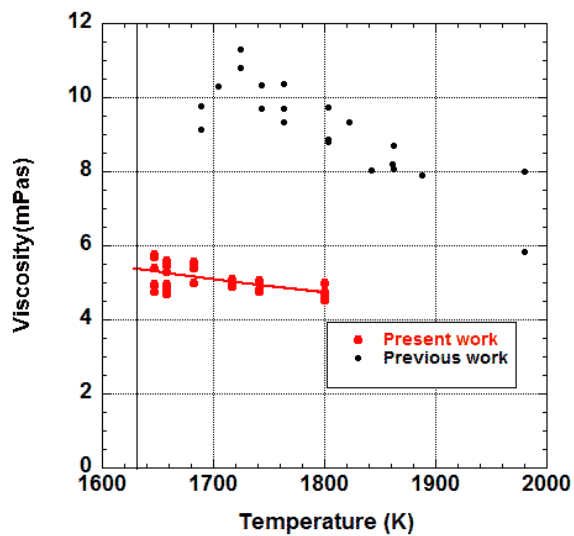
- P.-F. Paradis, T. Ishikawa, N. Koike, Y. Watanabe, *Journal of Rare Earths* 25 (2007), 665.
- **Reference:**  
A. A. Fogel, T. A. Sidorova, G. E. Chuprikov, M. M. Mezdrogina, *izv. Akad. Nauk SSSR Metal.*, 1 (1965), 50  
A.L. Sukhman, V. I. Kononenko, S. L. Gruverman, V. V. Torokiv, *Poverkhnostnye svoistva rasplavov (surface properties of melts)* 107, Nuaka Dumka, 1982

## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

**new**

Since the first viscosity measurement had been affected by sample position control, viscosity data was taken with an improved measurement method.



- **Data taken by improved measurement method (Present Works)** **new**

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

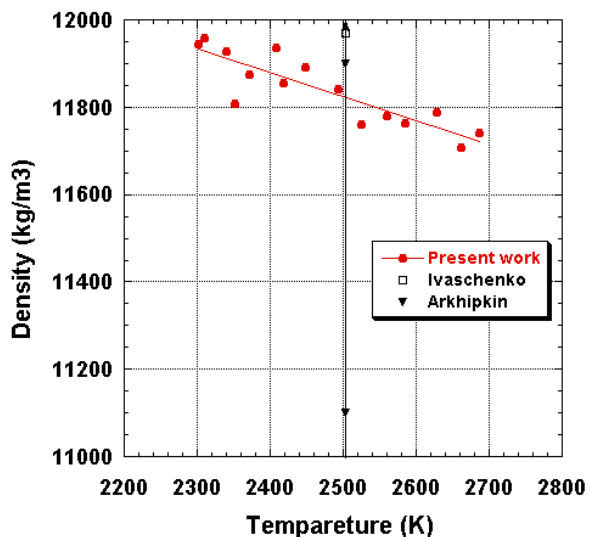
- **Reference (Previous work) :**

P.-F. Paradis, T. Ishikawa, N. Koike, Y. Watanabe, Journal of Rare Earths 25 (2007), 665.

# Hf(Hafnium)

Hafnium contains 3 wt% zirconium.

## Density graph

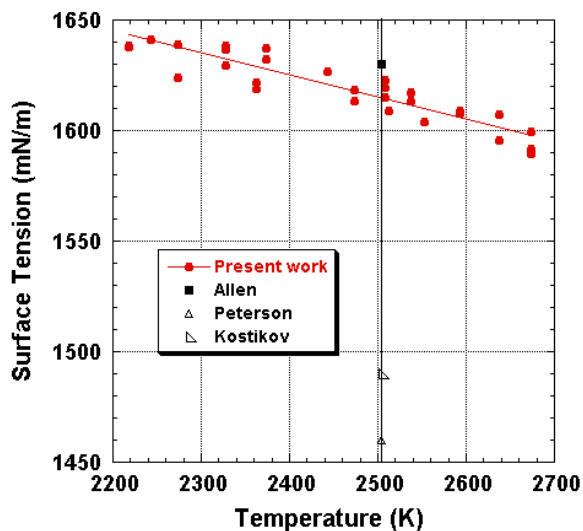


- P. -F. Paradis, T. Ishikawa, S. Yoda, *Int. J. Thermophys.*, 24 (2003),239-258.

- **Reference:**

Yu. Ivashchenko and P.S. Martsenyuk, *Zavod. Lab. (USSR)* 39,1, 42 (1973)  
 V.I. Arkhipkin, V.I. Kostikov, G.A. Grigorjev, and A.D. Agaev, in *Fiz. Khim. Granits Razdela Kontaktiryuschikh Faz.*, Naukova Dumka-Kiev, USSR, V.N.Eremenko, ed., 74-77 (1976)

## Surface tension graph



- P. -F. Paradis, T. Ishikawa, S. Yoda, *Int. J. Thermophys.*, 24 (2003),239-258.

- **Reference:**

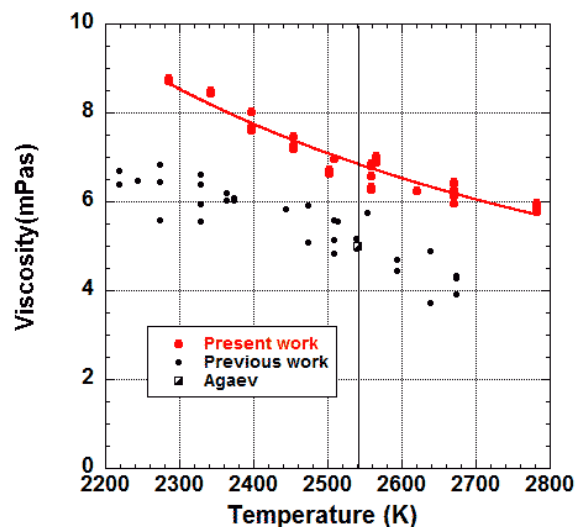
B. C. Allen, "Surface Tension of Liquid Metals", in *Liquid Metals Chemistry and Physics*, edited by S. Z. Beer, (Mercel Dekker, New York, 1972), 186-188.  
 W.Peterson, H. Kadesky, P. H. Keck, and E. Scharz"Surface Tension of Titanium, Zirconium, and Hafnium", *J. Appl. Phys.*,29(1958), 213  
 B. J. Keene, "Review of data for the surface tension of pure metals", *International Materials Reviews*, 38(1993), 157-192.

## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

◀new

Since the first viscosity measurement had been affected by sample position control, viscosity data was taken with an improved measurement method.



- **Data taken by improved measurement method (Present Works)** ◀new

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

- **Reference (Previous work) :**

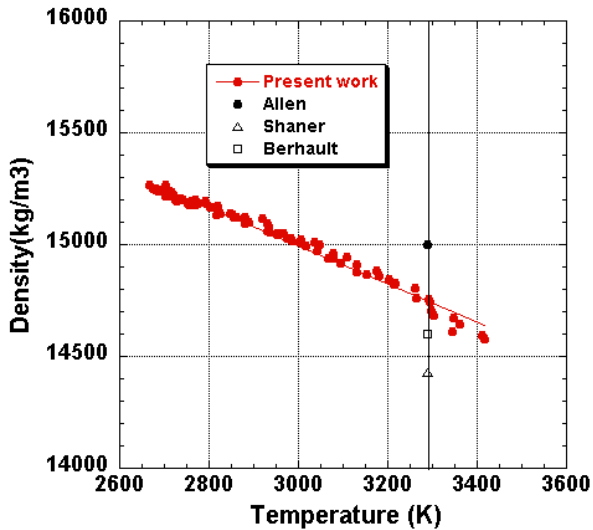
P. -F. Paradis, T. Ishikawa, S. Yoda, Int. J. Thermophys., 24 (2003), 239-258.

**Reference:**

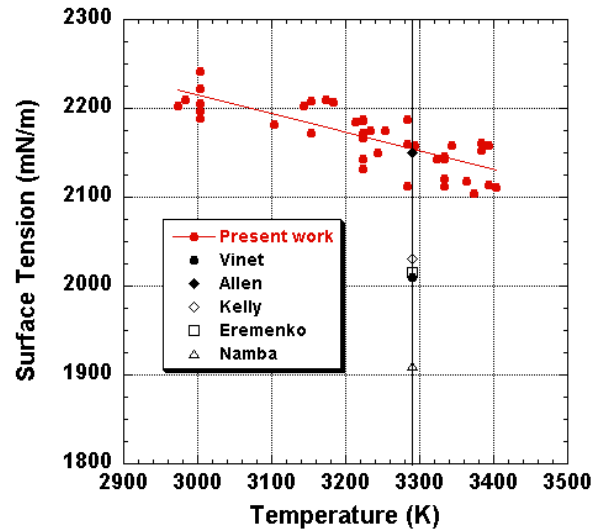
T. Itami, "Condensed Matter – Liquid Transition Metals and Alloys", in Condensed Matter Disordered Solids, edited by S. K. Srivastava and N. H. March (World Scientific, Singapore, 1995), 123-250.

# Ta(Tantalum)

## Density graph



## Surface tension graph



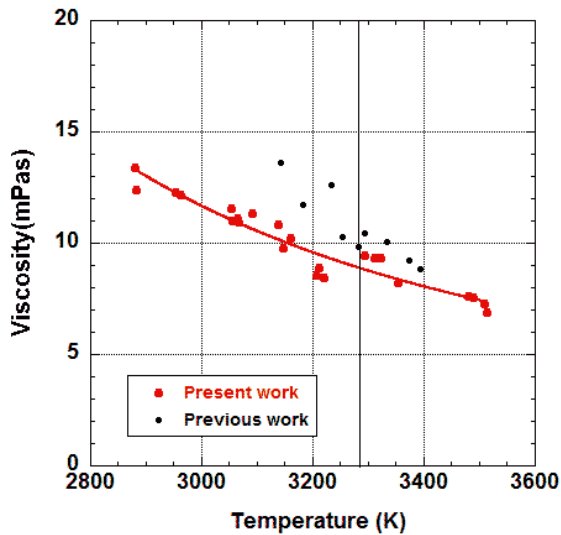
- T. Ishikawa, P. -F. Paradis, T. Itami, and S. Yoda, Measurement Science and Technology, 16 (2005), 443-451
- **Reference:**  
 B. C. Allen, Trans AIME, 227 (1963), 1175.  
 J. W. Shaner, G. P. Gathers, and C. Minichino, High Temp. High Press., 8(1976), 425  
 A. Berhaut, L. Arles, and J. Matricon, Int. J. of Thermophysics, 7(1986),167-179.

- P. -F. Paradis, T. Ishikawa, and S. Yoda, J. Appl. Phys. 97(2005), 053506.
- **Reference:**  
 B. Vinet, J.P. Garandet, and L. Cortella, J. Appl. Phys. 73, 3830 (1993).  
 B.C. Allen,Trans. AIME 227, 1175-1183 (1963).  
 J.C. Kelley and A. Calverley, SERL-Rep., 80 (1959), 53.  
 V. N. Eremenko, High Temp. 22 (1984), 705  
 S. Namba and T. Isobe, Sci. Papers I. P. C. R. 57 (1963), 51-54.

## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

◀new



- **Data taken by improved measurement method(Present Works)** ◀new

T. Ishikawa, P.-F Paradis, J. Okada, M. V. Kumar, Y. Watanabe, "Viscosity of molten Mo, Ta, Os, Re, and W measured by electrostatic levitation", J. Chem. Thermodynamics 65 (2013), 1-6.

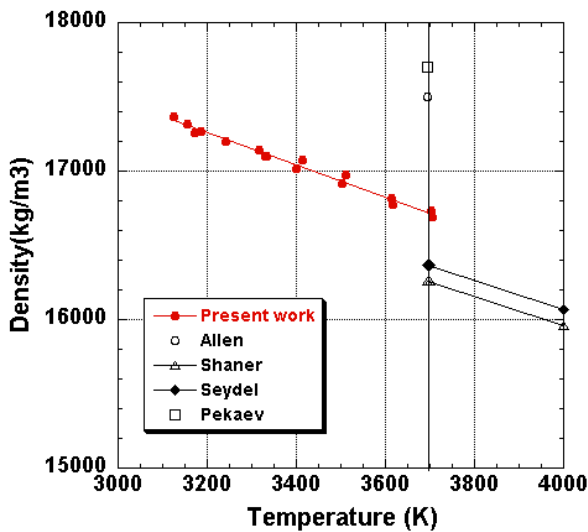
- **Reference(Previous work) :**

P. -F. Paradis, T. Ishikawa, and S. Yoda, J. Appl. Phys. 97(2005), 053506.

# W(Tungsten)

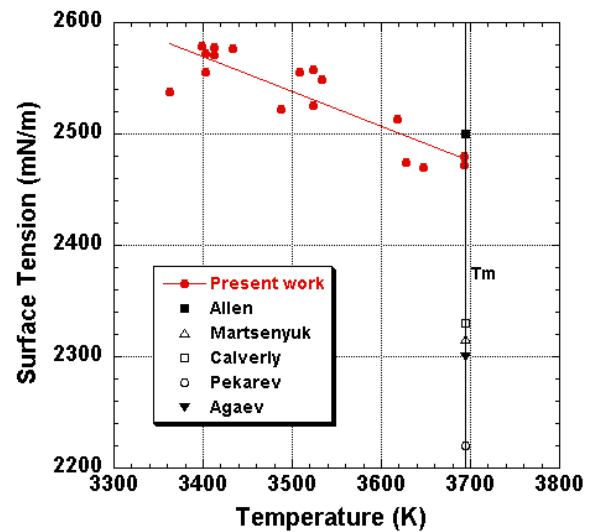
Tungsten has the highest melting temperature among metal elements. It was a big challenge for us to stably levitate molten tungsten. We added a 500 W YAG laser (shooting through top electrode) and re-design the arrangement of electrodes to improve horizontal sample stability.

## Density graph



- P. -F. Paradis, T. Ishikawa, R. Fujii, and S. Yoda, Appl. Phys. Lett 86(2005), 41901.
- **Reference:**  
 B. C. Allen, Trans AIME, 227 (1963), 1175.  
 J. W. Shaner, G. R. Gathers, C. Minichino, High temp. -High Press. 8 (1976), 425-429.  
 U. Seydel and W. Kitzel, J. Phys. F: Metal Phys., 9 (1979), L153  
 Pekaev, Izv. Vys. Uch. Sav., Tsvetn. Met. 6, (1963), 111

## Surface tension graph



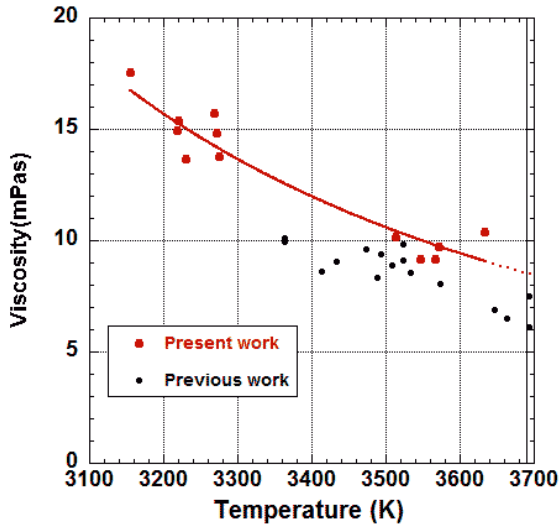
- P. -F. Paradis, T. Ishikawa, R. Fujii, and S. Yoda, Appl. Phys. Lett 86(2005), 41901.
- **Reference:**  
 B.C. Allen, Trans. AIME 227, 1175-1183 (1963).  
 P. S. Martsenyuk, Yu. N. Ivashchenko and V. N. Eremenko, Tep. Vys. Temp. 12 (1974), 1310.  
 A. Calverley, Proc. Phys. Soc., 70 (1957), 1040-104.  
 Pekaev, Izv. Vyss. Uch. Sav., Tsvetn. Met., 6 (1963), 111  
 A. D. Agaev, Dissertation, Moscow Steel and Alloys Institute, 1973.



## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

**new**



- **Data taken by improved measurement method(Present Works)** **new**

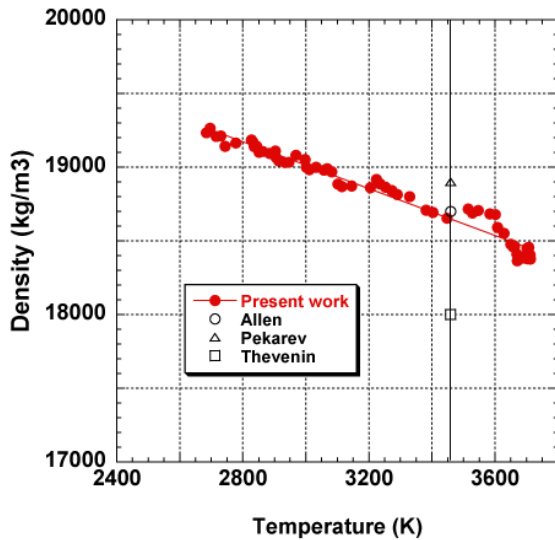
T. Ishikawa, P.-F Paradis, J. Okada, M. V. Kumar, Y. Watanabe, "Viscosity of molten Mo, Ta, Os, Re, and W measured by electrostatic levitation", J. Chem. Thermodynamics 65 (2013), 1-6.

- **Reference(Previous work) :**

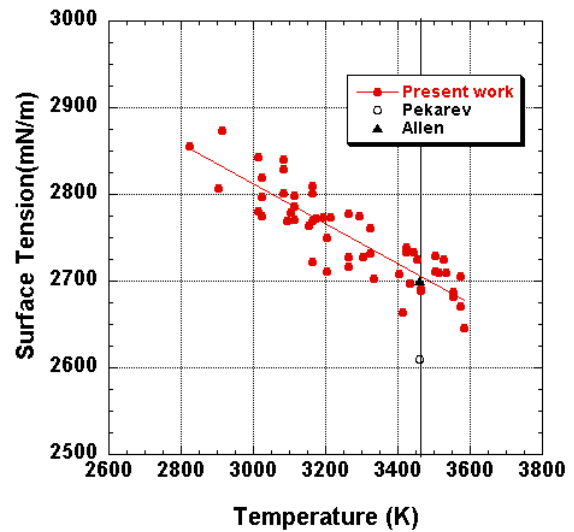
P. -F. Paradis, T. Ishikawa, and S. Yoda, J. Appl. Phys.,97 (2005), 10610.

# Re(Rhenium)

## Density graph



## Surface tension graph



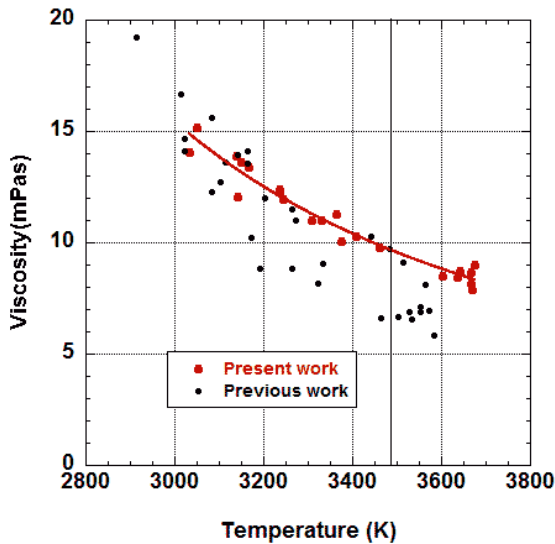
- T. Ishikawa, P. –F. Paradis, T. Itami, and S. Yoda, Measurement Science and Technology, 16 (2005), 443-451.
- **Reference:**  
B. C. Allen, Trans AIME, 227 (1963), 1175.  
Pekarev, Izv. Vys. Uch. Sav., Tsvetn. Met. 6, (1963),111.  
T.Thevenin, L. Alres, M. Boivineau, J. M. Vermeulen, Int. J. of Thermophysics, 14 (1993), 441.

- T. Ishikawa, P. –F. Paradis, and S. Yoda, Appl. Phys. Lett, 85 (2004), 5866-5868.
- **Reference:**  
Pekarev, Izv. Vys. Uch. Sav., Tsvetn. Met. 6, (1963),111  
B. C. Allen, Trans AIME, 227 (1963), 1175.

## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

◀new



- **Data taken by improved measurement method(Present Works)** ◀new

T. Ishikawa, P.-F Paradis, J. Okada, M. V. Kumar, Y. Watanabe, "Viscosity of molten Mo, Ta, Os, Re, and W measured by electrostatic levitation", J. Chem. Thermodynamics 65 (2013), 1-6.

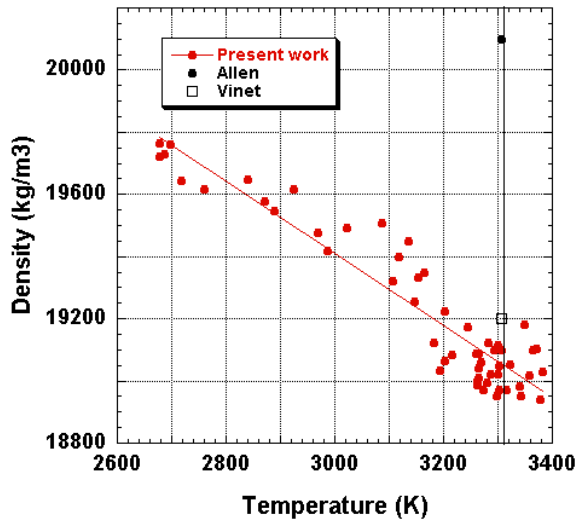
- **Reference(Previous work):**

T. Ishikawa, P. -F. Paradis, and S. Yoda, Appl. Phys. Lett, 85 (2004), 5866-5868.

# Os(Osmium)

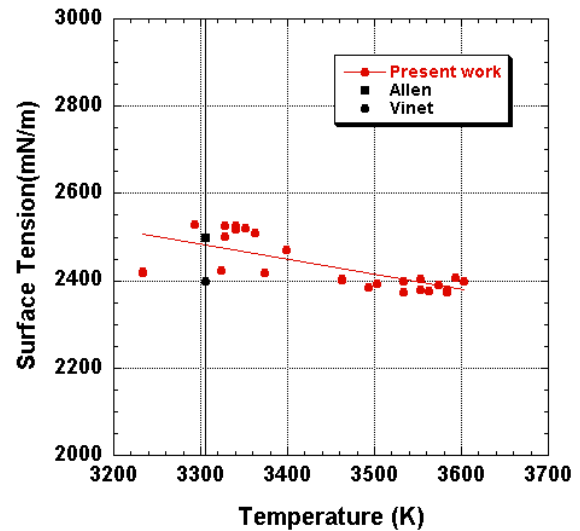
Since density of osmium is very high, molten sample becomes oblate when it melts. Relatively small samples were adequate for the experiments.

## Density graph



- P.-F. Paradis, T. Ishikawa, and N. Koike, "Physical properties of equilibrium and non-equilibrium liquid osmium measured by levitation techniques", JAP 100 (2006), 103523.
- **Reference:**  
B.C. Allen, Trans. AIME 227, 1175 (1963).  
B. Vinet, L. Magnusson, H. Fredriksson, and J.-P. Desre, J. Coll. Interf. Sci., 255: 363 (2002).

## Surface tension graph



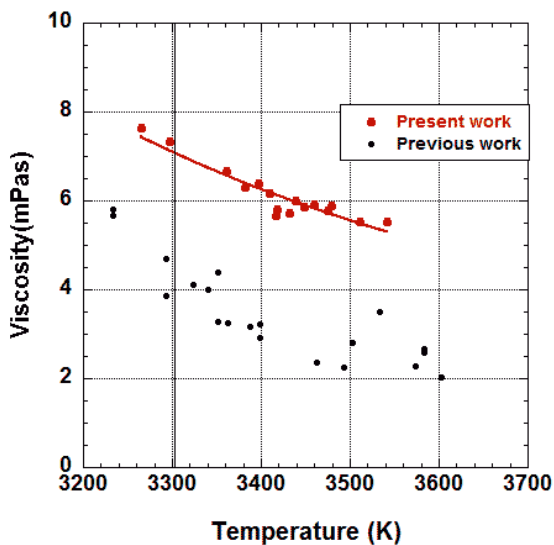
- P.-F. Paradis, T. Ishikawa, and N. Koike, "Physical properties of equilibrium and non-equilibrium liquid osmium measured by levitation techniques", JAP 100 (2006), 103523.
- **Reference:**  
B.C. Allen, Trans. AIME 227, 1175 (1963).  
B. Vinet, L. Magnusson, H. Fredriksson, and J.-P. Desre, J. Coll. Interf. Sci., 255: 363 (2002).

## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

**new**

Since the first viscosity measurement had been affected by sample position control, viscosity data was taken with an improved measurement method.



- **Data taken by improved measurement method(Present Works)** **new**

T. Ishikawa, P.-F Paradis, J. Okada, M. V. Kumar, Y. Watanabe, "Viscosity of molten Mo, Ta, Os, Re, and W measured by electrostatic levitation", J. Chem. Thermodynamics 65 (2013), 1-6.

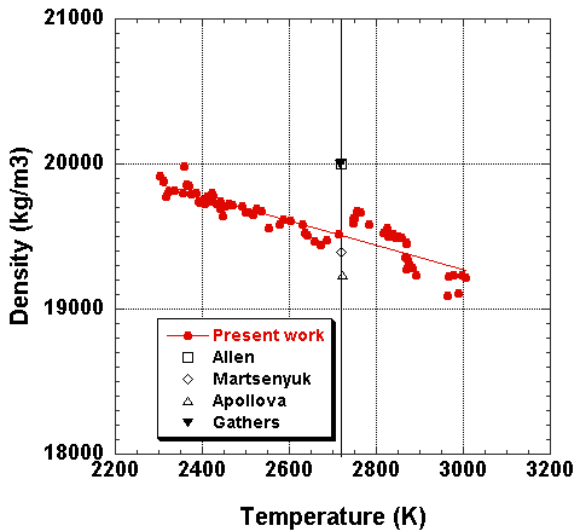
- **Reference(Previous work) :**

P.-F. Paradis, T. Ishikawa, and N. Koike, "Physical properties of equilibrium and non-equilibrium liquid osmium measured by levitation techniques", JAP 100 (2006), 103523.

# Ir(Iridium)

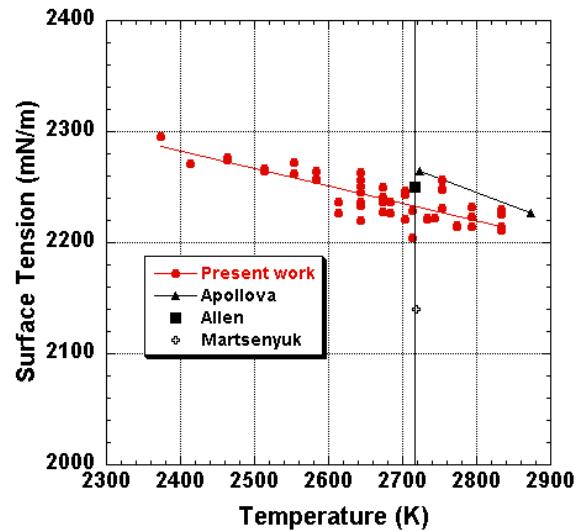
Based on our measurement, iridium has the highest liquid density @ Tm among metal elements.

## Density graph



- T. Ishikawa, P. -F. Paradis, R. Fujii, Y. Saita and S. Yoda Int. J of Thermophys, 26 (2005), 893-904.
- **Reference:**  
 B. C. Allen, Trans. AIME 227: 1175 (1963)  
 P. S. Martsenyuk and Yu. V. Ivaschenko, Ukr. Khim. Zhur. (SU)40: 431 (1974)  
 T. A. Apollova, E. L. Dubinin, M. M. Mitko, A. I. Chegodayev, and L. L. Bezuladnkova, Izv. Akad. Nauk SSSR, Met., 6: 55 (1982)  
 G. R. Gathers, J. W. Shaner, R. S. Hixson, and D. A. Jung, High Temp.-High Press. 11: 653 (1979)

## Surface tension graph

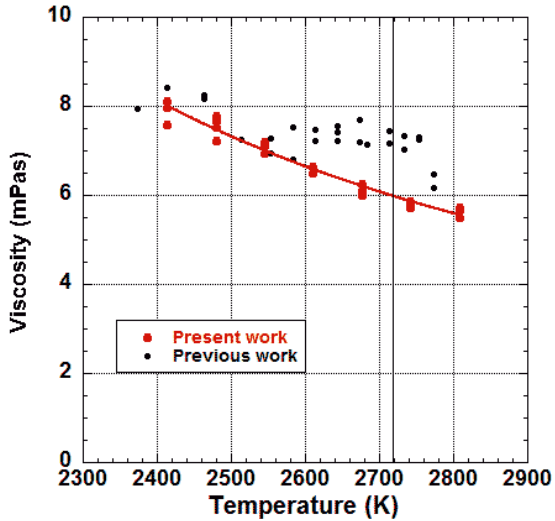


- T. Ishikawa, P. -F. Paradis, R. Fujii, Y. Saita and S. Yoda Int. J of Thermophys, 26 (2005), 893-904.
- **Reference:**  
 T. A. Apollova, E. L. Dubinin, M. M. Mitko, A. I. Chegodayev, and L. L. Bezuladnkova, Izv. Akad. Nauk SSSR, Met., 6: 55 (1982)  
 B. C. Allen, Trans. AIME 227: 1175 (1963)  
 P. S. Martsenyuk, Inst. Tekh. Probl. Mater. Akad. Nauk SSSR, 51-57 (1980)

## Viscosity graph

Viscosity data has been updated.  
 (Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

◀new



- **Data taken by improved measurement method(Present Works) ◀new**

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

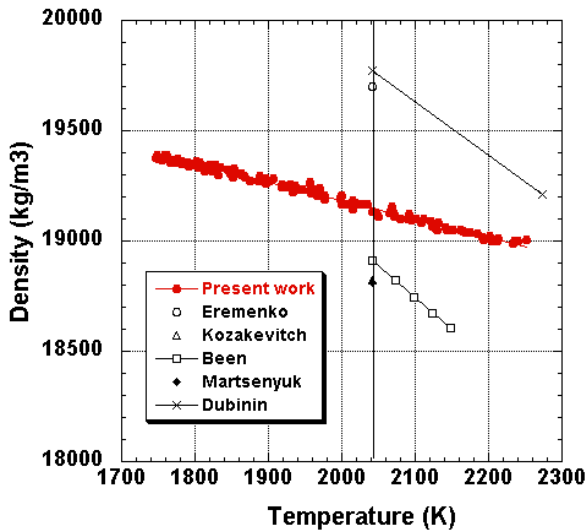
- **Reference(Previous work) :**

T. Ishikawa, P. -F. Paradis, R. Fujii, Y. Saita and S. Yoda Int. J of Thermophys, 26 (2005), 893-904.

# Pt(Platinum)

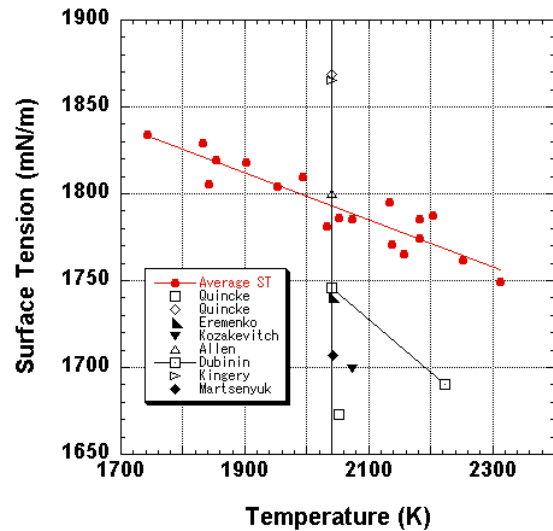
Due to its high density and relatively low surface tension, a platinum sample becomes oblate when it melts and very difficult to achieve stable levitation.

## Density graph



- T. Ishikawa, P.-F. Paradis and N.Koike, JJAP 45(2006), 1719-1724.
- **Reference:**  
 Eremenko and Naidich Izv. A. N. OTN 6(1959), 129.  
 Kozakevitch and Urbain C. R. Paris253(1961), 2229.  
 Been, Edwards, Teeter, and Chalkins NEPA-1585, US-AEC 1950. Martsenyuk and Iwaschtschenko Ukr. Chim. Sh.40 (1974), 431.  
 Dubinin, Vlasov, Timofejev, Safonov, and Chegodajev, Izv. Vyss. Uchebn, Saved. Tsvetn, Met.4 (1975),160.

## Surface tension graph



- T. Ishikawa, P.-F. Paradis and N.Koike, JJAP 45(2006), 1719-1724.
- **Reference:**  
 Quincke, Ann. D. Physik,134 (1868), 356.  
 Quincke, Ann. D. Physik,138 (1869), 141.  
 Eremenko and Naidich, Izv. A. N. O. T. N. 6(1959), 129  
 Kozakevitch and Urbain, C. R., Paris., 1253 ,(1961), 2229. Allen, Trans. AIME, 227, (1963), 1175.  
 Dubinin, Vlosov, Timofejev, and Tshagodajev, Izv. Vyss. Uch. Sav., Tsvetn. Met. 4, (1975), 160.  
 W. D. Kingery, Am. Ceram. Soc. Bull. (1956), 35, 108 (quoted in text as unpublished work by this author) P.S. Martsenyuk, Inst. Tekh. Probl. Mater. Akad. Nauk SSSR, (1980),51-57.

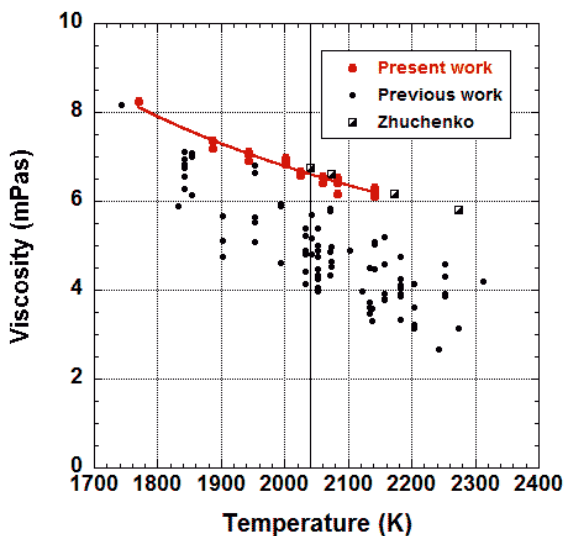


## Viscosity graph

Viscosity data has been updated.  
(Updated viscosity have been taken by improved measurement method with 120 Hz position control frequency)

new

Since the first viscosity measurement had been affected by sample position control, viscosity data was taken with an improved measurement method.



- **Data taken by improved measurement method(Present Works)** new

T. Ishikawa, P.-F. Paradis, J. T. Okada, Y. Watanabe, "Viscosity measurements of molten refractory metals using an electrostatic levitator", Meas. Sci. Technol. 23 (2012), 025305

- **Reference(Previous work) :**

T. Ishikawa, P.-F. Paradis and N.Koike, JJAP 45(2006), 1719-1724.

**Reference:**

A. A.Zhuchenko, E. L. Dubinin, A. I. Timofeev, and S. O. Safonov, Izv. Vyssh. Uchebn. Zaved. Tsvetn. Metall. 4 (1977), 142.