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Temperature Estimation of Tungsten-Rhenium Alloy Used in Plasma Facing Components

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Thermal diffusivity in Tungsten materials

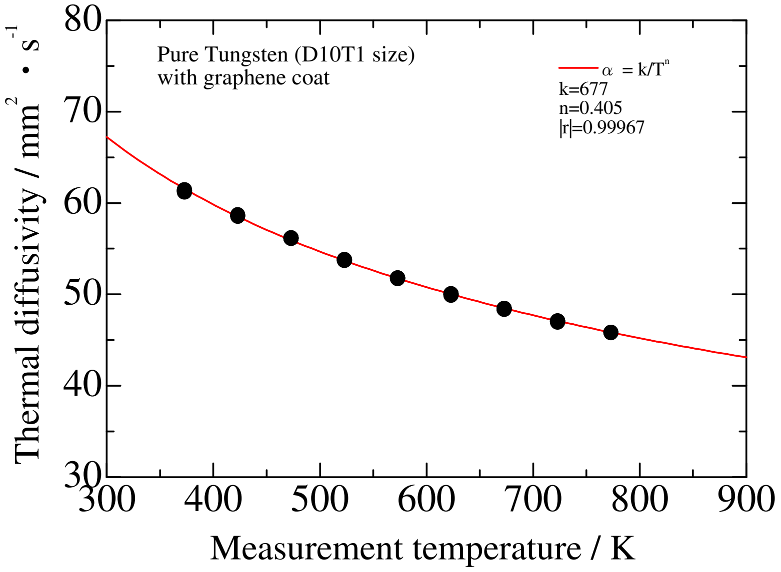
Thermal diffusivity in Metal / Ceramics

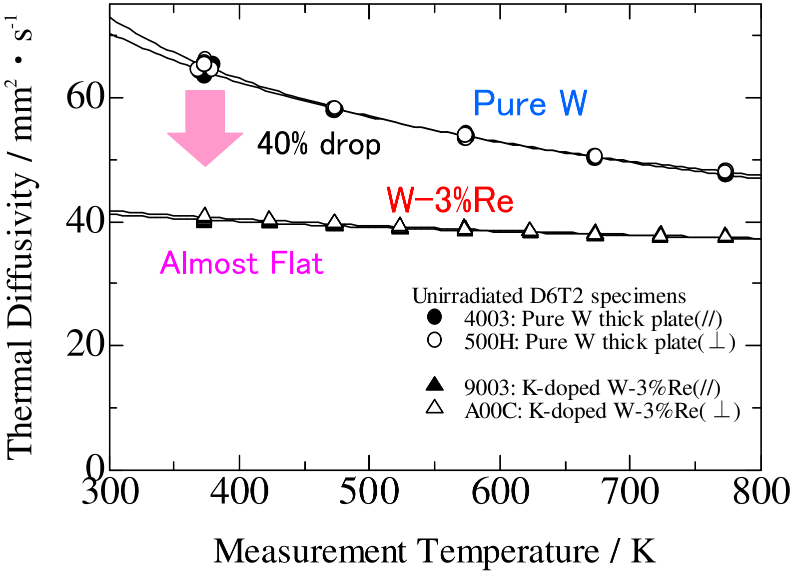
In Tungsten, heat is mainly carried by electron like typical metals, but about 1/3 of heat is carried by phonon like ceramics (at room temperature).

In ceramics, high temperature increase phonon-phonon scattering and thermal diffusivity α is described as $\alpha = k/T^n$ where unirradiated specimens show n = 1 and irradiated them show n < 1.

Unirradiated pure tungsten showed n~0.4 with the same function.

Furthermore, fusion neutron induces transmutation element such as Rhenium or Osmium that reduce thermal diffusivity drastically.





RB-19J Irradiation in PHENIX Project

In light water fission reactor, most neutrons are moderated to thermal neutrons that gives larger amount of transmutations than the fusion reactor at the same irradiation induced damage.

W → Re, Os

Thermal diffusivity change;

In the PHENIX project, irradiation in HFIR have been performed with the **Gadolinium** thermal neutron shield.

Separate the contribution to heat transfer

Separate effect of *lattice defects* from *transmutations*.

Electron conduction

Phonon conduction

Reduction of thermal diffusivity with transmuted Re and Os

W-184 (n, γ) W-185 → β decay (75.1day) → Re-185
Natural isotope ratio 30.4%, 1.7 barn (Thermal)

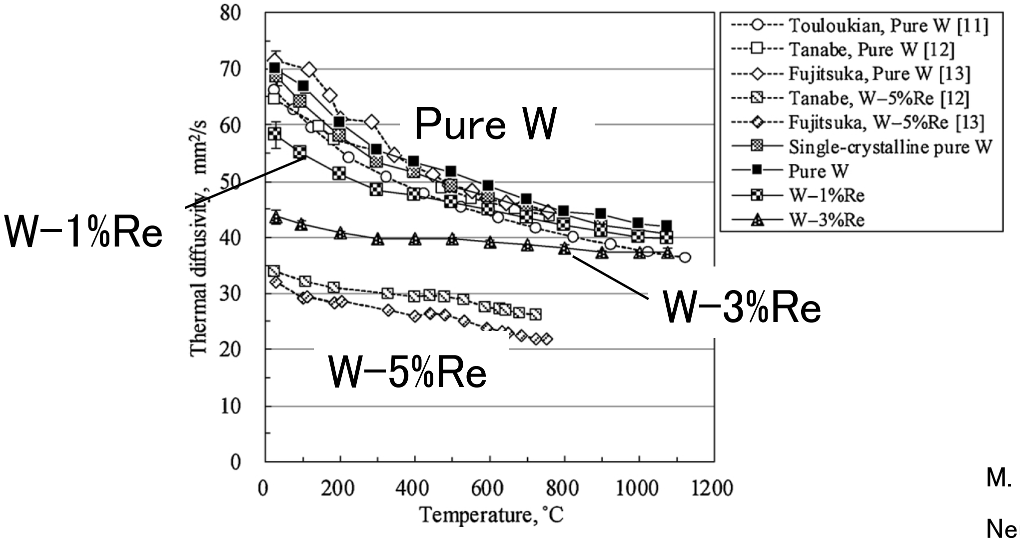
Major radio isotope in W after neutron irradiation

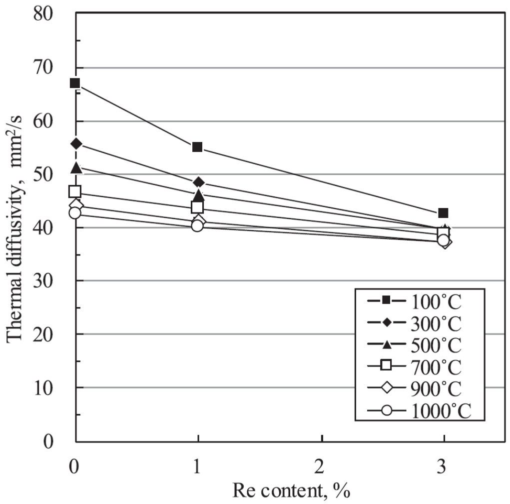
W-186 (n, γ) W-187 → β decay (2.37h) → Re-187
Natural isotope ratio 28.4%, 38.1 barn (Thermal)

Transmuted Re and Os in W decrease thermal diffusivity severely

Re-187 (n, γ) Re-188 → β decay (17h) → Os-188
Natural isotope ratio 62.6%, 76 barn (Thermal)

Re-185 (n, γ) Re-186 → β decay (3.7d) → Os-186
Natural isotope ratio 37.4%, 112 barn (Thermal)





M. Fukuda et al., Fusion Engineering Design, 132 (2018) 1-6.

Neutron absorption cross section @0.0253eV: JENDL-4.0

Rabbit Irradiation in PHENIX Project

Location: peripheral target position (Fuel trap region)

Dose: 0.42 dpa (PXW2) -0.47 dpa (PXW5) dpa, 1 cycles

1.1×10^{19} n/m^2・s (E > 0.1 MeV) and
1.7×10^{19} n/m^2・s (E < 0.5 eV)

→ Fluence: 3×10^{25} n/m^2 (E < 0.5 eV)

Temperature

850℃ (PXW2), 800-1100℃(PXW5)

GDOES (glow discharge optical emission spectroscopy) showed the amount of transmuted elements; [2022Gietl]

Re: 3.3% and Os: 1.9% (PXW2)
Re: 3.1% and Os: 1.3% (PXW5)

Location: Removable Beryllium position, RB-19J

Dose: 0.2~0.7 dpa, 4 cycles

4.7×10^{18} n/m^2・s (E > 0.1 MeV) and
9.5×10^{18} n/m^2・s (E < 0.5 eV)

→ Fluence: 5×10^{23} n/m^2 (E < 0.5 eV)

→ Shielded to about 1/60 of rabbit

Temperature regions

550℃, 850℃, 1050℃

Thermal diffusivity data showed that Gd shielded RB-19J pure W specimens in 550℃ zone corresponded with the reported W-1%Re alloy [2018Fukuda].

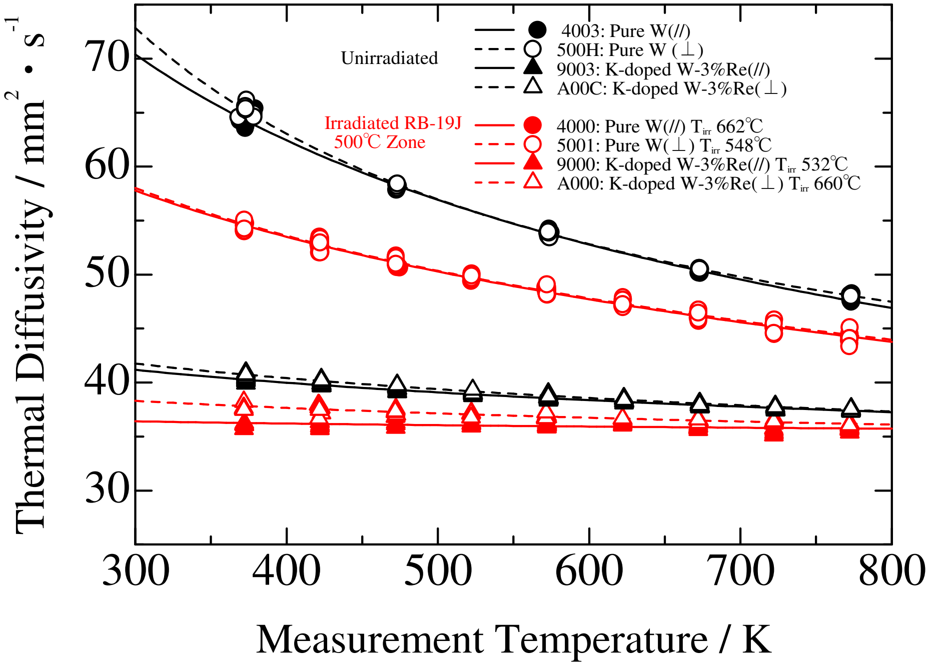
Rabbit vs RB-19J specimens

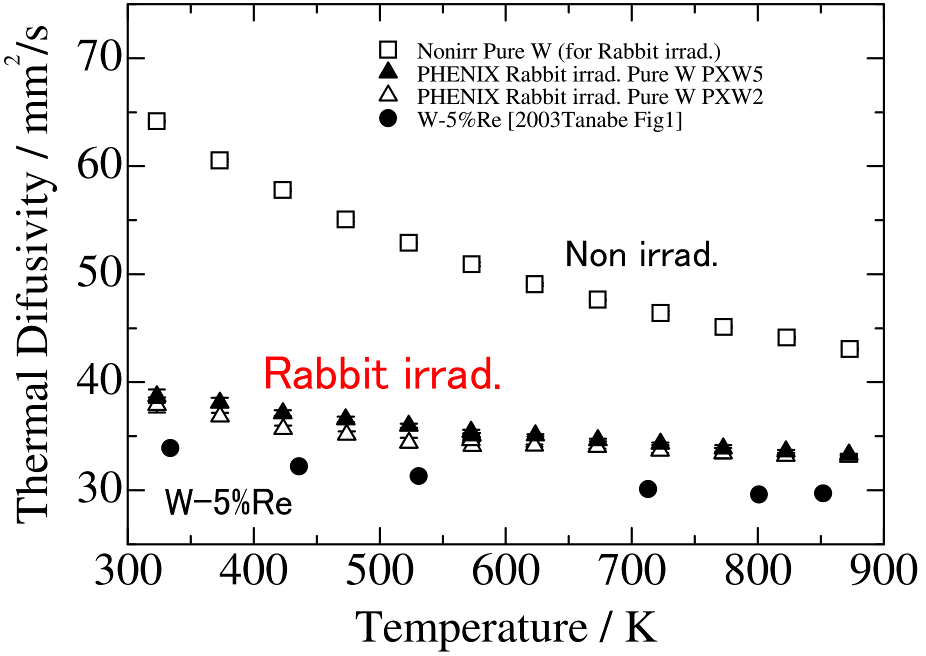
Rabbit irradiated pure W specimens showed far lower thermal diffusivity than the RB-19J irradiated pure W specimens. It showed a little higher TD than irradiated W-3%Re specimens, that considered to contain 3% + 1% Re, and also higher than unirradiated W-5%Re [2003Tanabe], while GDOES results for rabbit specimens showed (Re + Os) 5.2% (PXW2) and 4.4% (PXW5).

Neutron dose with fast neutrons (calculation):
RB-19J: 0.46 dpa (4000), 0.25 dpa (5001)
Rabbit: 0.42 dpa (PXW2), 0.47 dpa (PXW5)

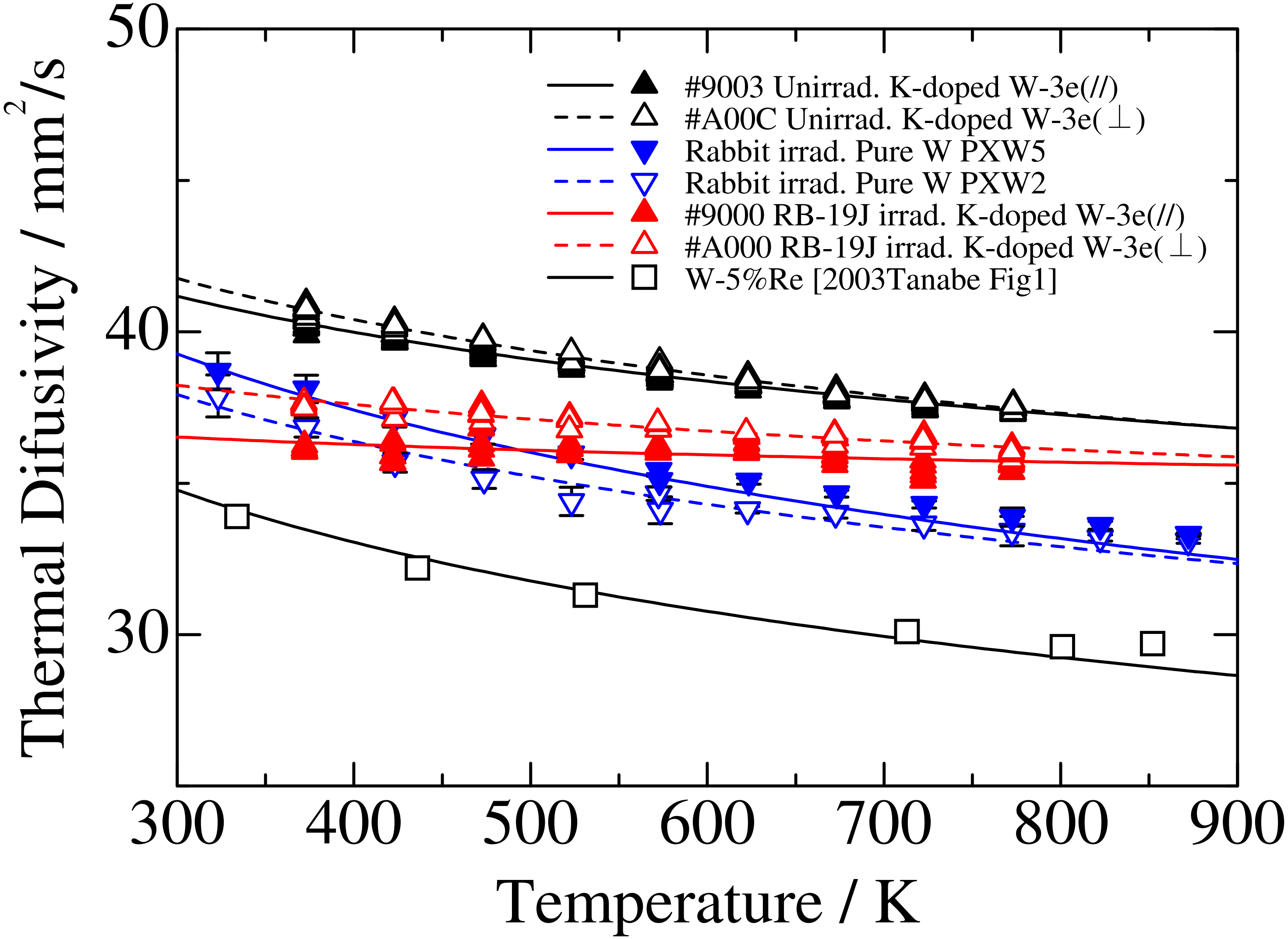
[2022Gietl]

Re: 3.3% and Os: 1.9% (PXW2)
Re: 3.1% and Os: 1.3% (PXW5)





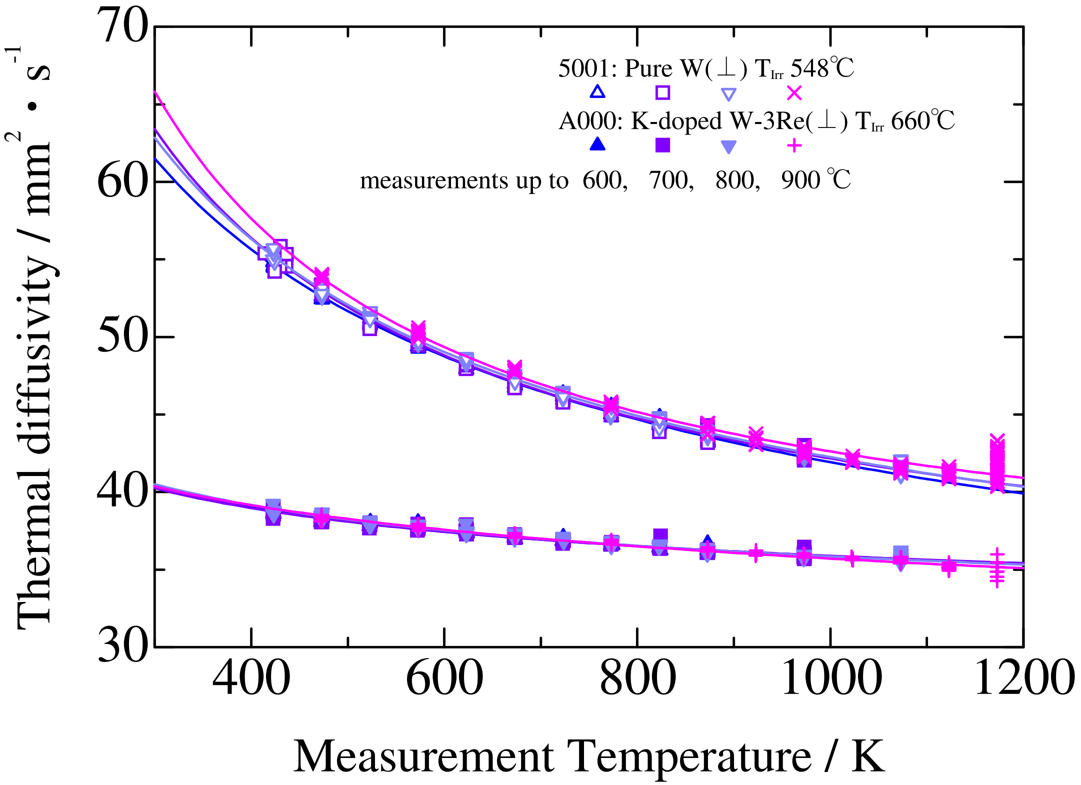
Rabbit vs RB-19J specimens



Annealing effect for RB-19J specimens

Annealing up to 900℃ for RB−19J irradiated pure W and W−3Re specimens were performed. No significant recovery in thermal diffusivity was observed.

→ Lattice scattering effect to phonon and electron conduction is limited.

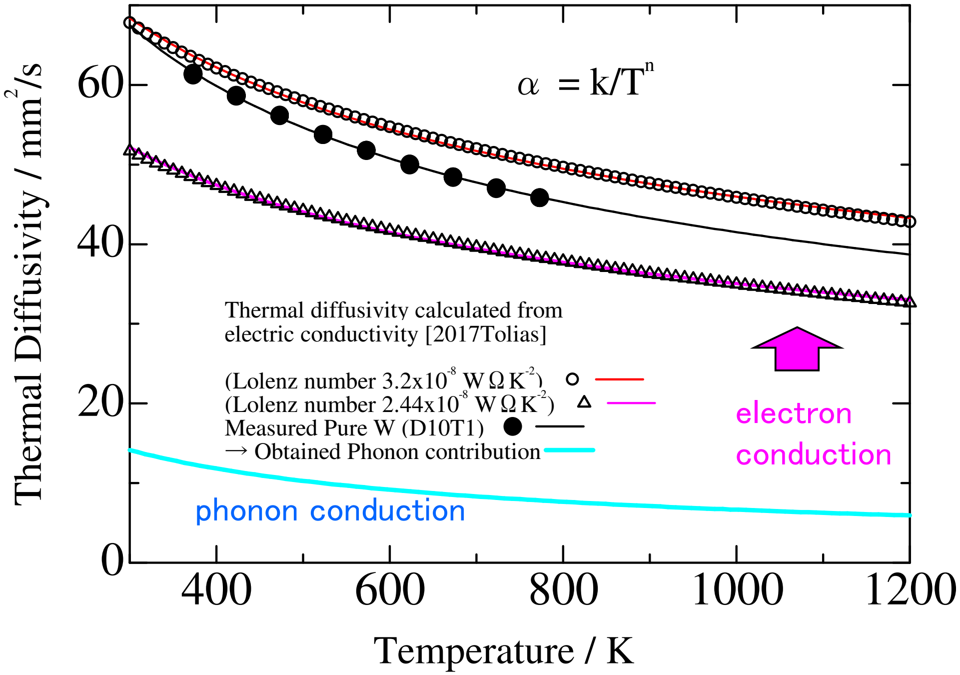


Ratio of thermal conductivity to electrical conductivity

The Wiedemann–Franz law ($\kappa / \sigma = LT$), which showes that the ratio of thermal conductivity κ to electrical conductivity σ is proportional to temperature T, is an empirical law. The Lorenz number L_0 for a conventional metal is constant value about $(\pi^{2/3})(kB/e)^2 = 2.44 \times 10^{-8}$ WΩK^{-2}, while that of pure tungsten is 3.2×10^{-8} WΩK^{-2}, 31% higher. In addition, this L value is matches at room temperature only (L for tungsten is changed by temperature).

This difference is attributed to phonon conduction.

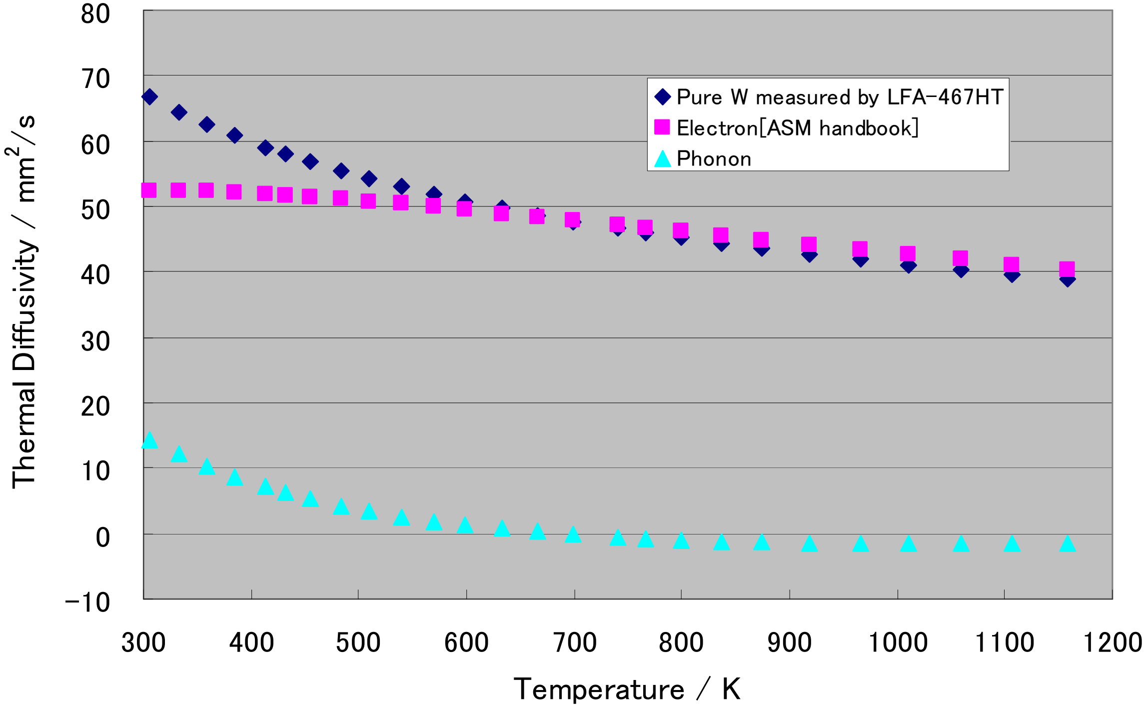
The electrical resistibility, specific heat, and density of pure W are summarized by Tolias and the EUROfusion MST1 Team in 2017, and from which the thermal conductivity carried by electron was obtained using the Wiedemann-Franz law and L_0, then, the thermal diffusivity can be calculated.



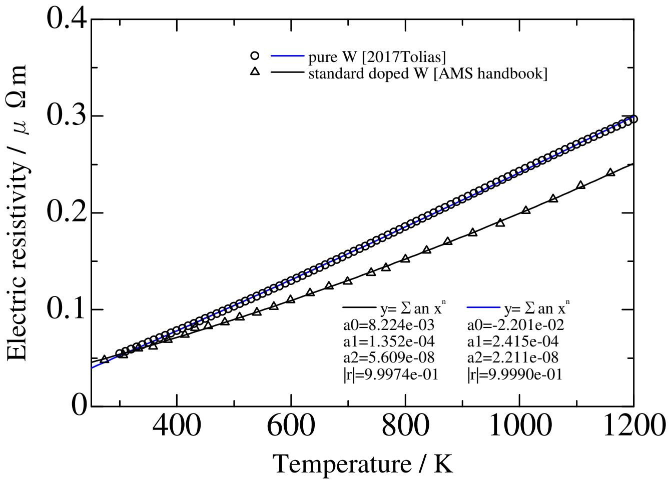
Phonon contribution

When we use electron resistivity of `standard doped tungsten' reported in AMS handbook, electron contribution in thermal diffusivity matched well to the thermal diffusivity of pure W measured by LFA-467HT at high temperature.

It represent that phonon contribution is negligible above 650 K.



The electron resistivity in this handbook showed smaller value compared with other literature for pure tungsten specimen.

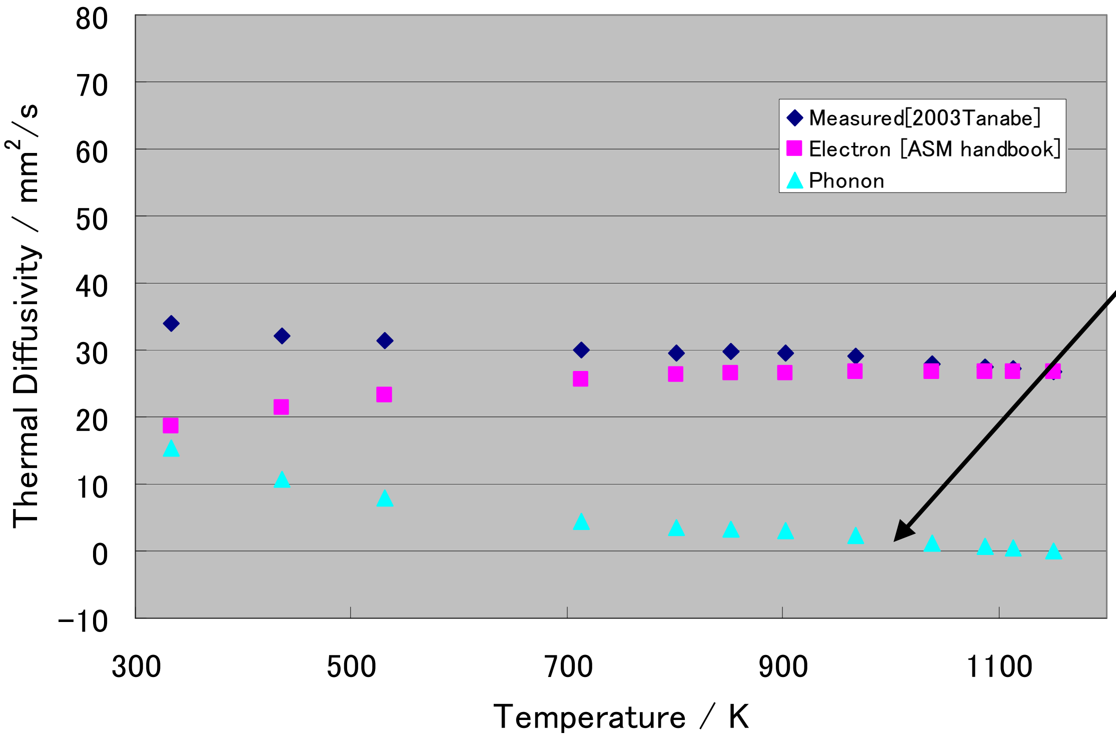


Electric resistivity measurement at elevated temperature using the same sample with thermal diffusivity measurement is required.

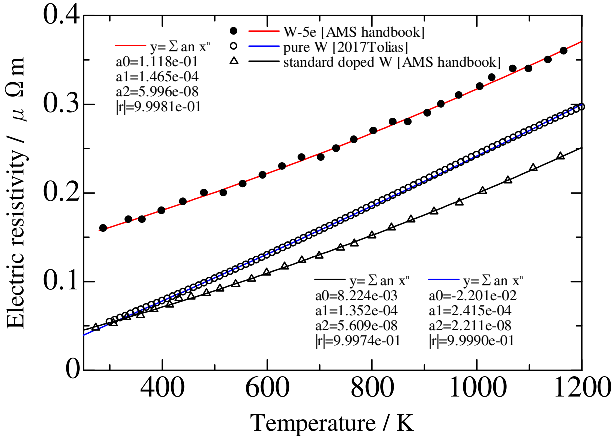
Phonon contribution in W-Re alloy

When the electron contribution in thermal diffusivity are calculated using the literature values of high-temperature electrical resistivity in W-5%Re [AMS handbook] and L_0, it shows a temperature dependence that increase with temperature at low temperature and that becomes flat around 800K.

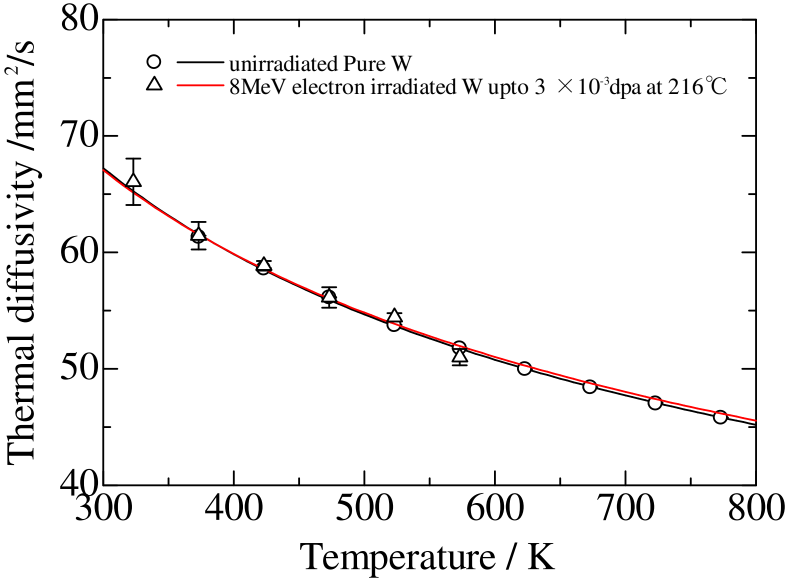
The experimental thermal conductivity of W-5%Re is reported by Tanabe et al. in 2003, then the phonon contribution was obtained with these two data.



Phonon contribution is almost same as in pure W.

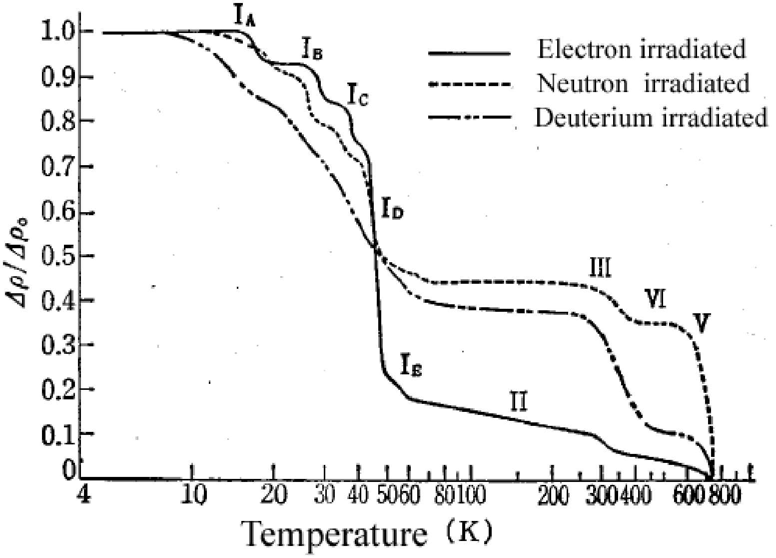


Point defects in tungsten



To clarify the lattice defect contribution, pure W specimens (same material as RB-19J) were irradiated by 8 MeV electron beams using KURRI-LINAC at 216℃ to 2.8×10^{-3} dpa. After the irradiation, this specimen did not show any degradation in thermal diffusivity while ceramics material such as β-SiC electron irradiated up to similar dose showed obvious change.

This result suggests that recovery after stage III in W is quite limited because no I-loops are induced in this specimen and most point defects have recovered below 300 K. In the case of pure Cu, stage III in electron irradiated specimen above 300 K is quite limited compared with neutron irradiated or deuterium irradiated specimens [1979Ishino].



Recovery of electric resistivity in pure Cu irradiated by different source (detail is not given) [1979Ishino].

Estimation of thermal conductivity

From the experimental and calculation results in this study, the phonon contribution in thermal diffusivity is about 15mm^2/s at room temperature for pure W and also W–5%Re.

The thermal diffusivity α is obtained by $\alpha = vl / 3$ (v: phonon velocity, l: phonon mean free path) and v = sqrt(E / ρ) (E: Young's modulus, ρ: density), so using E = 400 GPa and ρ = 19.25 g/cm^3, $v = 4.56 \times 10^3$ m/s and l is obtained as 9.87 nm (at higher temperature, this phonon mean free path is shorter).

It represent that large crystalline defect such as I–loops or grain boundary gives quite small contribution to thermal diffusivity in phonon conduction. There is no electric resistivity measurement at high temperature for neutron irradiated W specimen, but annealing measurement in this study indicates that the effect of crystalline defect to electric resistivity seems to be limited too.

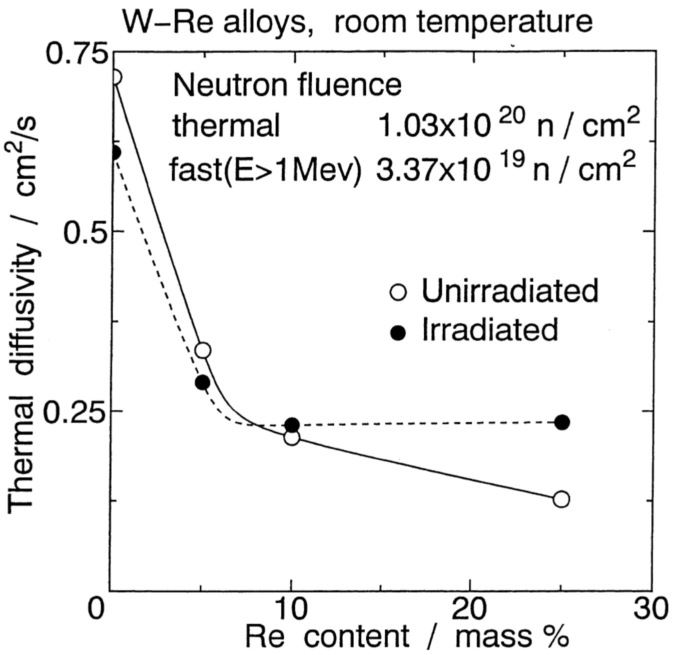
Then, only Re (and also Os) distribution (NOT only amount) is important to estimate thermal diffusivity in irradiated W and W-Re alloy.

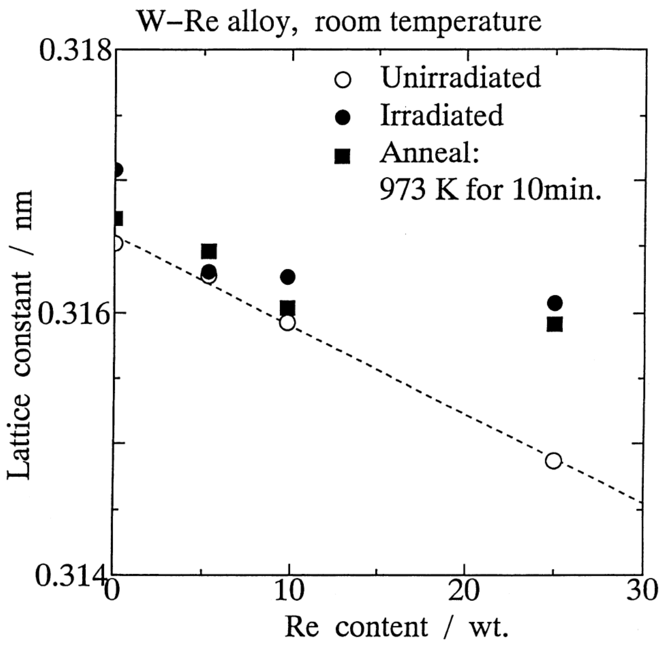
Re and Os distribution

Fujitsuka et al. reported thermal diffusivity of neutron irradiated (JMTR, 330K) high Re containing W alloy [2000Fujitsuka].

Degradation of thermal diffusivity after the irradiation was saturated at Re 10%

Precipitations of Re phase may extracted by the neutron irradiation.





Transmuted Re/Os is not considered. (+0.1 ～ 0.5% ?)

[2000Fujitsuka] Effect of neutron irradiation on thermal diffusivity of tungsten-rhenium alloys, J. Nucl. Matter., 283-287 (2000) 1148-1151.

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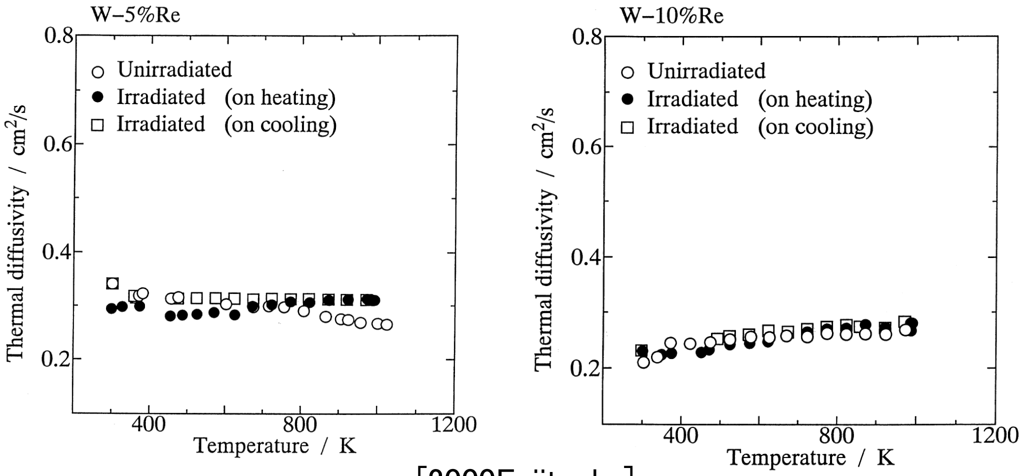

[2000Fujitsuka]

High Re containing W alloy shows almost flat dependence to temperature (thermal conductivity increased with temperature).

Heat flux 10 MW/m^2, Thickness 10 mm

Pure W: TC 170 W/m･K (RT) → 110 W/m･K (1000K)
ΔT 588℃ → 910℃
W−1%Re alloy: TC 120 W/m･K ΔT = 833℃ [2018Fukuda]
W−3%Re alloy: TC 110 W/m･K ΔT = 910℃ [2018Fukuda]
W−5%Re alloy: TC 80 W/m･K ΔT = 1250℃ [2003Tanabe]
W−10%Re alloy: TC 65 W/m･K ΔT = 1538℃ [2000Fujitsuka]

It must be considered that additional Re gives the reducing effect on the DBTT (ductile−to−brittle transition temperatures), however it increase the PFC temperature that causes recrystallization.