IAEA CRP on
Plasma-Wall Interaction for Irradiated Tungsten and Tungsten Alloys in Fusion Devices,
1st RCM 2013_11_26-28, IAEA, Vienna, Austria

Effects of Neutron Irradiation on Damage Structure Evolution of Tungsten in Fusion Device

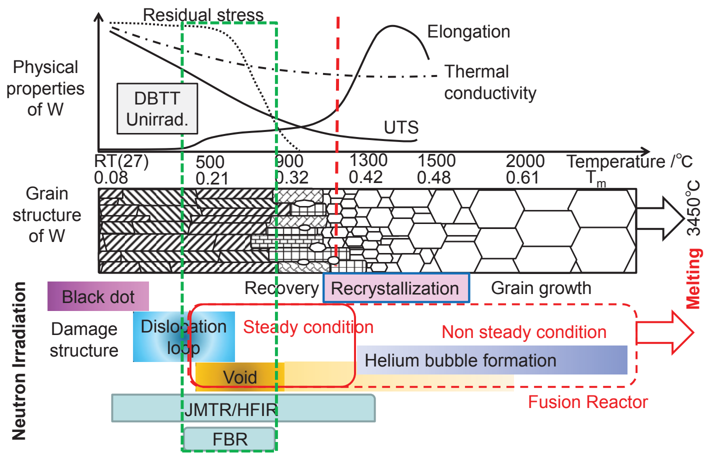
Akira HASEGAWA
Tohoku University, JAPAN

M. Fukuda, T. Tanno*, S. Nogami, K. Yabuuchi : Tohoku University
T.Tanaka : NIFS

* : Current affiliation JAEA

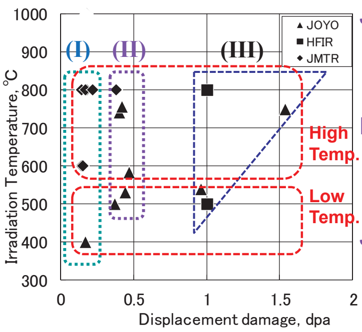
Contents

Temperature Dependence on Microstructure and Physical Properties of Tungsten



Test Matrix of Irradiation and Materials

Test Matrix of Neutron Irradiation



JMTR(JAEA) Mixed spectrum
600,800°C: 0.15 and 0.22dpa

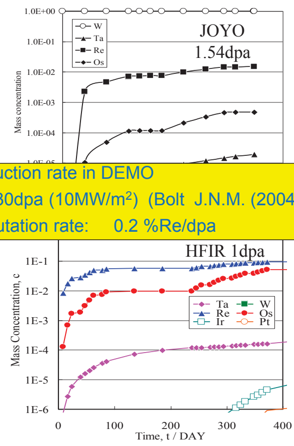
HFIR(ORNL) Mixed spectrum
500,800°C: 1dpa

JOYO(JAEA) Fast spectrum
400°C: 0.17dpa
538°C: 0.4dpa
583°C: 0.45dpa, 0.96dpa
740°C: 0.4dpa
750°C: 1.54dpa

Irradiation period: 1-12 month

PIE (mainly carried out in Oarai Lab. Tohoku Univ.)
Hardness test at RT
Microstructure observation by TEM
Electrical resistivity at RT

Nuclear Transmutation by Fission Reactor Irradiation



Re production rate in DEMO
6%Re/30dpa (10MW/m²) (Bolt J.N.M. (2004)
transmutation rate: 0.2 %Re/dpa

JOYO 1.54dpa	W	Re	Os
W	98.50	1.47	0.05
W-5Re	93.58	6.04	0.39
W-10Re	0.95%Re/dpa	10.61	0.74
W-26Re	72.94	25.22	1.86
W-5Os	93.57	1.40	5.03

JMTR 0.22dpa	W	Re	Os
W	98.22	1.75	0.05
W-5Re	93.33	6.17	0.53
W-10Re	8.0%Re/dpa	10.58	1.00
W-26Re	72.80	24.72	2.51
W-5Os	93.31	1.66	5.04

HFIR 1.0dpa	W	Re	Os
W	85.95	9.22	5.02
W-5Re	81.72	10.46	8.02
W-10Re	9.2%Re/dpa	11.69	11.03
W-26Re	63.98	15.64	20.64
W-5Os	81.65	8.76	9.59

By T. Tanaka(NIFS)

Materials

 # Tungsten Alloys (Plansee) : Hot rolled sheet (0.15mmt)

	W	Re(%)	C(ppm)	O(ppm)	N(ppm)
pure W	bal.	-	<30	<30	<10
W-3Re	bal.	3.00	3	16	<10
W-5Re	bal.	4.99	20	37	<10
W-10Re	bal.	9.12	15	52	<10
W-26Re	bal.	26.0	<30	<30	<10

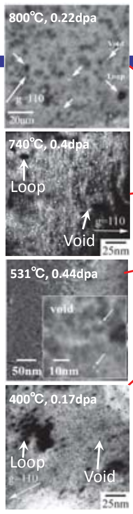
Final heat treatments before irradiation:
(a) Pure-W and W-Re alloys : 1300 °C for 1h in vacuum
(b) 1600 °C for 1h in vacuum

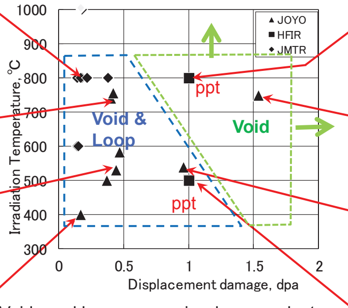
 # Arc-melt Tungsten alloys : Fabricated in IMR Tohoku Univ.
Pure W, W-5Re, W-10Re, W-26Re, W-xRe-yOs
(c) 1400 °C for 1h in vacuum after arc melting

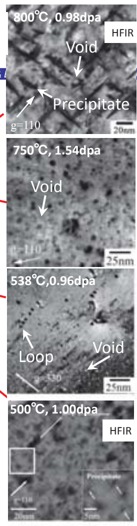
 # Powder Metallurgical Processed W-alloys (A.L.M.T)
Pure W, W-1%La_2O_3, K-dope W : Hot rolled
(d) 1200°C for 1h in vacuum

Microstructural Observation of Irradiated W

Microstructure Map of Irradiated Pure W





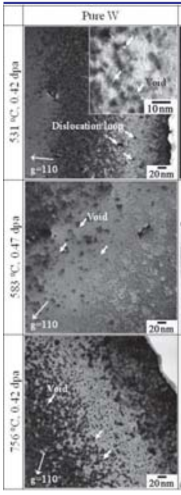


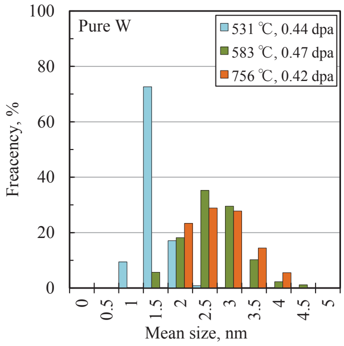
#Voids and loops are major damage clusters in the irradiated pure Tungsten except for irradiated one in HFIR.

#Void lattice was observed after 1.54dpa irradiated at 750C in JOYO.

Hasegawa, Presented in ISFNT-11(2013)

Microstructure of Irradiated W and W alloys





Irradiated in JOYO

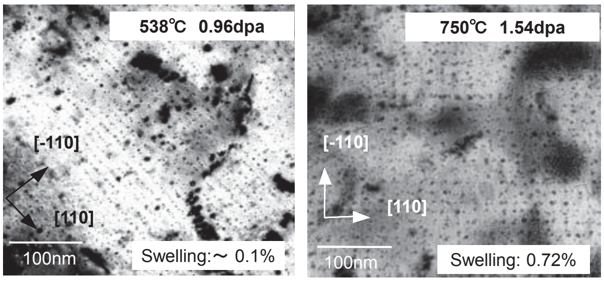
531 ℃: Nucleation dominant

583 and 756 ℃: Growth dominant

Temperature dependence of void size distribution of pure –W after JOYO irradiation to 0.4dpa.

Fukuda, Hasegawa et al., J. Nucl. Mater. (2013) in print

Characteristic Microstructure of pure W after Higher Fluence Irradiation



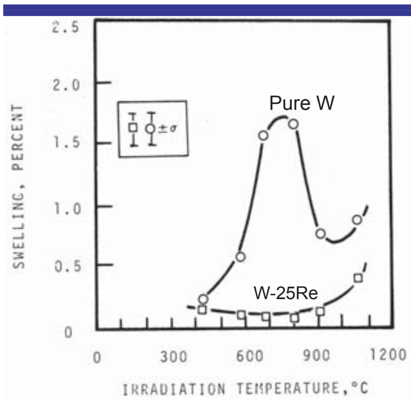
	538℃ 0.96dpa	750℃ 1.54dpa
Mean Size	2.1nm	4.7nm
Number Density	$4.9 \times 10^{22}/m^3$	$1.2 \times 10^{22}/m^3$

Void lattice formation → Stable damage structure → Saturation of irradiation effects ?

Hardening of higher fluence irradiated specimen mainly caused by the void formation. → Saturation of hardening ?

A. Hasegawa, Mater. Trans., 54 (2013)

Swelling of neutron irradiated Tungsten



Temperature dependence of swelling.

Swelling estimated by density measurement.

No microstructural observation.

W-25Re: Suppression of swelling by Re addition to W.

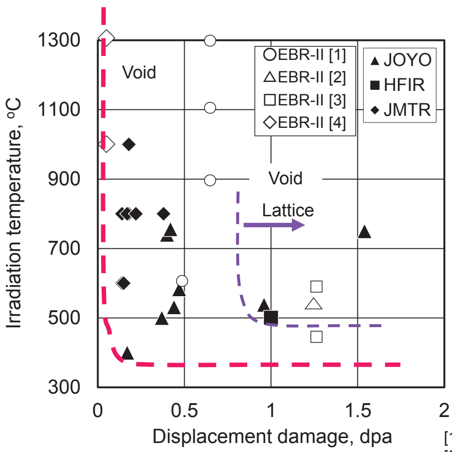
Recrystallized at 1750℃

EBR-II $5.5 \times 10^{26} n/m^2$

(E>0.1MeV) 9.5dpa

J.Motolich et al., Scripta Metallurgica, 8 (1974) 837-842

Summary of Damage Structure Map of W



#Void was observed above 0.1dpa irradiation, above 400C up to 1300C.

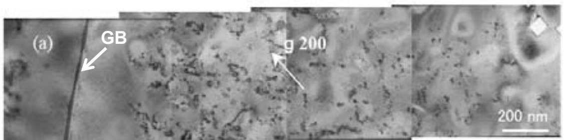
#Loop was also observed above 400C. Upper limit of loop formation could not be confirmed.

#Void lattice formed after higher level irradiation (>1dpa).

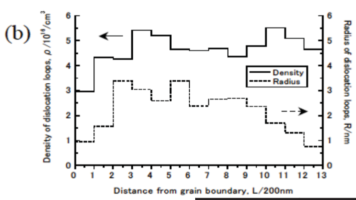
[1] Williams(1983), [2] Sikka(1972), [3] Sikka(1973),[4] Rau (1969)

Defect Distribution Near GB

Microstructure Near G. B. of pure W



Denuded zone of dislocation loop



Pure W 600℃ 0.15dpa in JMTR

Denuded zone of dislocation loop was clearly observed.

Defects data in the matrix

Void Number Density 10^{22} /m³	Void Radius nm	Void Swelling %	Loop Number Density 10^{21}/m³	Loop Radius nm	Dislocation Density m/m³
6.4	1.3	0.09	4.6	7.9	4.0

J. C. He A. Hasegawa et al., Nucl. Fusion 46 (2006) 877-883.

Results of HFIR Irradiation

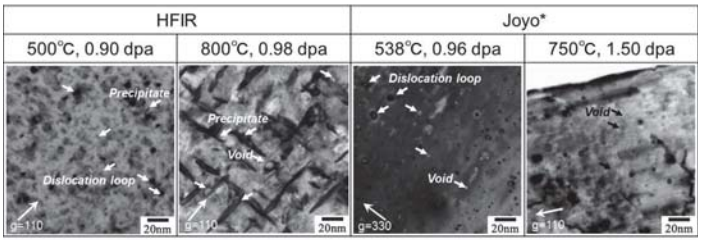
Microstructural development of W under high transmutation rate condition

Microstructure of pure-W

Dept. Quantum Science & Energy Engineering, Tohoku University

#Lower irradiation temperature (500 °C,538 °C) : void and loop.
#Higher irradiation temperature (800 °C,750 °C) : void

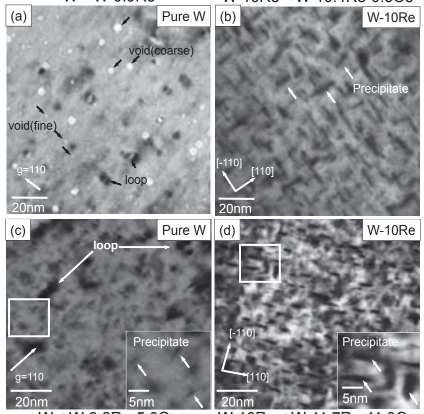
#Precipitates were observed in HFIR irradiated pure W specimens.
#The precipitates might be χ–phase(Re_3W).



M. Fukuda et al., ICFRM-16 (2013) submitted
T. Tanno et al, Mater. Trans., 52 No. 7 (2011) 1447-1451.

Microstructure of W after JOYO and HFIR Irradiation at ～500℃

Dept. Quantum Science & Energy Engineering, Tohoku University



Void is major damage structure of pure W at 500-800℃ around 1dpa.

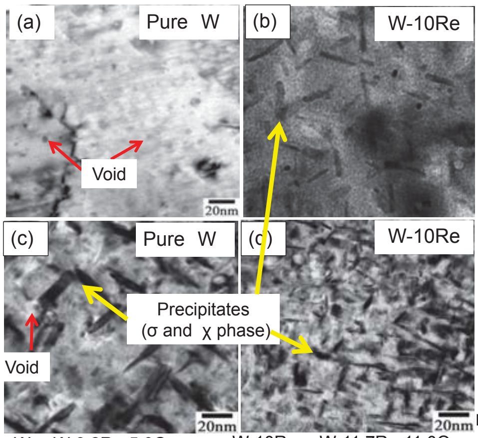
In HFIR irradiated W, void was not major damage structure. Small precipitates were formed.

Precipitates in HFIR irradiated pure-W was caused by higher Re concentration by nuclear transmutation.

Fukuda, Hasegawa. ICFRM-16 (2013)

Microstructure of W after JOYO and HFIR Irradiation at ～800℃

Dept. Quantum Science & Energy Engineering, Tohoku University



 # Precipitates were not observed in JOYO irradiated pure-W.

 # Precipitates in 800℃ irradiated specimen became larger than 500℃ irradiation.

Fukuda, Hasegawa. ICFRM-16 (2013)

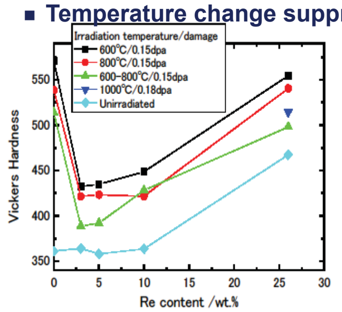
Dept. Quantum Science & Energy Engineering, Tohoku University

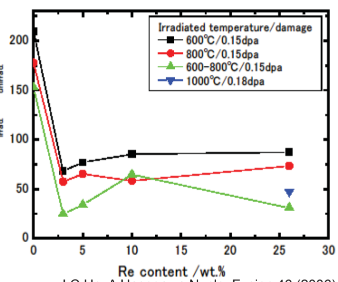
Irradiation Hardening

Re Effects on Irradiation Hardening(0.15dpa)

Dept. Quantum Science & Energy Engineering, Tohoku University

- **Irradiation hardening of pure W was significantly larger than W-Re alloys.**
- **Re addition suppressed irradiation hardening.**
- **Lower temperature irradiation caused larger irradiation hardening.**
- **Temperature change suppressed irradiation hardening.**





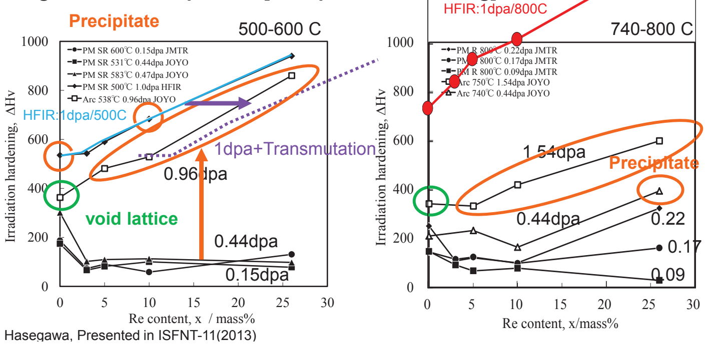
J.C.He, A Hasegawa Nucle. Fusion 46 (2006)

Irradiation Hardening Behavior of W and W-Re Alloys

Dept. Quantum Science & Energy Engineering, Tohoku University

 # Irradiation hardening of pure W appeared in lower fluence compared to W-Re alloys. [Void and loop hardening]

 # When precipitates were observed, irradiation hardening of W-Re was larger than that of pure W. [Precipitation hardening]



Hasegawa, Presented in ISFNT-11(2013)

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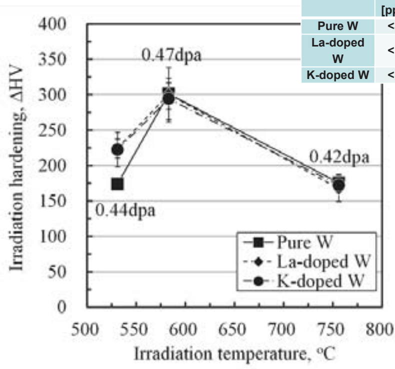
Irradiation Damage of Advanced W-Alloys

Irradiation Hardening of Advanced Tungsten Alloys

Dept. Quantum Science & Energy Engineering, Tohoku University



	C [ppm]	O [ppm]	N [ppm]	La [%]	K [ppm]	Al [ppm]	Si [ppm]
Pure W	<30	<30	<10	–	–	–	–
La-doped W	<10	1320	20	0.82	<5	6	<5
K-doped W	<10	<10	10	–	30	16	21

Irradiation Temperature (° C)	Neutron fluence (10^{25} n/m²) (E_n > 0.1 MeV)	dpa*
531	3.4	0.44
583	3.7	0.47
756	3.3	0.42

*1 dpa=8 × 10^{25} n/m² (E_n > 0.1 MeV), E_d=90 eV

Behavior of the microstructure development in the matrix and irradiation hardening in pure-W, La, and K-doped W under neutron irradiation at 531–756℃ and 0.42–0.47 dpa were similar.

M. Fukuda et al., J. Nucl. Mater. (2013) in print

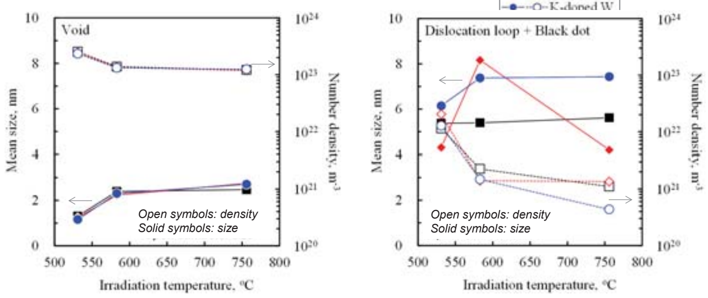
Defect Clusters in Matrix after JOYO Irradiation

M. Fukuda et al., J. Nucl. Mater. (2013) in print

Calculate void swelling (%)

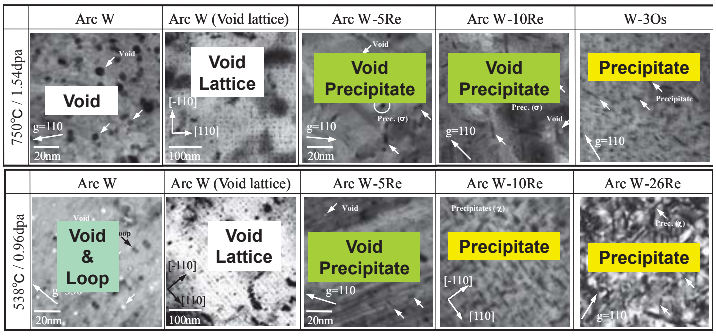
Irradiation conditions	Pure W	La-doped W	K-doped W
531°C, 0.44dpa	0.017	0.014	0.011
583°C, 0.47dpa	0.056	0.044	0.047
756°C, 0.42dpa	0.054	0.072	0.073

- Irradiation response of the advanced W alloys were almost the same as pure W.
- Matrix condition for defect clustering were considered to be similar between these specimens.



Damage Structure of W and W-Re Alloys

Irradiated in JOYO



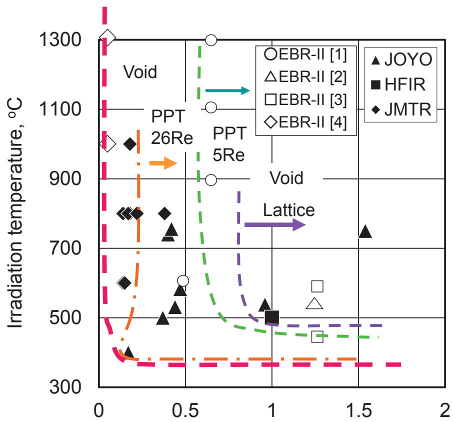
Void lattice were observed in pure W. (pure W → W-1.5Re-0.05Os after 1.5dpa)

Void formation was drastically suppressed in W-Re and acicular precipitates were observed above 5%Re.

Hasegawa, Mater. Trans., 54 (2013)

Prediction of Damage Structure Development

Summary of Damage Structure Map of W



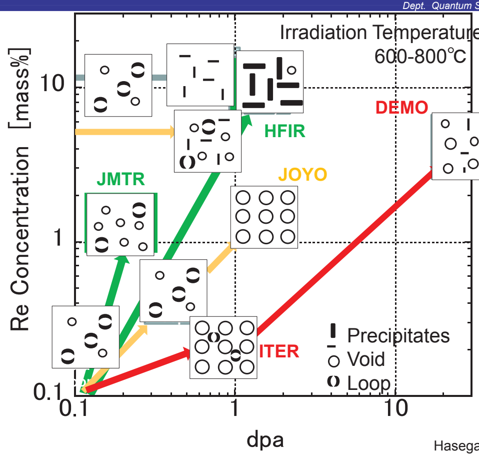
#Void was observed above 0.1dpa irradiation, above 400C up to 1300C.

#Loop was also observed above 400C. Upper limit of loop formation could not be confirmed.

#Void lattice formed after higher level irradiation (>1dpa).

[1] Williams(1983), [2] Sikka(1972), [3] Sikka(1973),[4] Rau (1969)

Summery and Prediction of Microstructural Development of W



DEMO
3-6%Re
15-30dpa
→Void + Precipitate

ITER
Below 1%Re
Around 1dpa
→ Void (Lattice?)

Hasegawa, Presented in ISFNT-11(2013)

Required Data on Irradiation and Subjects

#Data on mechanical property change by irradiation is not enough.
Tensile data at operating temperature is needed for component design.

#Heavy Irradiation up to 10 to 30 dpa is required.

Limitation of irradiation field and irradiation rate. 1-2dpa/yr
Fast Reactor → Temperature limit : <800C
Additional heating system is needed.
Material testing reactor (HFIR) <1300C by high γ–heating
→ Thermal neutron shield is needed
Drastic structure change and mechanical properties by transmutation

Limitation of irradiation volume in test reactors.
→ Small size specimen

He effects on microstructural development and mechanical properties
→ Is it negligible ? → Accelerator irradiation ?

Material Development
Large production scale is needed.
Economical benefits and reliability of material qualification are important.

Plans of Irradiation Experiments in Japan

Reactor irradiation at high temperature up to high fluence irradiation with thermal neutron shield

→ Us-Japan Collaboration program: PHENIX (2013-2017)
HFIR irradiation dpa: <2.5dpa (W)
#Mechanical property measurement of irradiated tungsten
#Hydrogen retention behavior of irradiated tungsten
#High heat load response of irradiated tungsten

→ Japan JOYO 2015？？～

Accelerator Irradiation (Japan)
TIARA : 10dpa, 800-1300C 18MeV W^{6+} ion (+ He ion)
Cyclotron : 50appm at 600C implantation
and annealing or tensile test at high temperature

Thank you for your attention.

References of our works

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7) A. Hasegawa, T. Tanno, S. Nogami and M. Satou, "Property change mechanism in tungsten under neutron irradiation in Various reactors" , J. Nucl. Mater. 417 (2011) 491-494.
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14) M. Fukuda, K. Yabuuchi, S. Nogami, A. Hasegawa, T. Tanaka, "Microstructural development of tungsten and tungsten-rhenium alloys due to neutron irradiation in HFIR", ICFRM-16 (2013) Beijing, China, submitted.