INNUMAT Workshop in Madrid from 16 – 17, November 2023

Development of Material Database and Material Property Handbook for EU DEMO

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Structural, armour and heat sink materials for DEMO

Harsh operational environment of DEMO **First Wall** (FW) and **Divertor** Plasma Facing Components (PFCs)

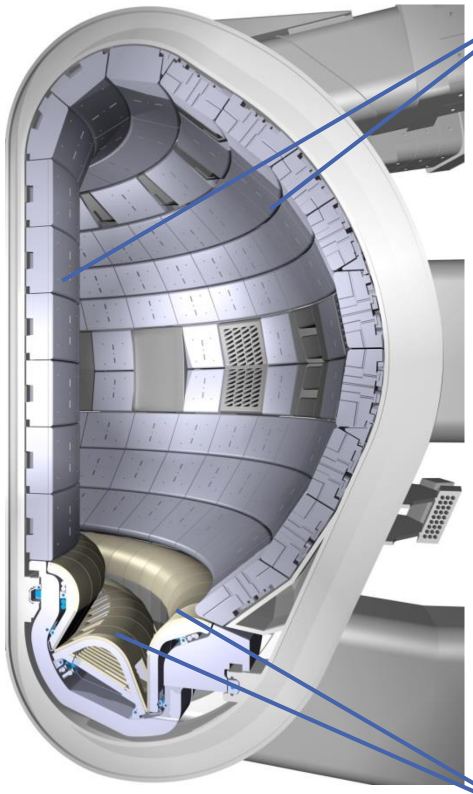
- High fluence of neutrons
- Energetic ions escaping plasma
- High thermal flux

EUROFER97, owing to good balance of mechanical and thermo-physical properties and good resistance to neutron irradiation – a baseline structural material for DEMO First Wall/Blanket

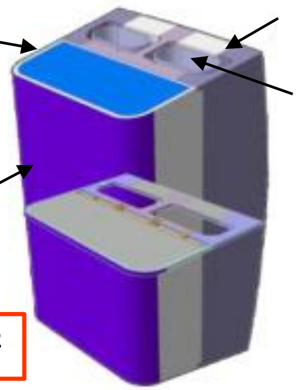
Tungsten, owing to low sputtering yield, high melting point and high thermal conductivity – a baseline armour material for DEMO PFCs

CuCrZr, owing to favorable combination of high thermal conductivity and good mechanical properties – a baseline DEMO divertor heat sink material

Source: www.iter.org

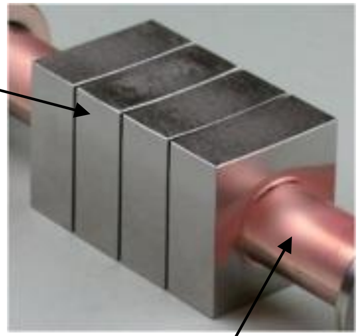


DEMO Blanket module



F. Hernández et al., FED 124 (2017)

ITER-like tungsten monoblock

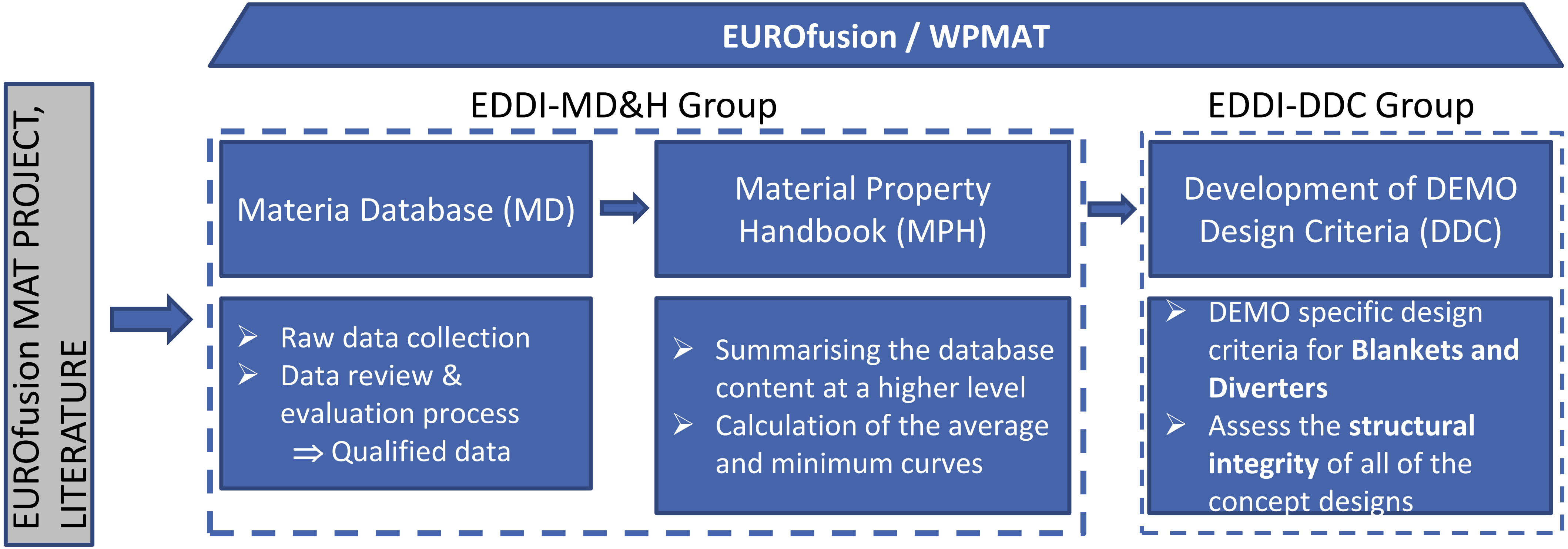


J..H. You et al., Nucl. Mater. Energy 33 (2022)

EUROfusion EDDI Material Database & Handbook (MD&H)

Realization of in-vessel components for DEMO

- Development of sound **material databases (MD)** on **structural, heat sink, armour** and **functional materials**
- Development of **DEMO Design Criteria (DDC)** for in-vessel components



Objective: Development of **MD** & **MPH** on **EUROFER97, CuCrZr, W**

MPH - Properties to be covered

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Materials: EUROFER97, CuCrZr, W

Mechanical properties
- Tensile properties
  - Yield strength
  - Tensile strength
  - Elongation
  - Reduction of area
- Young's modulus
- Hardness
- Poisson's ratio
- Charpy impact properties
- Fracture toughness
- Fatigue crack growth
- Low cycle fatigue
- Creep
- Irradiation creep
- Swelling
- Helium effects

Thermo-Physical properties
- Coefficient of thermal expansion
- Density
- Thermal conductivity
- Thermal diffusivity
- Specific heat
- Electrical resistivity
- Melting temperature
- …

Magnetic properties (EUROFER97)
- Magnetic saturation
- Remnant magnetization
- Coercive field
- …

Materials: W

Recrystallization behavior
- DBTT
- Hardness
- …

Oxidation and corrosion
- Low-T corrosion
- High-T oxidation & corrosion
- …

Fusion-specific properties
- High heat flux properties
- Neutron irradiation & transmutation
- Plasma-material interaction
- Erosion & redeposition
- Hydrogen implantation & retention

Data qualification & storage

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DATA QUALIFICATION

Data collection templates

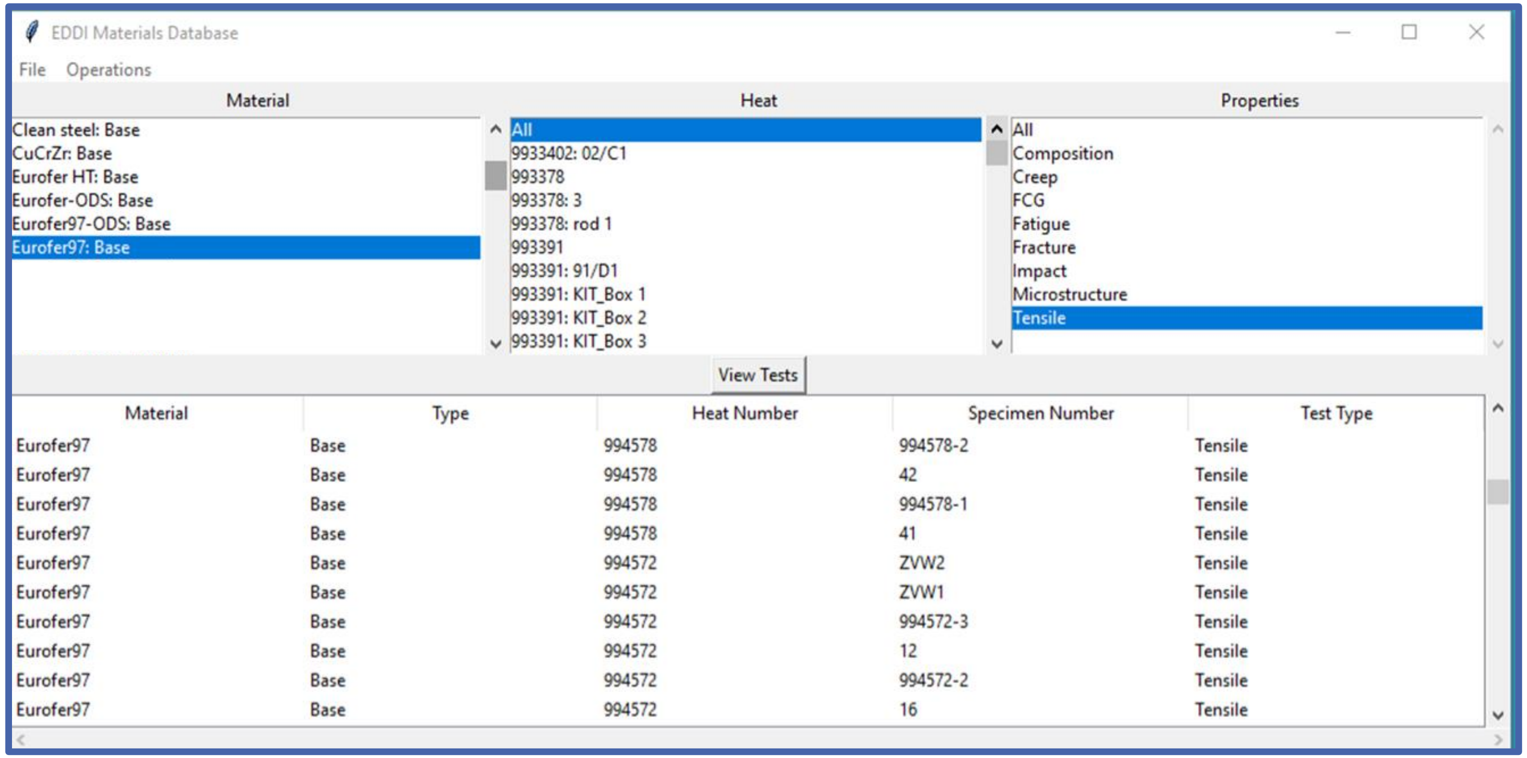
MATERIAL IDENTIFICATION
- manufacturer
- heat/product/sub-product
- thermo-mechanical treatment …

SPECIMEN IDENTIFICATION
- geometry
- extraction direction
- surface finish …

IRRADIATION CONDITION
- irradiation facility
- temperature
- dose ...

TESTING and RESULTS
- testing standard, parameter
- temperature
- environment
- results, validity …

EDDI MATERIALS DATA STORAGE



Material	Type	Heat Number	Specimen Number	Test Type
Eurofer97	Base	994578	994578-2	Tensile
Eurofer97	Base	994578	42	Tensile
Eurofer97	Base	994578	994578-1	Tensile
Eurofer97	Base	994578	41	Tensile
Eurofer97	Base	994572	ZVW2	Tensile
Eurofer97	Base	994572	ZVW1	Tensile
Eurofer97	Base	994572	994572-3	Tensile
Eurofer97	Base	994572	12	Tensile
Eurofer97	Base	994572	994572-2	Tensile
Eurofer97	Base	994572	16	Tensile

- Custom database for storage materials test data
- Importing the data from data collection Excel templates
- Exporting function for further data handling

EUROFER MPH

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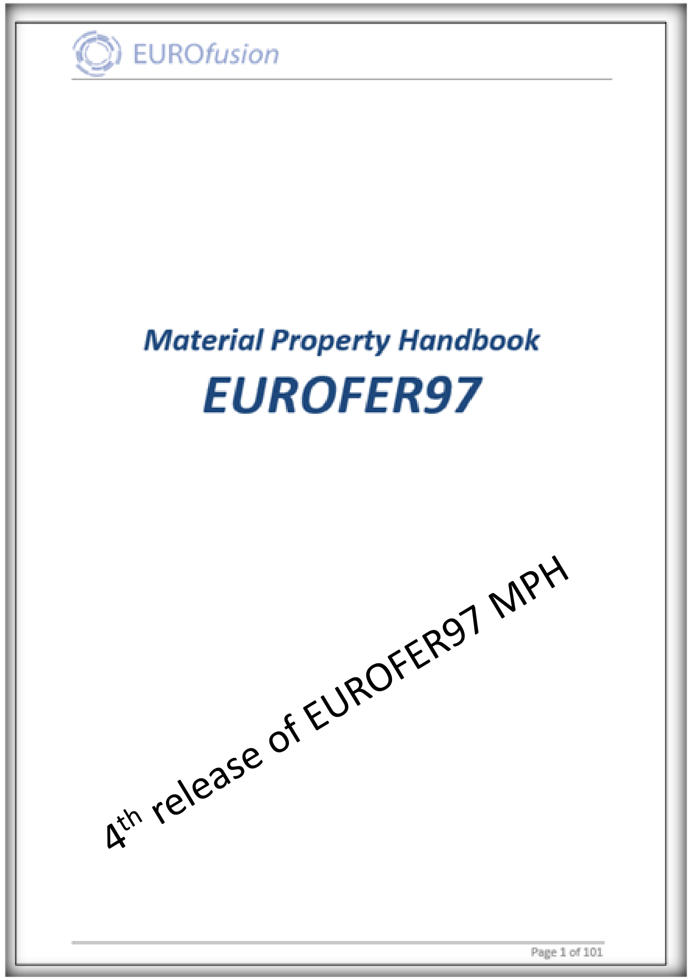
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Material Property Handbook

EUROFER97

4th release of EUROFER97 MPH

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Reduced Activation Ferritic/Martensitic (RAFM) steel EUROFER97 – European reference structural material for ITER TBM and DEMO Blanket

Chemical composition (RCC-MRx)

	C%	S%	P%	Si%	Mn%	Ni%	Cr%	Mo%	W%	As+Sn+Sb+Zr%
min	0.09	-	-	-	0.2	-	8.5	-	1	0
max	0.12	0.005	0.005	0.05	0.6	0.01	9.5	0.005	1.2	0.05

	Ta%	V%	Nb%	Cu%	B%	Al%	Co%	N_2%	Ti%	Fe%-
min	0.1	0.15	-	-	-	-	-	0.015	-	Balance
max	0.14	0.25	0.005	0.01	0.002	0.01	0.01	0.045	0.02	Balance

- Production of large industrial batches: EUROFER 97-1, …, EUROFER97-4
- Availability of different product forms: plates, rods
- Development of joining technologies
- Examination & characterization by several European Research Units (RUs)
- Investigation of irradiation influence

EUROFER MPH – Property sheet structure

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DEMO MATERIAL PROPERTIES HANDBOOK

MATERIAL	PROPERTY
EUROFER97	4.1. Yield strength

4 Mechanical properties

4.1 Yield strength

The **yield strength, R_{p02}, YS or S_y [MPa]**, is the engineering stress at which, by convention, it is considered that plastic deformation of the material has commenced.

The following types of yield strengths, which correspond to the approaches listed above, may be specified:

Specified offset yield strength, (usually an offset strain of 0.2% is specified)—the engineering stress at which the material has been plastically strained by an amount equal to the specified offset strain. This stress is reached at the point where the stress-strain curve intersects a line having a slope equal to the modulus of elasticity and constructed such that it is offset from the linear portion of the stress-strain curve by an amount equal to the specified strain.

Upper or lower yield strengths. The upper (first maximum) or the lower (minimum, ignoring transient effects) engineering stress measured during discontinuous yielding occurring at or near the onset of plastic deformation. Figure 4.1-1 shows the yield strength in as received state together with the average and minimum curves. The average curve was calculated by fitting the data with a 5th order polynomial function. The minimum curve is calculated on the base of the statistical analysis of the entire dataset according with the following equation

$$R_{p02\,min}(T) = R_{p02\,average}(T) - 1.96\ \mathrm{SD},$$

where SD is the standard deviation obtained for the entire dataset in the procedure for the determination of $R_{p02\,average}(T)$ curve. The function for both curves is provided in Table 4.1-1 and the determined average yield strength data as a function of temperature are listed in Table 4.1-2.

- General description of the property
- Relevant formulas

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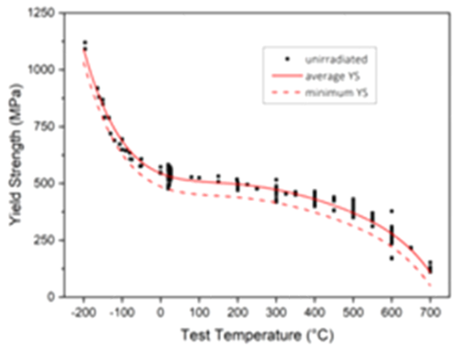

Figure 4.1-1 Yield strength of as-received EUROFER97 together with average and minimum curves. Rapid drop of the yield strength at elevated temperatures is due to the approach to α–γ transition (Austenization start and end temperatures for EUROFER97, Ac_{1b}=820°C, Ac_{1e} =890°C)

Table 4.1-1 Average and minimum yield strength curves of as-received EUROFER97

	Function (T in °C, Stress in MPa)
Average yield strength	$544.39601-0.6983T+0.00506T^2-1.895E\text{-}5T^3+2.92096E\text{-}8T^4-1.74917E\text{-}11T^5$
Minimum yield strength	$486.78671-0.6983T+0.00506T^2-1.895E\text{-}5T^3+2.92096E\text{-}8T^4-1.74917E\text{-}11T^5$

- Property diagram along with average and minimum curves
- Formulas describing the evolution of the average and minimum values

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Table 4.1-2: Average yield strength values determined on as-received EUROFER97

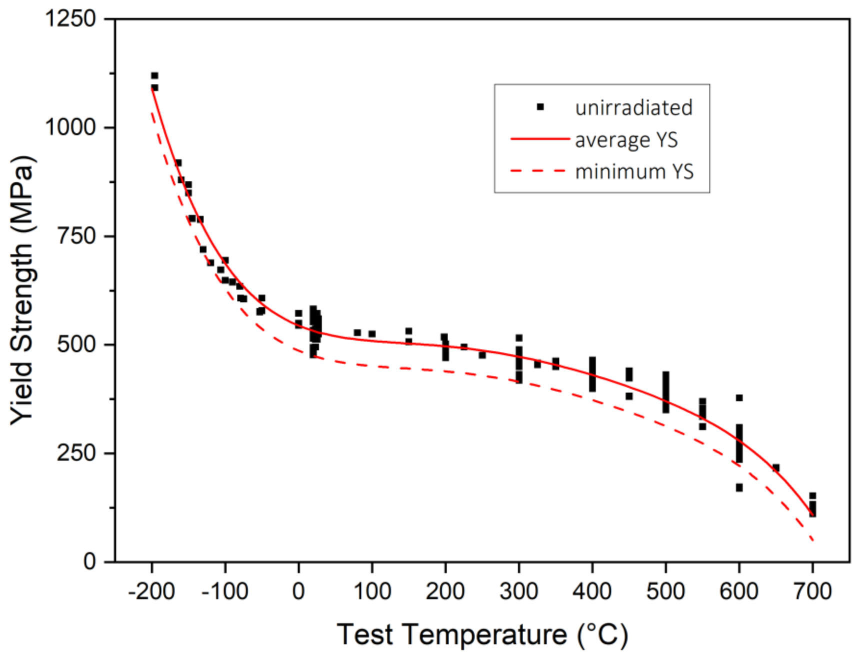
Temperature	$R_{p02\,average}$
°C	MPa
-200	1090
-150	843
-100	689
-50	595
0	544
20	532
50	520
100	509
150	503
200	497
250	487
300	473
350	454
400	431
450	403
500	370
550	331
600	279
700	109

References

1. ASTM E-6-03 "Standard Terminology Relating to Methods of Mechanical Testing"
2. ISO-6892:1998. Metallic Materials-Tensile testing
3. ASTME8/8M Standard Test Methods for Tension Testing of Metallic Materials
4. E. Gaganidze: "Final report on PPPT Material Property Handbook on Eurofer" (KIT, 2015)

- Tabulated values of the properties
- References

EUROFER MPH – Average and minimum curves



- Determination of the ***average values*** by means of statistical analysis (best fit)
- Determination of the ***minimum values*** followed internationally established methodologies

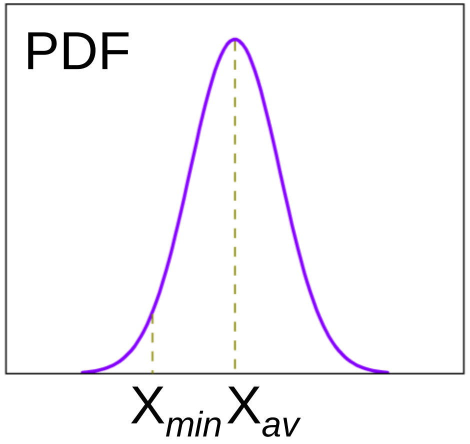
Minimum Curve

- Calculate an average $S_{y,av}$ curve by a statistical analysis
- Determine standard deviation – σ
- Built the minimum curve by offsetting the average curve

$$S_{y,min}(T) = S_{y,av}(T) - 1.96\sigma$$

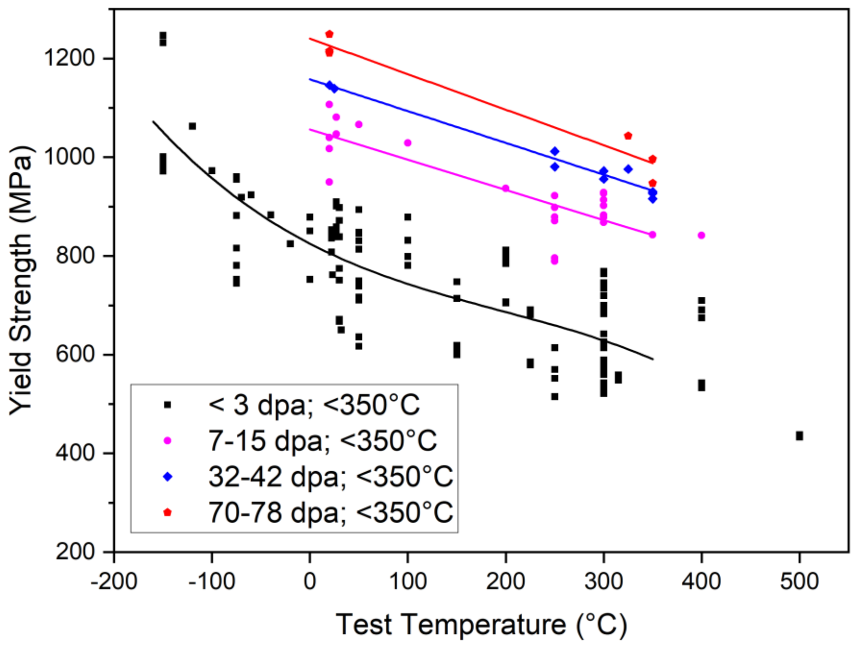
Alternative Minimum Curve

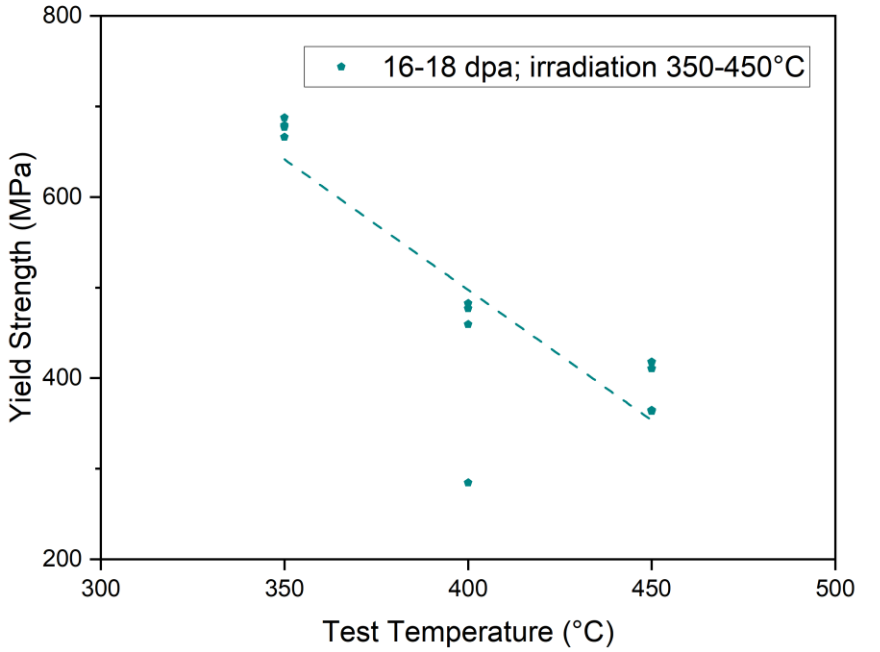
$$X_{min}(T) = \frac{X_{min}(RT)}{X_{av}(RT)} X_{av}(T)$$



$\pm 1.96\sigma \leftrightarrow$ *bounds of* 95% confidence

EUROFER MPH – Yield Strength in the irradiated state



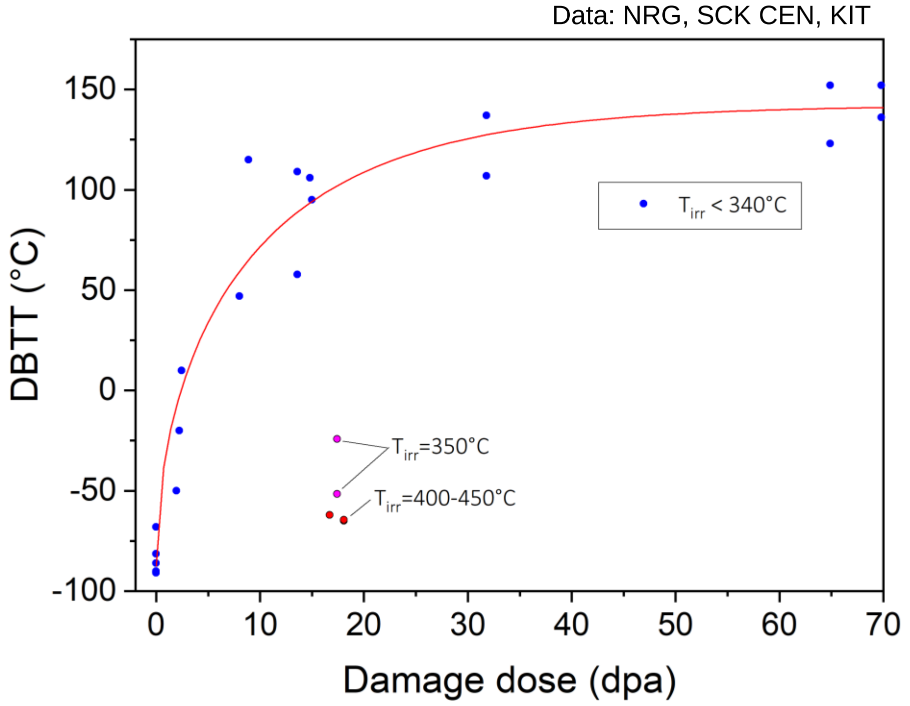


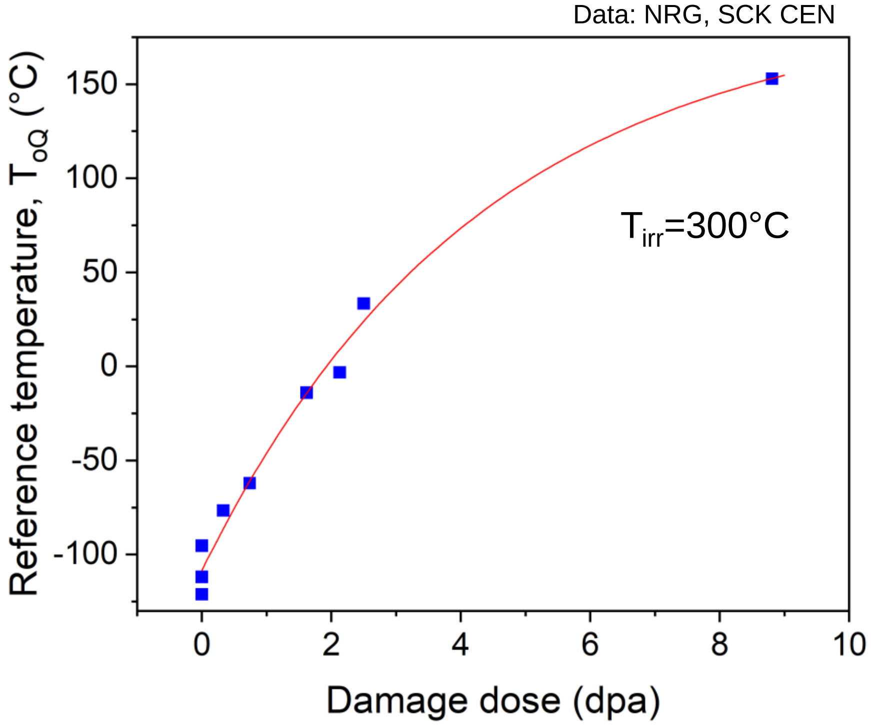
- Grouping the results according to the irradiation (DPA, T_{irr}) and testing conditions
- Determination of the ***average values*** by means of statistical analysis (best fit)

Testing conditions	Function (T in °C, Stress in MPa)
<3 dpa, <350°C	$825.1-1.02703T+0.00254T^2-4.3385E-6T^3$
7-15 dpa, <350°C	1056-0.61046T
30-42 dpa, <350°C	1157.9-0.644T
70-78 dpa, <350°C	1240.3-0.72T

Testing conditions	Function (T in °C, Stress in MPa)
16-18 dpa, ≥350°C	1651.1-2.884T

EUROFER MPH – n-irradiation induced embrittlement





- DBTT (KLST) as a function of damage dose
- Grouping of the results according to irradiation temperature
- Saturation behaviour of the low temperature embrittlement at the achieved damage doses

- Evolution of the ASTM E1921 reference temperature (T_{0Q}) with the irradiation dose at T_{irr}=300 °C.
- Lack of high dose irradiation data
- Lack of J-R curve behavior

EUROFER MPH – Gap analysis & testing

Unirradiated (EUROFER97-3 & EUROFER97-4)

- **Fatigue** properties (tests in progress)
- **Fracture Mechanical (FM)** properties (J_{Ic}, J-R …) (tests in progress)
- **Fatigue crack growth** (tests in progress)
- **Creep** properties (tests in progress)
- **Thermal aging** effects (tensile, Charpy-V, FM) (tests in progress)
- **Mechanical properties** on **weldments** for proper PWHT (tests to be prepared)

Irradiated (EUROFER97-3 & EUROFER97-4)

- **Tensile properties** in a **wide temperature** (T_{irr}=200-550°C) and **dose** range (irradiation in progress)
- **Fatigue** properties (irradiation in progress)
- **Fracture Mechanical (FM)** properties (J_{Ic}, J-R …) (irradiation in progress)
- **Fatigue crack growth** properties (tests to be prepared)
- **Swelling & Helium** effects (tests in progress & to be prepared)
- **Irradiation creep** (tests in progress)
- **Mechanical properties** on **weldments** for proper PWHT (tensile, FM) (tests to be prepared)

CuCrZr MPH – Reference composition and heat treatment

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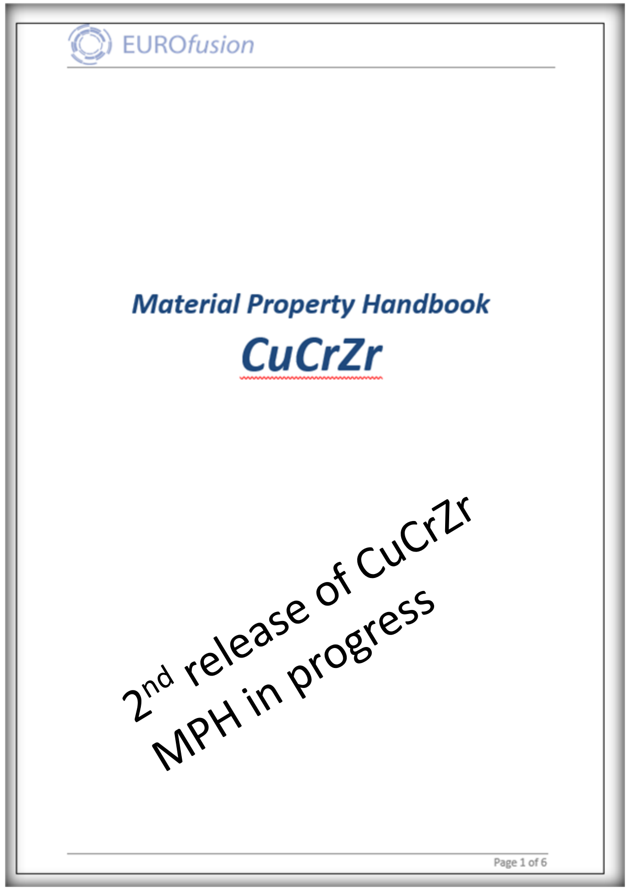
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Material Property Handbook

CuCrZr

2nd release of CuCrZr MPH in progress

Page 1 of 6

Chemical composition

a) **CuCrZr (ITER-Grade)**
→ 0.6-0.9 wt%Cr, 0.07-0.15 wt% Zr, <0.002 wt% O, <0.03 wt% others

b) **CuCr1Zr (European Copper Insititute, German Copper Institute, C18150):**
→ 0.5-1.2 wt%Cr, 0.03-0.3 wt% Zr, 0-0.08 wt% Fe, 0-0.1 wt% Si, 0.2 wt% others

Heat treatment

a) **SAA:** Solution annealing at 980~1000°C for 30~60 min, water quenched and aged at 460~500 °C for 2~4 h.

b) **SAcwA:** Solution annealing at 980~1000°C for 30~60min, subsequent cooling in water, further cold working by 40~70%, and ageing at 450~470°C for 2~4 h.

c) **SCA:** received as SAA, HIPped at 1040°C for 2h at 140 MPa followed by solution annealing at 980°C for 0.5 h with a slow cooling rate of 50~80°C/min between 980 and 500°C, and final aging at 560 °C for 2h.

d) **SAoverA:** Solution annealing and ageing at non-optimal condition (over-aged) due to specific manufacturing processes.

e) **PA** (Prime aged): material supplied by Outokumpu Oyj: solution annealed at 960°C for 3h, water quenched and then PA at 460°C for 3 h. After PA specimens received further annealing

CuCrZr MPH – Tensile properties for SAcwA condition

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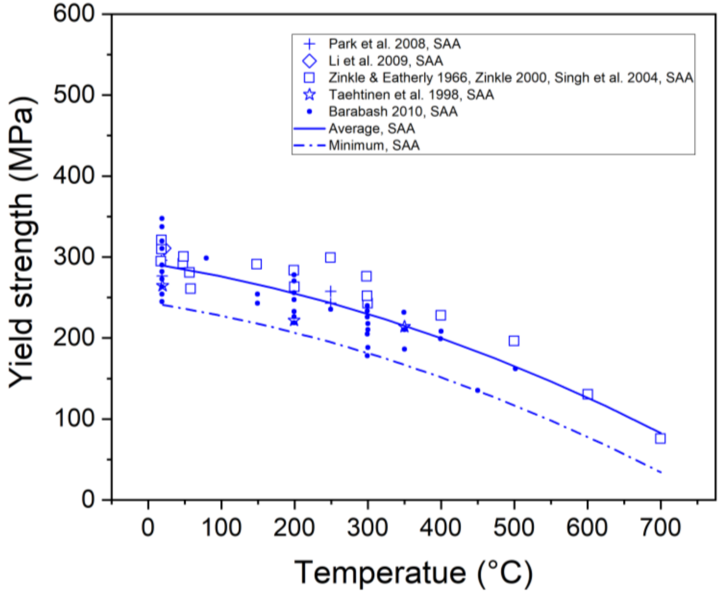
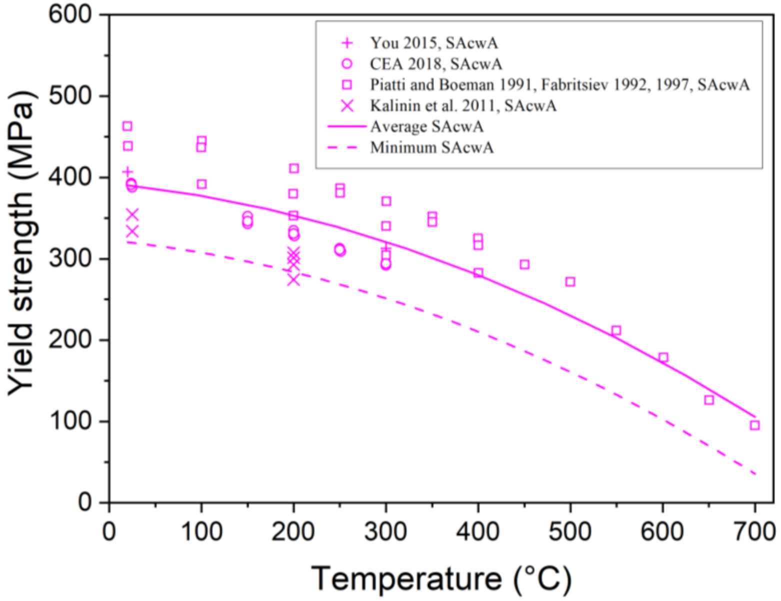
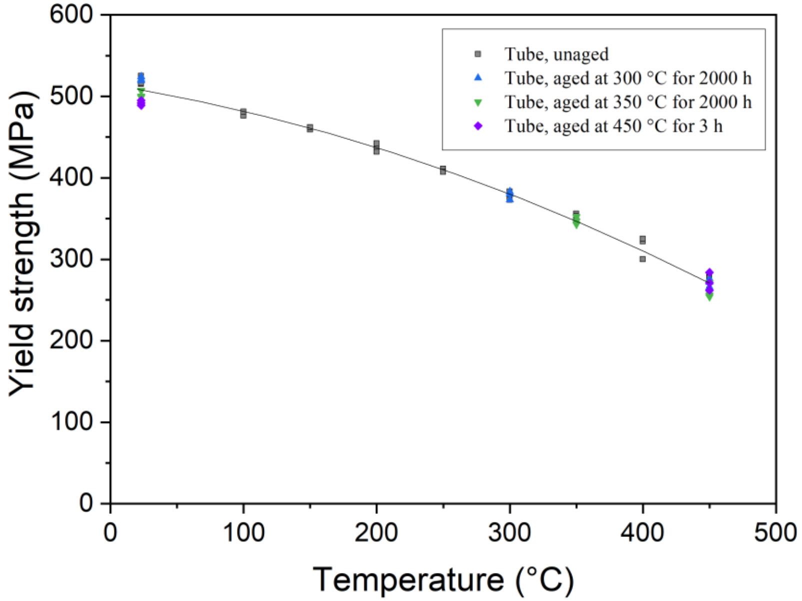
- Collection and assessment of literature data on CuCrZr for different thermo-mechanical treatments
- Generation of new data in the frame of EUROfusion MAT project







- Average and minimum 0.2% yield strength for CuCrZr for SAA
- Average and minimum 0.2% yield strength of CuCrZr for SAcwA
- Average 0.2% yield strength of CuCrZr **tube** (SAcwA)
  - unaged
  - aged

CuCrZr MPH – Dose dependent tensile properties

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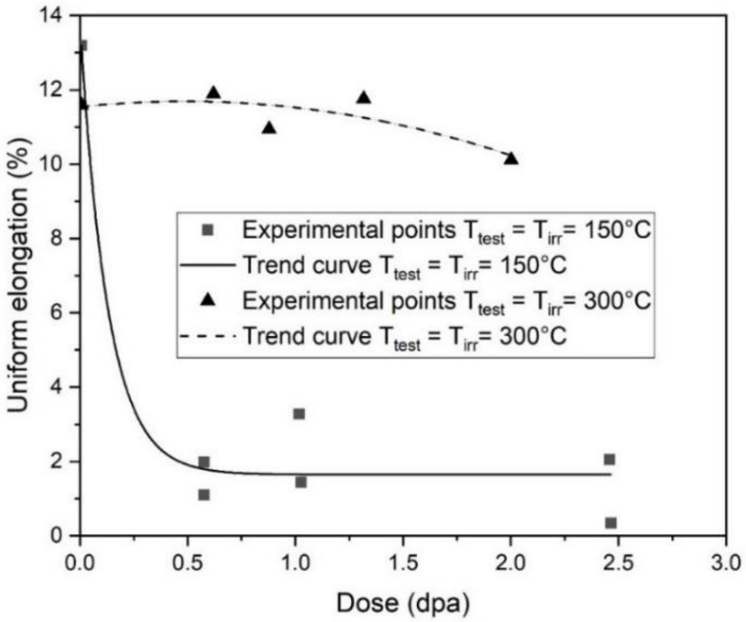
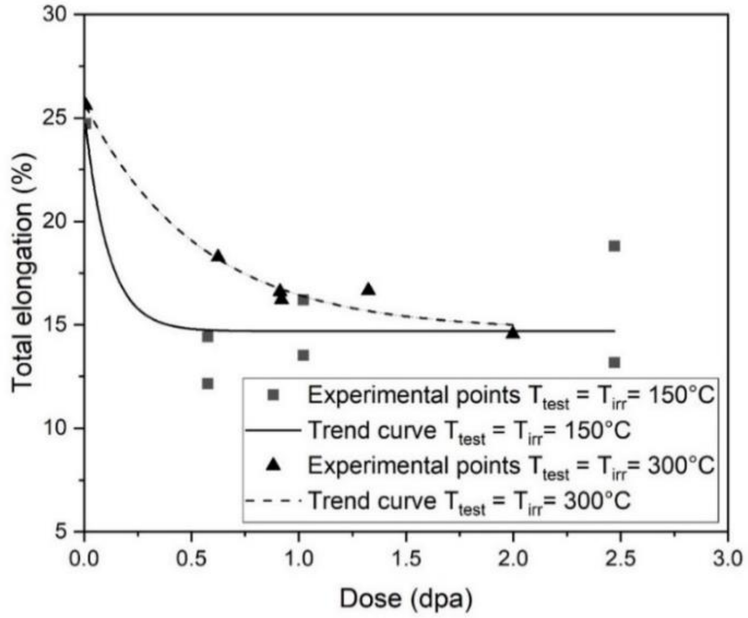
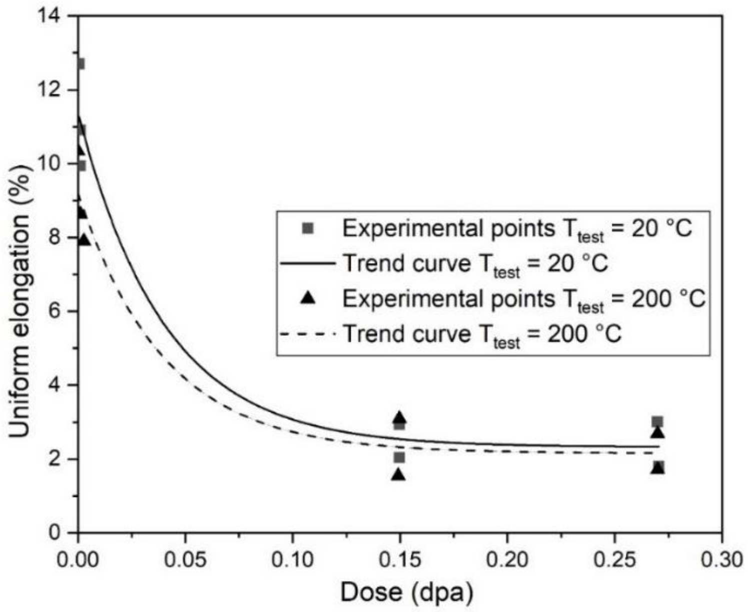
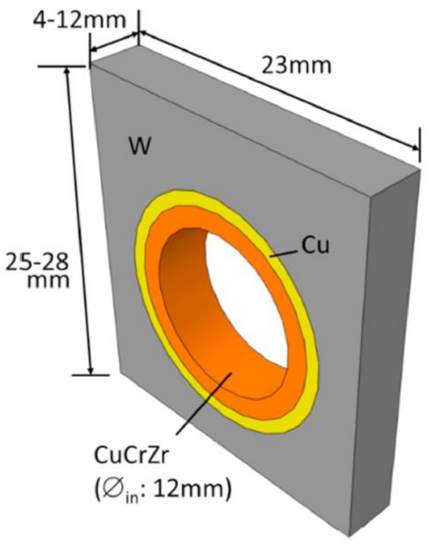






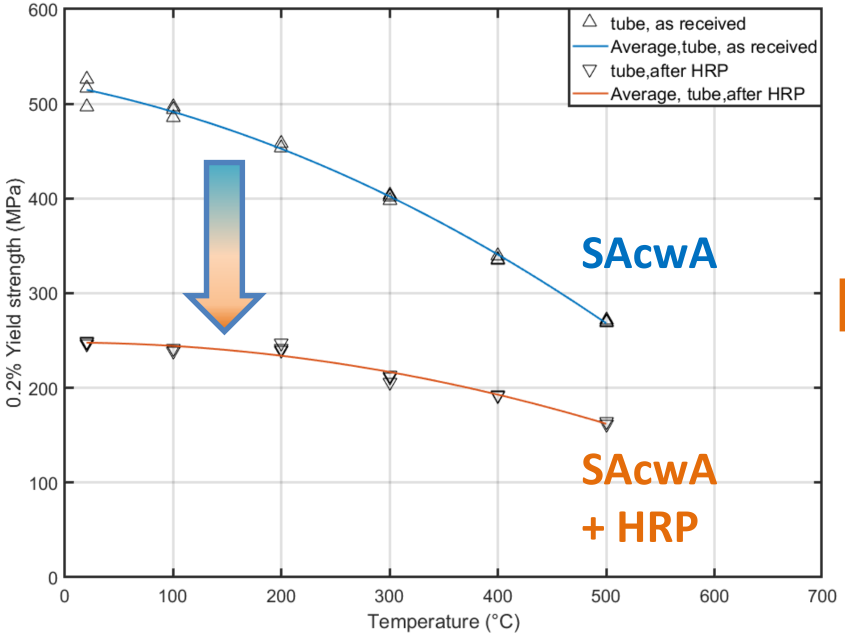
- UE vs irradiation dose of CuCrZr for SAA condition after irradiation at 150°C and 300°C
- TE vs irradiation dose of CuCrZr alloy for SAA condition after irradiation at 150°C and 300°C
- UE vs irradiation dose of CuCrZr for SAcwA condition (irradiation temperature in between 158-192 and 162-184 °C

CuCrZr MPH – Tensile properties for SAcwA & HRP conditions



J.H. You et al., FED 164 (2021)

E. Visca, ENEA (2016)



Reference state: HRP treated CuCrZr

Manufacturing process - Hot Radial Pressing (HRP)

– Heating & holding component to **580°C** for **2h** under **60 MPa**

Strong reduction of strength after HRP treatment

CuCrZr MPH – Testing needs

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Reference state: CuCrZr (SAcwA + HRP)

CuCrZr						
	Unirradiated		Irradiated			
	Testing temperature [°C]	note	Irradiation dose [dpa]	Irradiation temperature [°C]	Testing Temperature [°C]	note
Tensile properties	RT-600	True stress vs. true strain data	1, 3, 9	150, 250, 350, 450	RT, Tirr	Basic input parameter for simulation works
Creep	100-600	e.g. Creep curve, negligible creep temperature curve	1, 3, 9	300, 350	Tirr	post irradiation creep
			9	150, 250, 350	Tirr	interrupted irradiation creep
Charpy impact	0-400		1, 3, 9	150, 250, 350	0-400	
Fatigue strain-controlled	RT-450		1, 3, 9	150, 250, 350	Tirr	
Fatigue creep	RT-400 RT-400	Stress and strain controlled				
Fracture toughness	RT-400	Elastic-plastic fracture toughness	1, 3, 9	150, 250, 350, 450	RT, Tirr	Linear-elastic and elastic-plastic fracture toughness
Fatigue crack growth	RT-400		1, 3, 9	150, 250, 350	RT, Tirr	
Creep Crack Growth	300, 350					

W MPH – Baseline material

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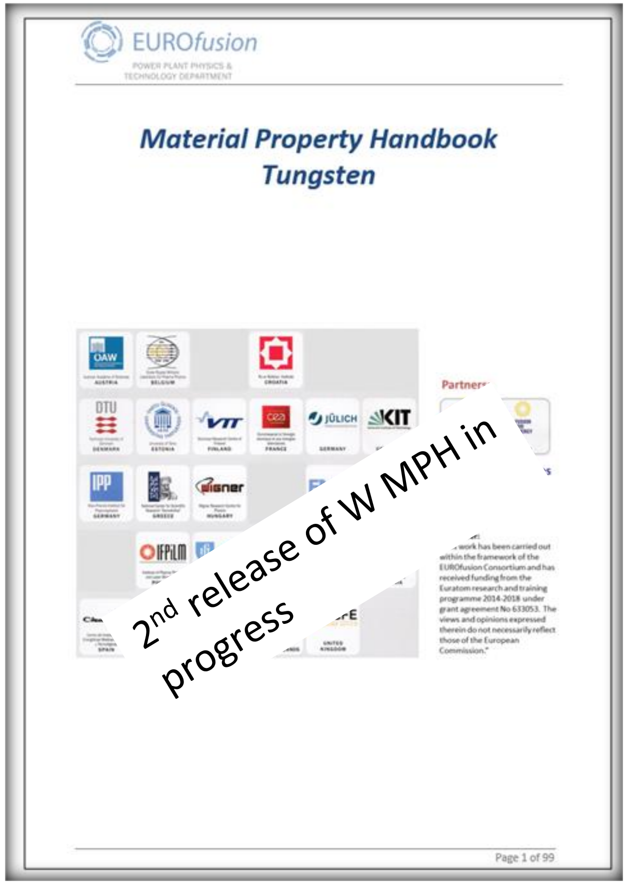


ITER grade tungsten

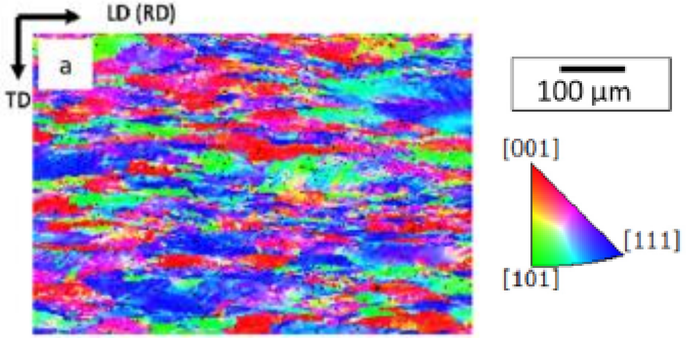
- Elongated grain microstructure
- Grain size number:
  3 or finer, ASTM E112
- Density:
  ≥19.0 g/cm³, ASTM B311
- Purity: ≥ 99.94%
- Vickers hardness:
  ≥410 HV30, ASTME92

Hirai et al., Fus. Eng. Design 125 (2017)

Identified tungsten materials

- Forged bar, PLANSEE SE, Austria
- Rolled plate, A.L.M.T. Corp., Japan
- …

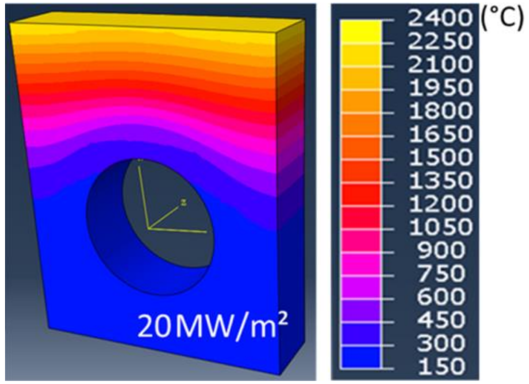
Yin, Materials Science & Engineering A 750 (2019) 20–30



Forged bar, PLANSEE

- Anisotropic microstructure/properties

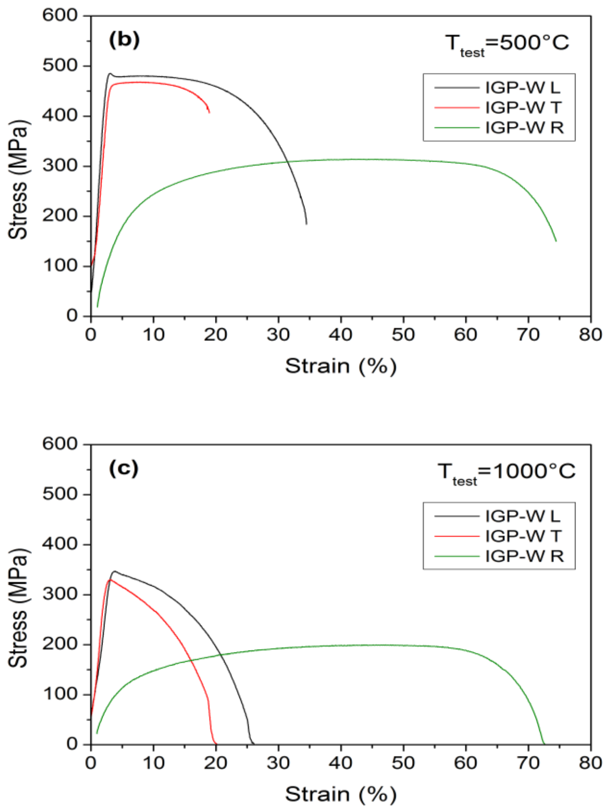
J.-H. You et al., Fus. Eng. Design 164 (2021)

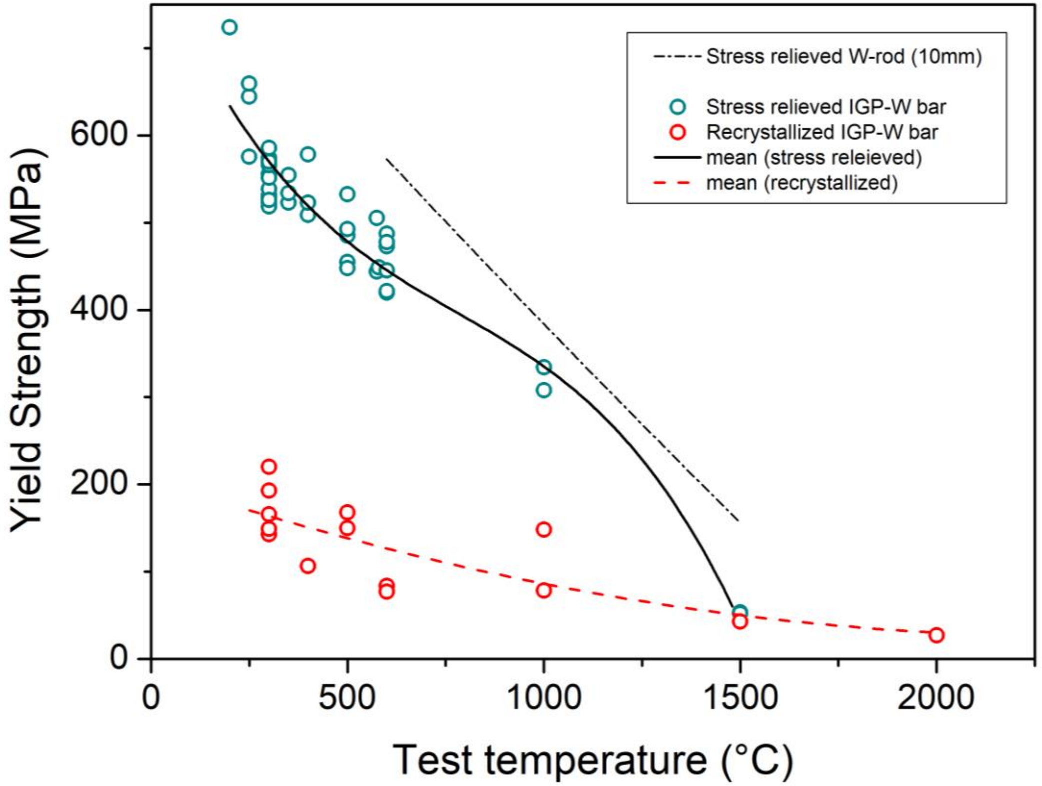


Relevant states

- Stress relieved
- Recrystallized

W MPH – Tensile properties and best estimate trend curves





ITER grade tungsten

- Forged bar, PLANSEE SE, Austria

M. Wirtz et al., Nucl. Fusion 57 (2017) 066018

M. Wirtz et al., Phys. Scr. T167 (2016) 014015

C. Yin et al, Int. J. Refract. Met. Hard Mater. 75 (2018) 153-162

- Generation of preliminary "best estimate" trend curves
- Large scatter in low-T data due to inherent brittleness ⇒ Weibull analysis of fracture strength

W MPH – fracture toughness

E. Gaganidze et al., J. Nucl. Mater. 547 (2021)
E. Gaganidze et al., Fus. Eng. Des. (2022)

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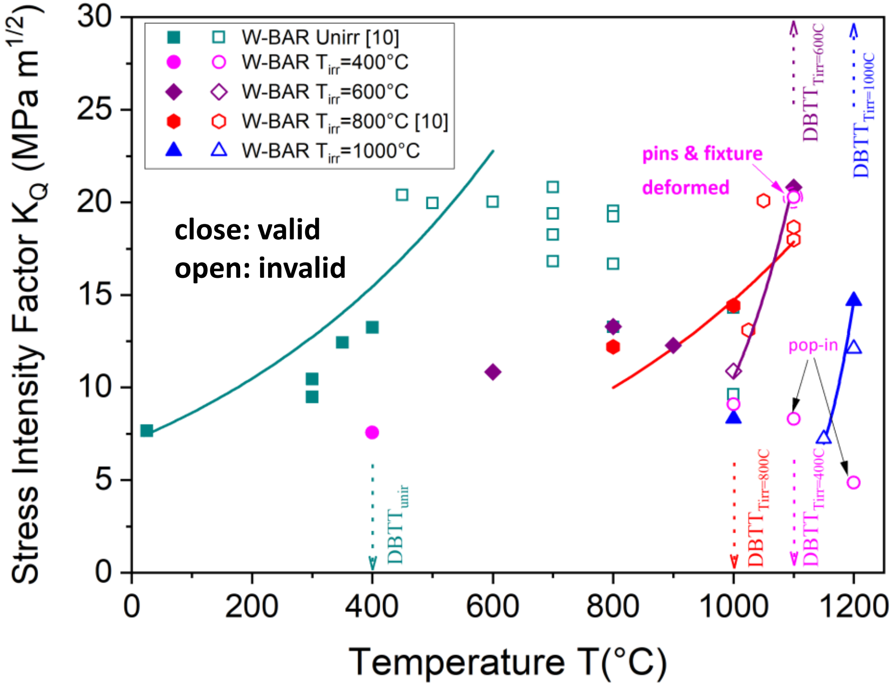
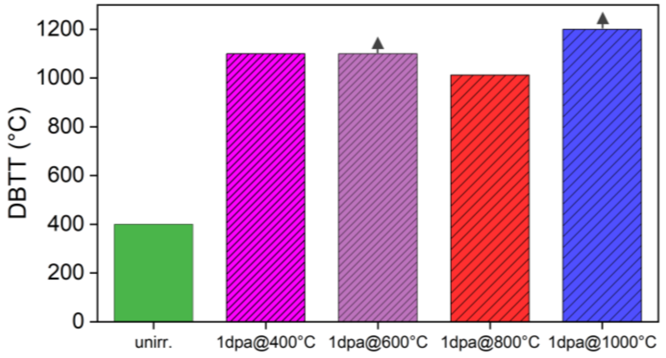
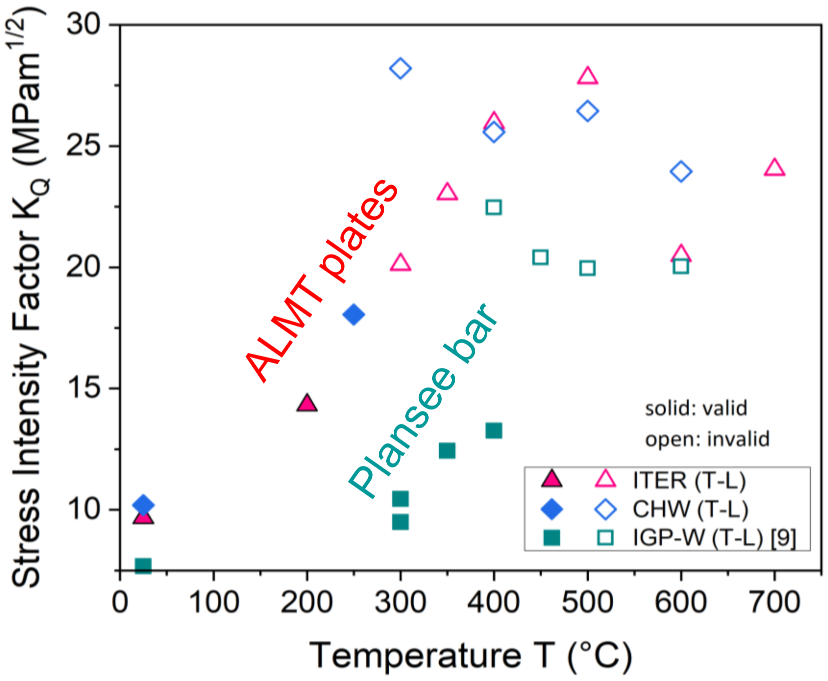
E. Gaganidze et al., JNM 556 (2021) 153200



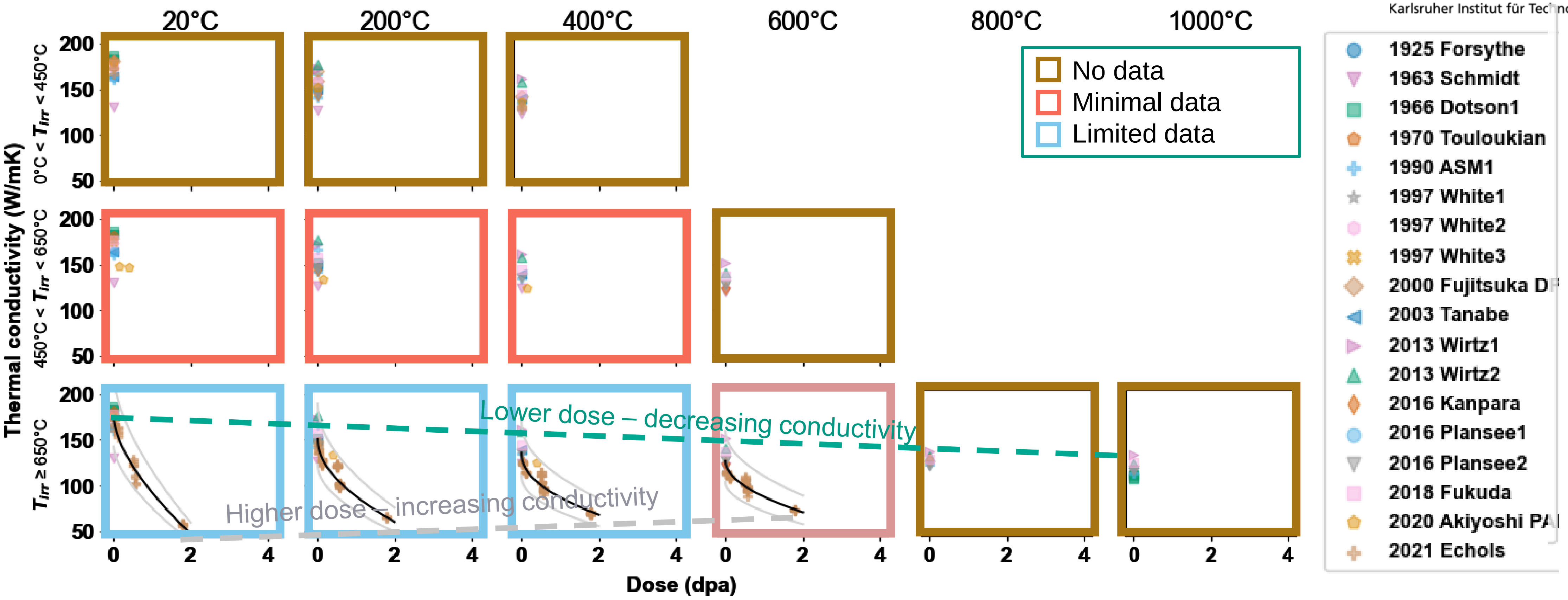




Superior behavior of ITER & CHW A.L.M.T plates over forged bar IGP W in terms of DBTT and high T behavior

Future focus on uniaxially rolled A.L.M.T. plate

W MPH – Thermal conductivity



Note:

- Trend with dose mostly attributed to Re content in literature
- Measurement Temp/conductivity relationship inverts at high dose/high irradiation temperature
- Even at high irradiation temp, data still extremely limited

W MPH – Testing needs

Reference material ITER grade plate from A.L.M.T

	Tungsten (sr: stress relieved, rc: recrystallized)						
		Unirradiated			Irradiated		
		Temperature range [°C]	note	Irradiation dose [dpa]	Irradiation temperature [°C]	Testing Temperature [°C]	note
Mechanical property	**Tensile properties**	sr: 300-1200 rc: 300-2000	Need for true stress vs. true strain data	0.5, 1, 3 (4)	sr: 600, 800, 1200 rc: 800, 1300	RT, Tirr	Basic input parameter for simulation works
	Creep	sr: 600-1200		0.5, 1, 3 (4)		Tirr	post irradiation creep
		rc: 600-1800		3 (4)		Tirr	interrupted irradiation creep
	Bending	sr: RT-300 rc: RT-300	No data for DEMO relevant tungsten grades	1		Tirr	No data
	Charpy impact	RT, iterative approach to identify DBTT		0.5, 1, 3 (4)		Iterative approach to identify DBTT	
	Fatigue strain controlled	sr: 300-1200 rc: 300-2000	No data for DEMO relevant tungsten grades	0.5, 1, 3 (4)		600, Tirr (Tirr)	No data for DEMO relevant tungsten grades
	Fracture toughness	sr: 300-1200 rc: 300-2000	K_{IC} and DBTT J-R curve	0.5, 1, 3 (4)		RT, Tirr	K_{IC} and DBTT J-R curve
	Fatigue crack growth	sr: 300-1200 rc: 300-2000	Temperature effects	0.5, 1, 3 (4)		RT, Tirr	No data

Summary

- Development of EURO*fusion* **Material Databases (MD)** *and* **Material Properties Handbook (MPH)** chapters on **EUROFER97**, **CuCrZr** and **W** is well advanced
- **MPH** includes most up-to-date qualified material data

EUROFER97:

- The database gaps are identified; Closing gaps in the unirradiated and fission n-irradiated states is in progress
- Irradiation facility with fusion relevant neutron spectrum is mandatory for the assessment of He effects

CuCrZr:

- Scarce data for baseline CuCrZr in SAcwA+HRP condition
- The gaps are identified and the experimental campaign is in progress

W:

- Available data in the unirradiated state is scattered due to different grades (and orientation) of W
- Effects of orientation and heat treatment (stress relieved and recrystallized) are not systematically assessed
- The gaps are identified and the experimental campaign is in progress for ITER specification W

Thank you for your attention!