
CERN

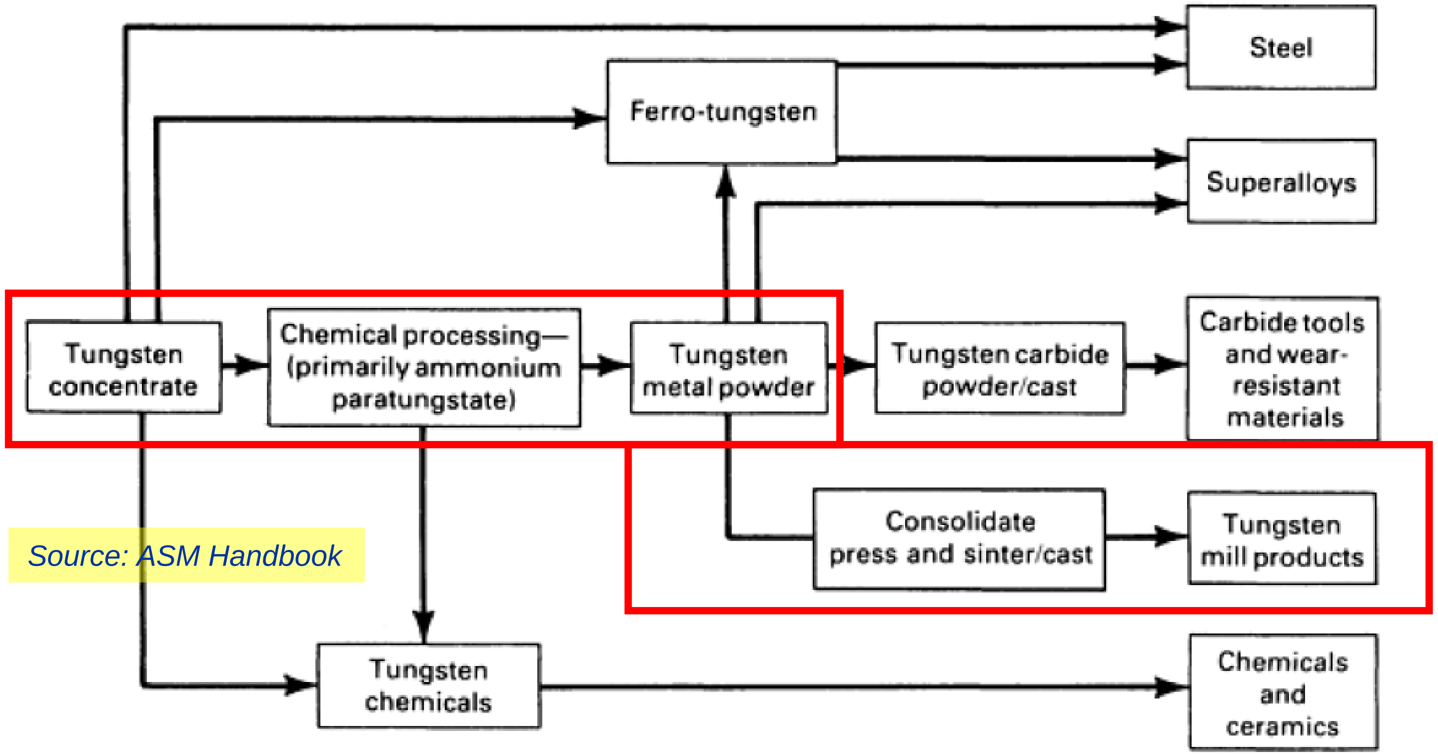
# Target materials R&D & procurement

- Ongoing and required material R&D to meet the project requirements
- Palette of tests for the material target – and why
- Explain the choice of hot rolled W as baseline, procurement considerations
- Radiation damage considerations on materials – do we care?

**Stefano Sgobba, Katie Elizabeth Buchanan, Patrick Michael Curran, Enrique Rodriguez Castro, Ignacio Aviles Santillana, Ana Teresa Perez Fontenla, Marlini Simoes**

04/03/2025

# Pure W - Metallurgy and processing background



*Source: ASM Handbook*

Tungsten mill products divided into three distinct groups on the basis of recrystallization behavior:

1) EB-melted, zone-refined, or arc-melted unalloyed tungsten
    - Exhibit equiaxed grain structures upon primary recrystallization.
    - Recrystallization T and grain size both decrease with increasing deformation
    - In EB-melted tungsten wire, the recrystallization T can be 900 °C or lower
2) Commercial grade or undoped P/M tungsten, sensitive to purity
    - Like the first group, these materials exhibit equiaxed grain structures, but their recrystallization temperatures are higher than those of the first-group materials.
    - Also, these materials do not necessarily exhibit decreases in recrystallization temperature and grain size with increasing deformation
    - In commercially pure (undoped) tungsten Recrystallization T can be as high as 1205 to 1400 °C
3) The third group of materials consists of doped tungsten

*Courtesy of Plansee SE*

# Pure W - Metallurgy and processing background

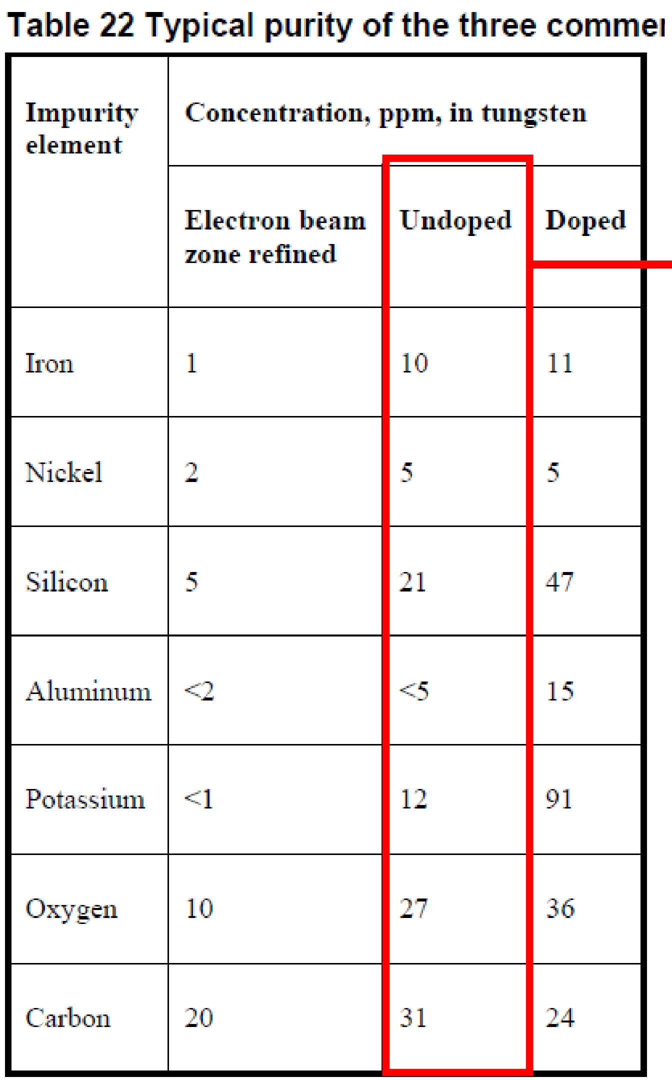
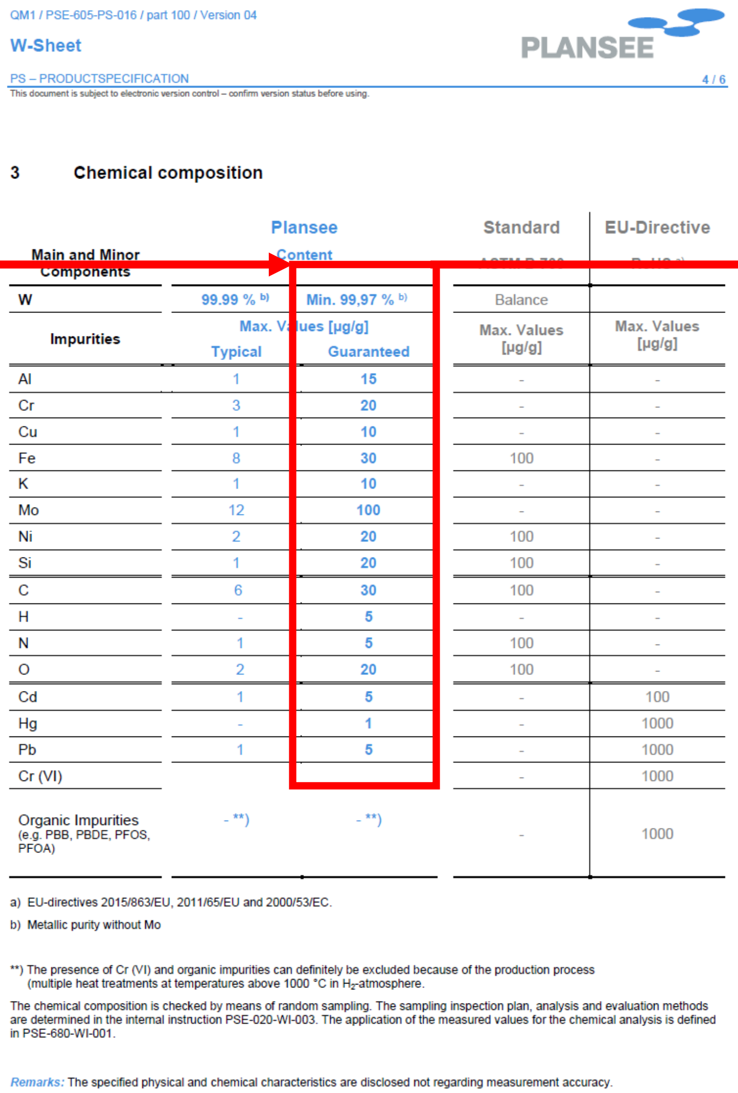


Table 22 Typical purity of the three commer

| Impurity element | Concentration, ppm, in tungsten | | |
|---|---|---|---|
| | Electron beam zone refined | Undoped | Doped |
| Iron | 1 | 10 | 11 |
| Nickel | 2 | 5 | 5 |
| Silicon | 5 | 21 | 47 |
| Aluminum | <2 | <5 | 15 |
| Potassium | <1 | 12 | 91 |
| Oxygen | 10 | 27 | 36 |
| Carbon | 20 | 31 | 24 |



QM1 / PSE-605-PS-016 / part 100 / Version 04

**W-Sheet**

PLANSEE

PS – PRODUCTSPECIFICATION 4 / 6

This document is subject to electronic version control – confirm version status before using.

3 Chemical composition

| Main and Minor Components | Plansee Content | | Standard | EU-Directive |
|---|---|---|---|---|
| W | 99.99 % b) | Min. 99,97 % b) | Balance | |
| Impurities | Max. Values [µg/g] Typical | Max. Values [µg/g] Guaranteed | Max. Values [µg/g] | Max. Values [µg/g] |
| Al | 1 | 15 | - | - |
| Cr | 3 | 20 | - | - |
| Cu | 1 | 10 | - | - |
| Fe | 8 | 30 | 100 | - |
| K | 1 | 10 | - | - |
| Mo | 12 | 100 | - | - |
| Ni | 2 | 20 | 100 | - |
| Si | 1 | 20 | 100 | - |
| C | 6 | 30 | 100 | - |
| H | - | 5 | - | - |
| N | 1 | 5 | 100 | - |
| O | 2 | 20 | 100 | - |
| Cd | 1 | 5 | - | 100 |
| Hg | - | 1 | - | 1000 |
| Pb | 1 | 5 | - | 1000 |
| Cr (VI) | | | - | 1000 |
| Organic Impurities (e.g. PBB, PBDE, PFOS, PFOA) | - **) | - **) | - | 1000 |

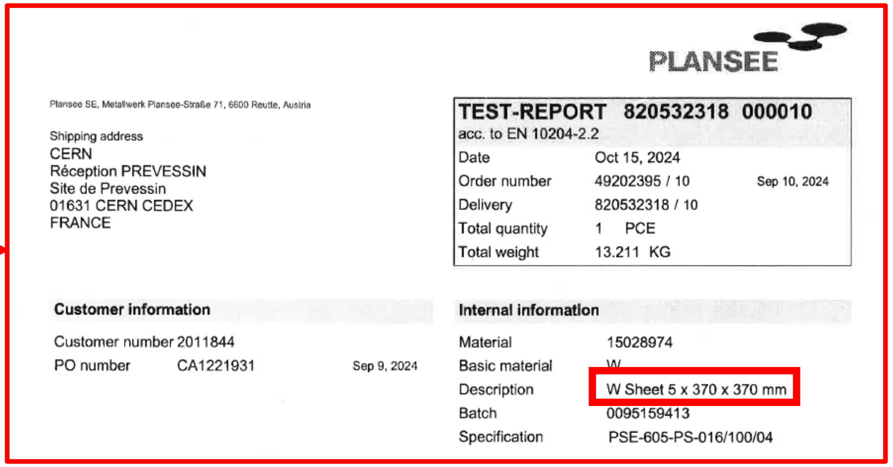
a) EU-directives 2015/863/EU, 2011/65/EU and 2000/53/EC.

b) Metallic purity without Mo

**) The presence of Cr (VI) and organic impurities can definitely be excluded because of the production process (multiple heat treatments at temperatures above 1000 °C in $H_2$-atmosphere.

The chemical composition is checked by means of random sampling. The sampling inspection plan, analysis and evaluation methods are determined in the internal instruction PSE-020-WI-003. The application of the measured values for the chemical analysis is defined in PSE-680-WI-001.

*Remarks:* The specified physical and chemical characteristics are disclosed not regarding measurement accuracy.



PLANSEE

Plansee SE, Metallwerk Plansee-Straße 71, 6600 Reutte, Austria

Shipping address
CERN
Réception PREVESSIN
Site de Prevessin
01631 CERN CEDEX
FRANCE

**TEST-REPORT 820532318 000010**
acc. to EN 10204-2.2

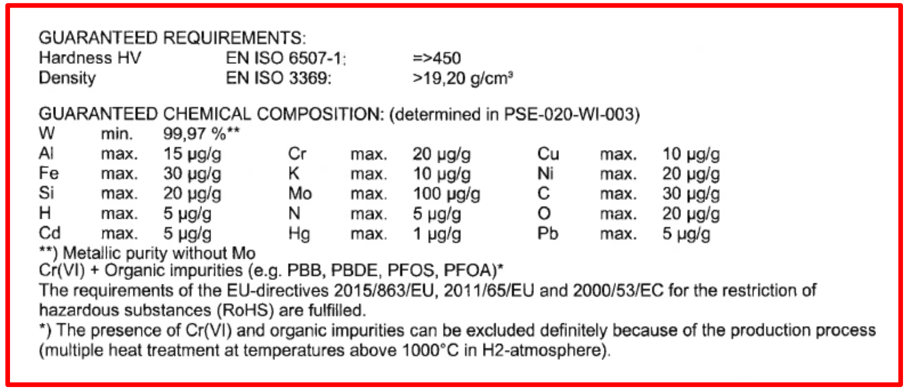
| | | |
|---|---|---|
| Date | Oct 15, 2024 | |
| Order number | 49202395 / 10 | Sep 10, 2024 |
| Delivery | 820532318 / 10 | |
| Total quantity | 1 PCE | |
| Total weight | 13.211 KG | |

**Customer information**

| | | |
|---|---|---|
| Customer number | 2011844 | |
| PO number | CA1221931 | Sep 9, 2024 |

**Internal information**

| | |
|---|---|
| Material | 15028974 |
| Basic material | W |
| Description | W Sheet 5 x 370 x 370 mm |
| Batch | 0095159413 |
| Specification | PSE-605-PS-016/100/04 |



GUARANTEED REQUIREMENTS:

| | | |
|---|---|---|
| Hardness HV | EN ISO 6507-1: | =>450 |
| Density | EN ISO 3369: | >19,20 g/cm³ |

GUARANTEED CHEMICAL COMPOSITION: (determined in PSE-020-WI-003)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| W | min. | 99,97 %** | | | | | | |
| Al | max. | 15 µg/g | Cr | max. | 20 µg/g | Cu | max. | 10 µg/g |
| Fe | max. | 30 µg/g | K | max. | 10 µg/g | Ni | max. | 20 µg/g |
| Si | max. | 20 µg/g | Mo | max. | 100 µg/g | C | max. | 30 µg/g |
| H | max. | 5 µg/g | N | max. | 5 µg/g | O | max. | 20 µg/g |
| Cd | max. | 5 µg/g | Hg | max. | 1 µg/g | Pb | max. | 5 µg/g |

**) Metallic purity without Mo

Cr(VI) + Organic impurities (e.g. PBB, PBDE, PFOS, PFOA)*

The requirements of the EU-directives 2015/863/EU, 2011/65/EU and 2000/53/EC for the restriction of hazardous substances (RoHS) are fulfilled.

*) The presence of Cr(VI) and organic impurities can be excluded definitely because of the production process (multiple heat treatment at temperatures above 1000°C in H2-atmosphere).

- HR product ordered in 5 mm and 17 mm thickness
- Limited availability in heavy gauges with guaranteed properties - due to a minimum reduction to be provided to achieve final properties

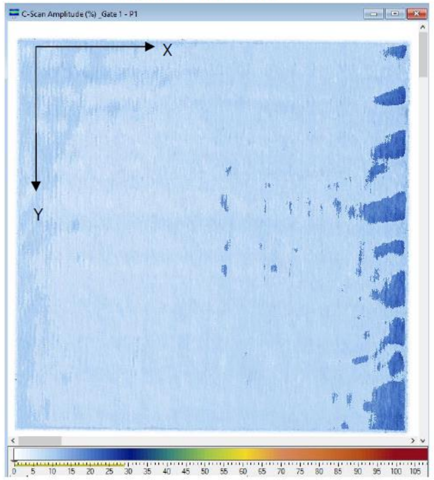
# Pure W - Metallurgy and processing background

**Testing results**

**No indications above TFP 1.2mm detected.**

**All pieces are acceptable to EN 4050-4 Class 5**

**Amplitude of defect echoes**

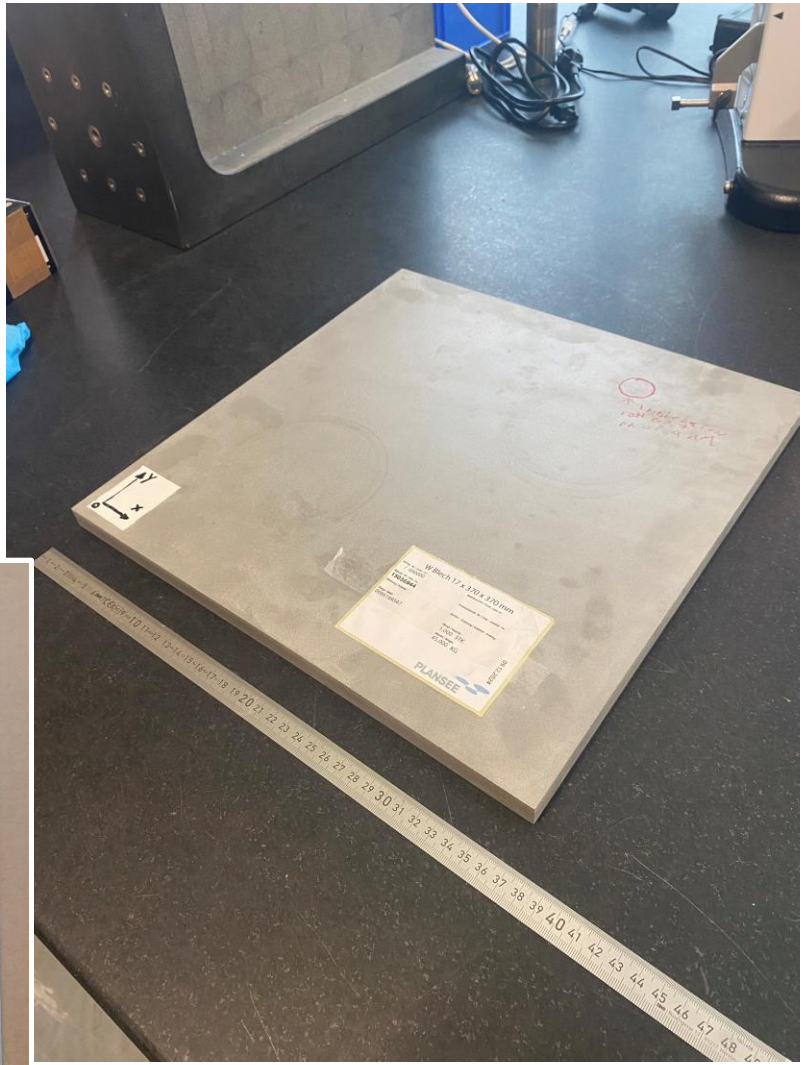


**Amplitude of backwall echo**

⇑ UT results on the 5 mm plate: excellent homogeneity and high acceptance level (to 1.2 mm FBH equivalent), EDMS 3190589

To the extent of the inspections performed, dimensions and tolerances conforming to ASTM B760, see EDMS 3180443

HR 5 mm ↓ and 17 mm thick → plates ordered and received from Plansee



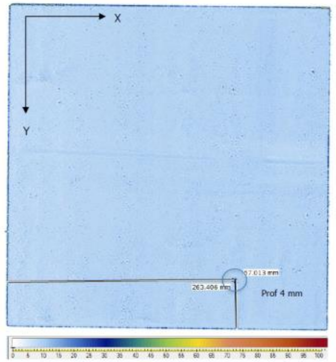
**No indications above FBH 1.2mm detected.**

**The piece is acceptable to EN 4050-4 Class 5**

Several reflectors with equivalent reflectivity up to FBH ø0.7 mm are observed at depth ~4 mm from the label face

**C-SCAN RESULTS – amplitude part N°1**

**Amplitude of defect echoes**



**Amplitude of backwall echo**

⇑ UT results on the 17 mm plate: excellent homogeneity and high acceptance level (to 0.8 mm FBH equivalent), EDMS 3237640

# Pure W - Metallurgy and processing background

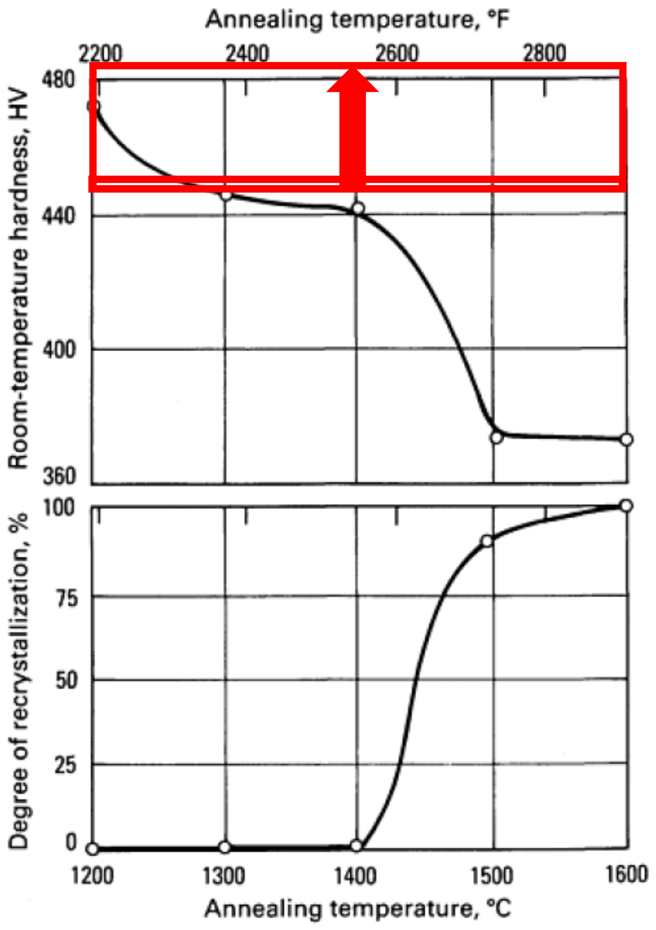
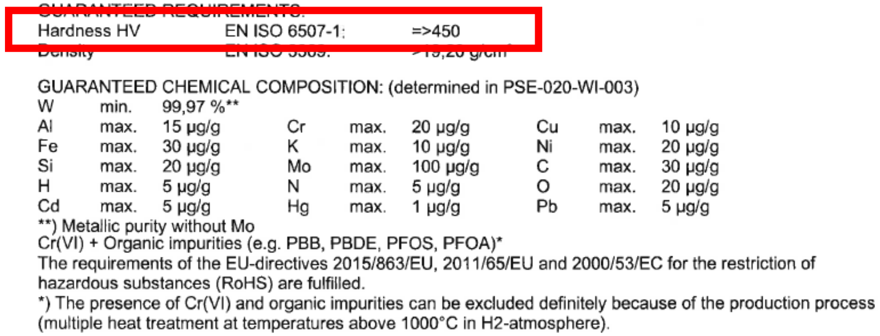


**Fig. 26** Recrystallization behavior of undoped tungsten bar



GUARANTEED REQUIREMENTS:

| | | |
|---|---|---|
| Hardness HV | EN ISO 6507-1: | =>450 |
| Density | EN ISO 3369: | >19,20 g/cm³ |

GUARANTEED CHEMICAL COMPOSITION: (determined in PSE-020-WI-003)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| W | min. | 99,97 %** | | | | | | |
| Al | max. | 15 µg/g | Cr | max. | 20 µg/g | Cu | max. | 10 µg/g |
| Fe | max. | 30 µg/g | K | max. | 10 µg/g | Ni | max. | 20 µg/g |
| Si | max. | 20 µg/g | Mo | max. | 100 µg/g | C | max. | 30 µg/g |
| H | max. | 5 µg/g | N | max. | 5 µg/g | O | max. | 20 µg/g |
| Cd | max. | 5 µg/g | Hg | max. | 1 µg/g | Pb | max. | 5 µg/g |

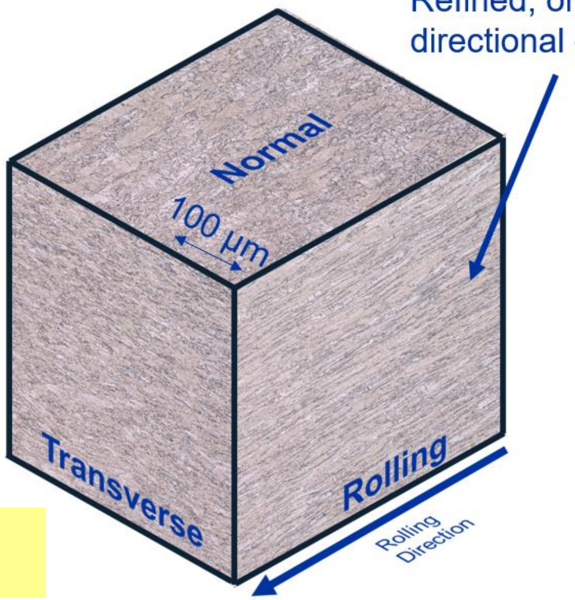
**) Metallic purity without Mo

Cr(VI) + Organic impurities (e.g. PBB, PBDE, PFOS, PFOA)*

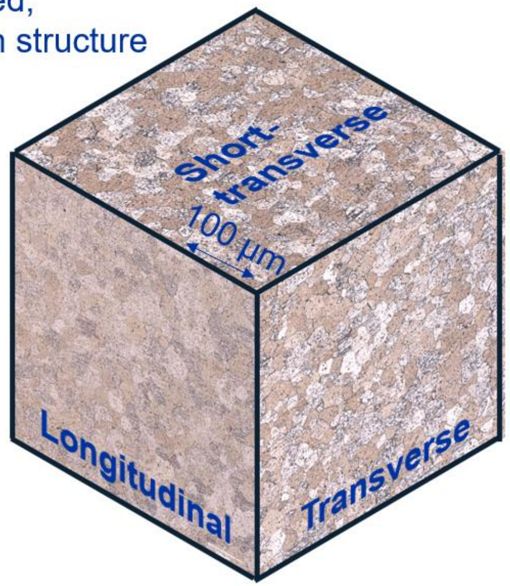
The requirements of the EU-directives 2015/863/EU, 2011/65/EU and 2000/53/EC for the restriction of hazardous substances (RoHS) are fulfilled.

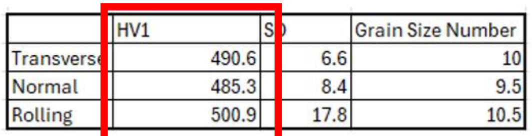
*) The presence of Cr(VI) and organic impurities can be excluded definitely because of the production process (multiple heat treatment at temperatures above 1000°C in H2-atmosphere).

*Benjamin Corbett,*
*https://indico.cern.ch/event/1480601/*



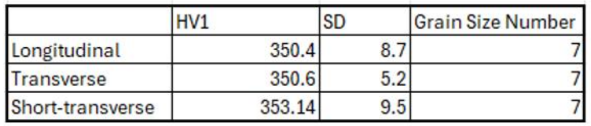
Refined, oriented, directional grain structure





| | HV1 | SD | Grain Size Number |
|---|---|---|---|
| Transverse | 490.6 | 6.6 | 10 |
| Normal | 485.3 | 8.4 | 9.5 |
| Rolling | 500.9 | 17.8 | 10.5 |

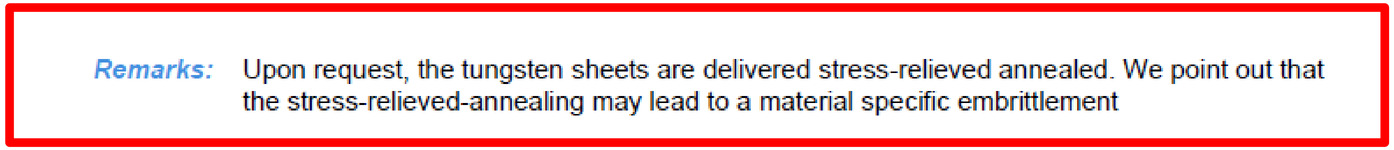
5mm rolled Hardness and Grain Size



| | HV1 | SD | Grain Size Number |
|---|---|---|---|
| Longitudinal | 350.4 | 8.7 | 7 |
| Transverse | 350.6 | 5.2 | 7 |
| Short-transverse | 353.14 | 9.5 | 7 |

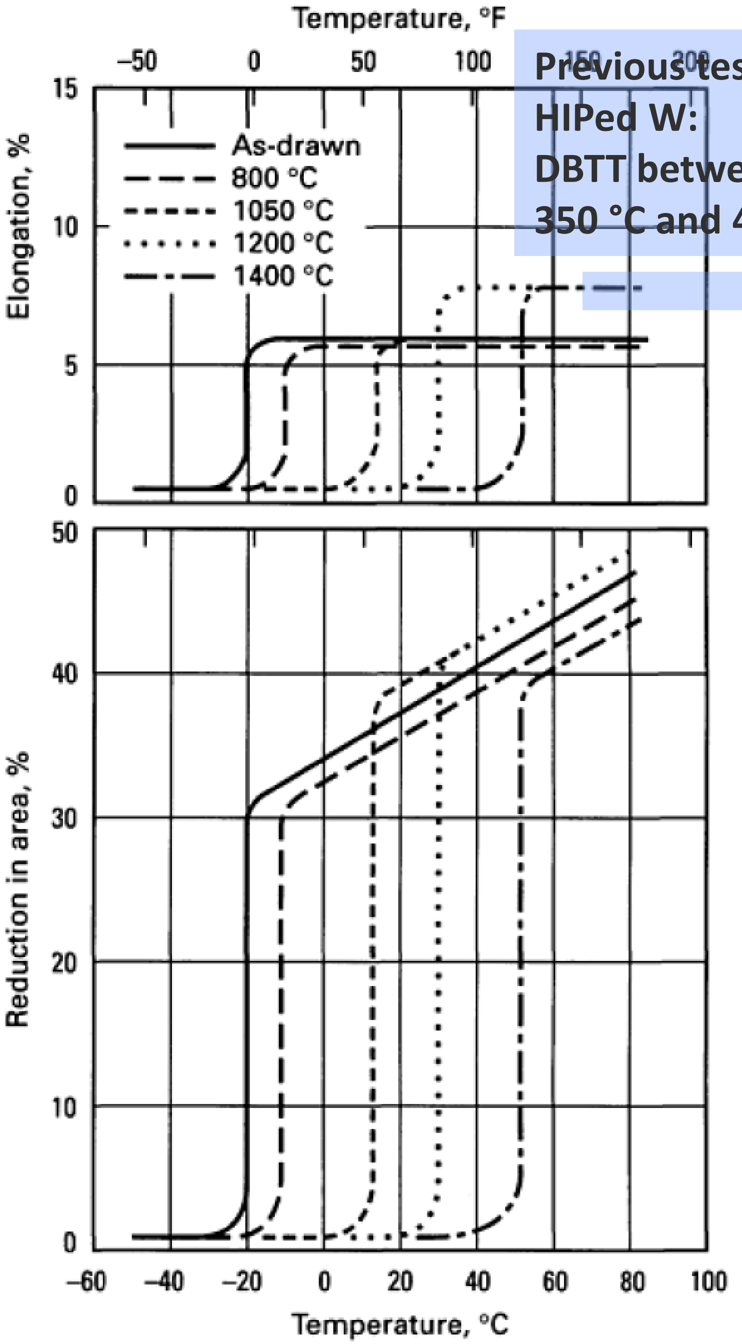
Forged Hardness and Grain Size

# Pure W - Metallurgy and processi


**Remarks:** Upon request, the tungsten sheets are delivered stress-relieved annealed. We point out that the stress-relieved-annealing may lead to a material specific embrittlement

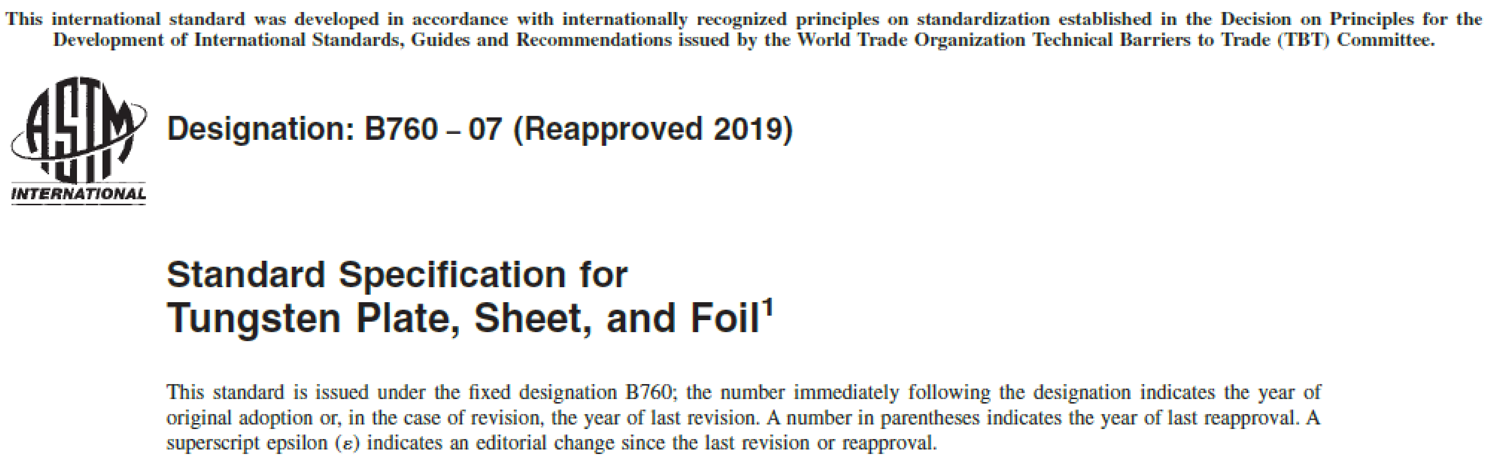
- **Recrystallized tungsten** undergoes a ductile-to-brittle transition **above 205 °C** .
- Only by **heavy warm or cold working is the DBTT lowered to below room temperature**
- **Annealing raises the DBTT of cold-worked tungsten until it approaches that of recrystallized material**

- The exact ductile-to-brittle transition temperature is influenced by many factors, including **grain size**, strain rate, and **impurity levels**
- The DBTT **decreases with grain size unless the grains are larger than 1 mm** in diameter.
- The DBTT also drops with increases in strain rate, but it **climbs rapidly as impurity levels increase**.
- Like all brittle metals, **tungsten is very notch sensitive. Therefore, removal of even minute surface flaws by grinding**, oxidizing, or **electrolytic polishing** prior to service improves ductility and lowers the DBTT



Previous tests on HIPed W:
DBTT between 350 °C and 450 °C

# Pure W flat products – Standard framework

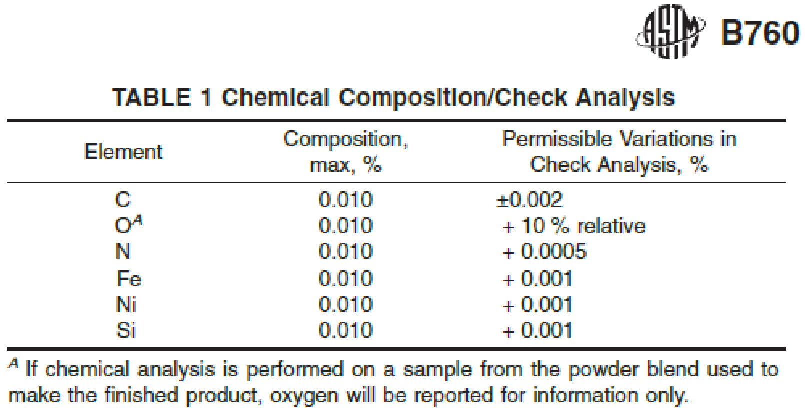


This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: B760 – 07 (Reapproved 2019)

## Standard Specification for Tungsten Plate, Sheet, and Foil[1]

This standard is issued under the fixed designation B760; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

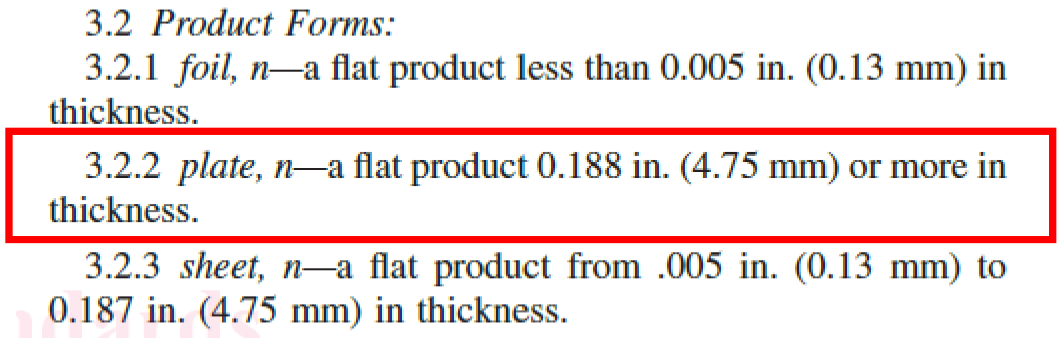


B760

TABLE 1 Chemical Composition/Check Analysis

| Element | Composition, max, % | Permissible Variations in Check Analysis, % |
|---|---|---|
| C | 0.010 | ±0.002 |
| $O^A$ | 0.010 | + 10 % relative |
| N | 0.010 | + 0.0005 |
| Fe | 0.010 | + 0.001 |
| Ni | 0.010 | + 0.001 |
| Si | 0.010 | + 0.001 |

[A] If chemical analysis is performed on a sample from the powder blend used to make the finished product, oxygen will be reported for information only.

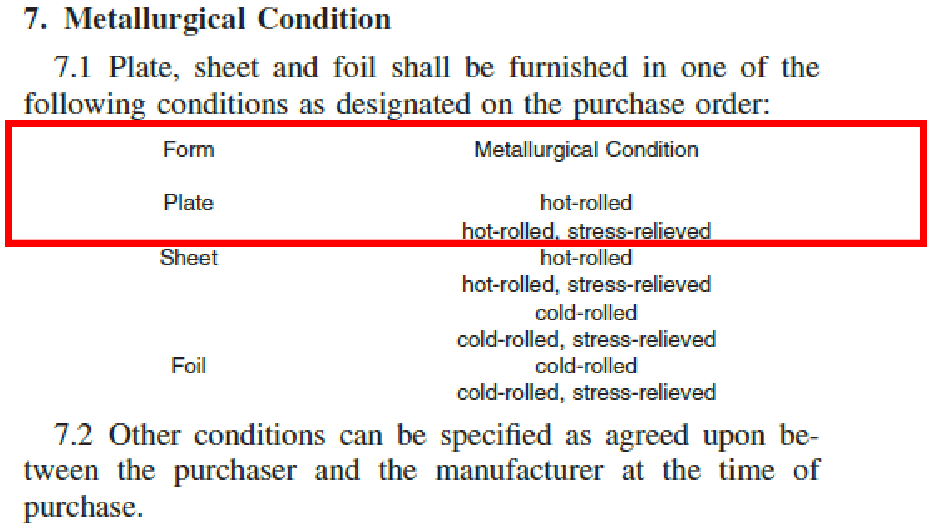


3.2 *Product Forms:*

3.2.1 *foil, n*—a flat product less than 0.005 in. (0.13 mm) in thickness.

3.2.2 *plate, n*—a flat product 0.188 in. (4.75 mm) or more in thickness.

3.2.3 *sheet, n*—a flat product from .005 in. (0.13 mm) to 0.187 in. (4.75 mm) in thickness.

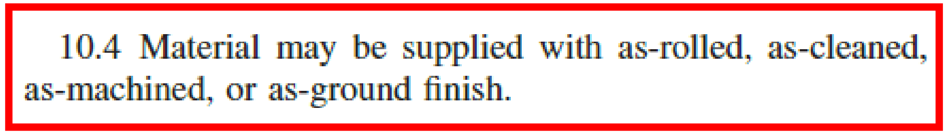


### 7. Metallurgical Condition

7.1 Plate, sheet and foil shall be furnished in one of the following conditions as designated on the purchase order:

| Form | Metallurgical Condition |
|---|---|
| Plate | hot-rolled<br>hot-rolled, stress-relieved |
| Sheet | hot-rolled<br>hot-rolled, stress-relieved<br>cold-rolled<br>cold-rolled, stress-relieved |
| Foil | cold-rolled<br>cold-rolled, stress-relieved |

7.2 Other conditions can be specified as agreed upon between the purchaser and the manufacturer at the time of purchase.



10.4 Material may be supplied with as-rolled, as-cleaned, as-machined, or as-ground finish.

# Ongoing and required material R&D to meet the project requirements

**Operating conditions:**

- RT to 400°C
- Stresses: -100 MPa to 150 MPa
- Fatigue life of $10^7$ cycles
- Irradiation: approximately 1.2 - 1.6 dpa (< 2 dpa)
- Individual block height: 17 mm (as HR?) to 350 mm (as HIPed) thick and 250 mm diameter (present baseline)
- Chemical additions from He: 143-220 ppm(at)
- Beam Parameters: sigma 8 mm (possibly 16 mm)
- As HR and HR + HIPed properties are relevant
- HR product form looks a reasonable choice – availability in heavy gauges with guaranteed properties limited

*J. Habainy et al. / Journal of Nuclear Materials 465 (2015) 438–447*

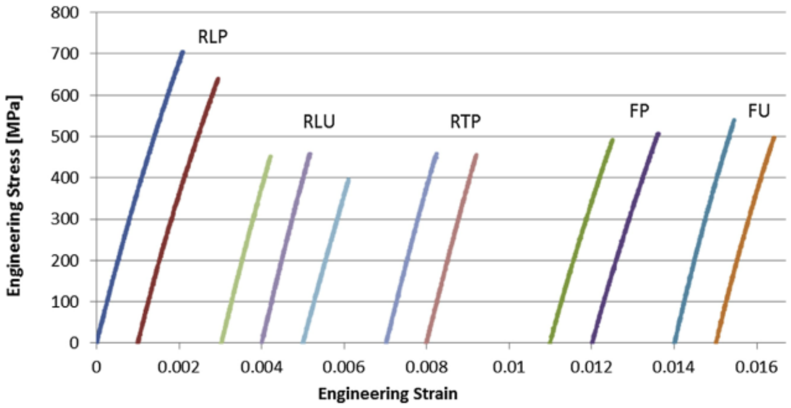


**Fig. 3.** Tensile data for rolled and forged specimens at 25 °C.

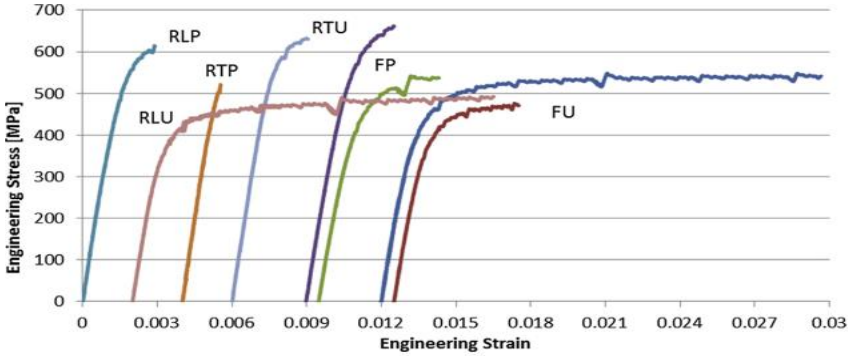


**Fig. 4.** Tensile data for rolled and forged tungsten at 280 °C.

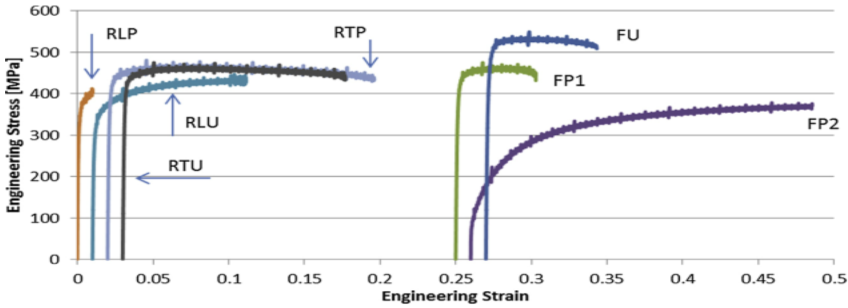


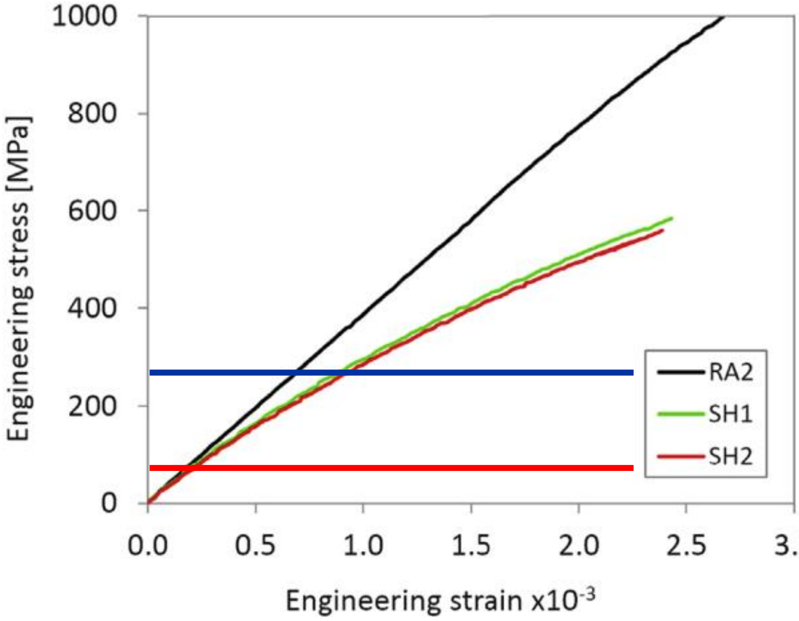
**Fig. 5.** Tensile data for rolled and forged tungsten at 480 °C.

# Ongoing and required material R&D to meet the project requirements

## Limited mechanical properties in SH material

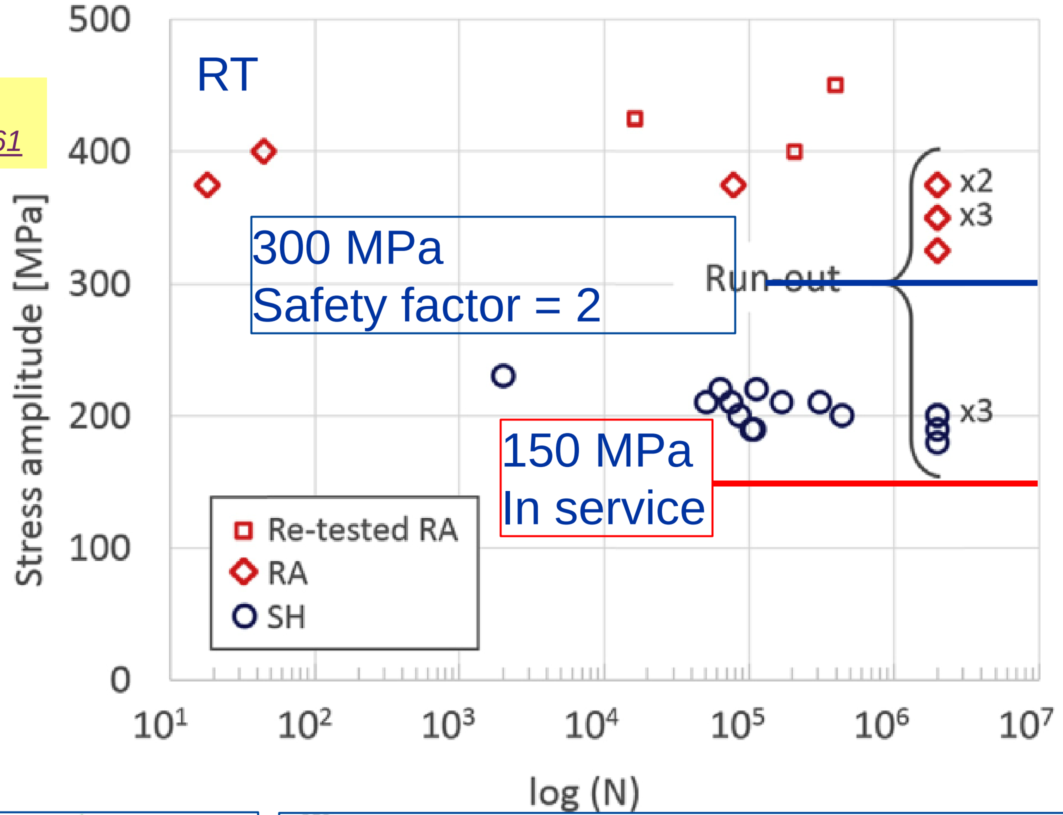
- Limited fatigue endurance limit
- Limited yield

*J. Habainy, S. Iyengar, Y.Lee, Y.Dai.*
*https://doi.org/10.1016/j.jnucmat.2017.10.061*



300 MPa
Safety factor = 2

150 MPa in service



300 MPa
Safety factor = 2

150 MPa
In service

*J. Habainy, Y. Lee, Y. Dai, S. Iyengar,*
*https://doi.org/10.1016/j.jnucmat.2015.06.032*

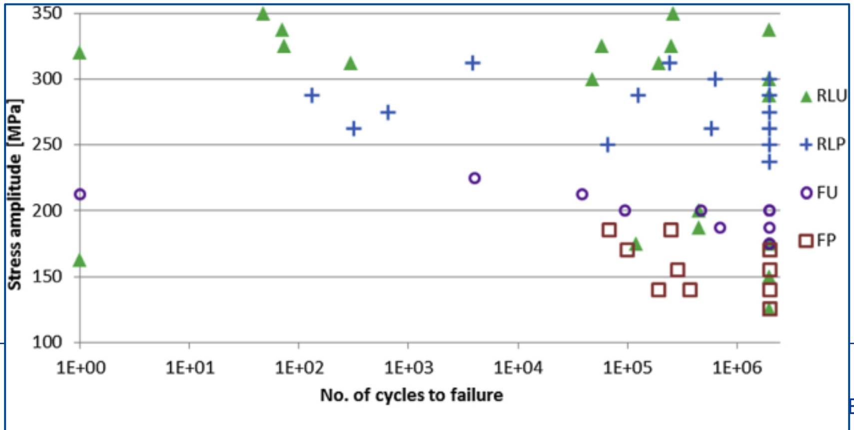


**Fig. 8.** Wöhler diagram for rolled and forged tungsten at 25 °C.

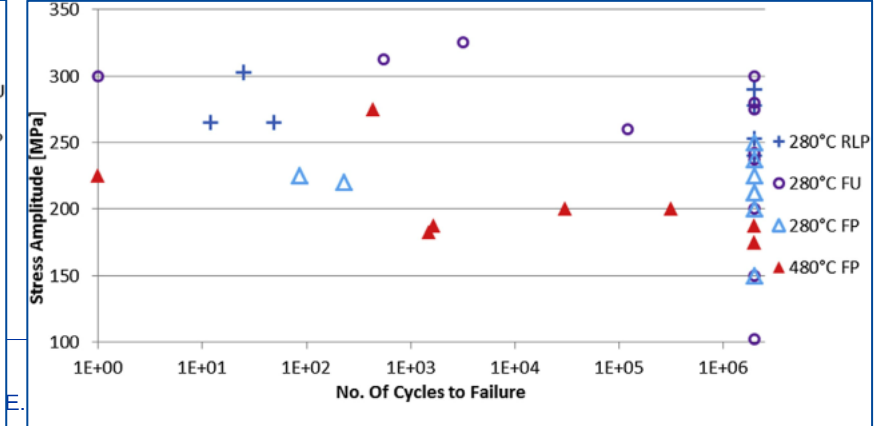
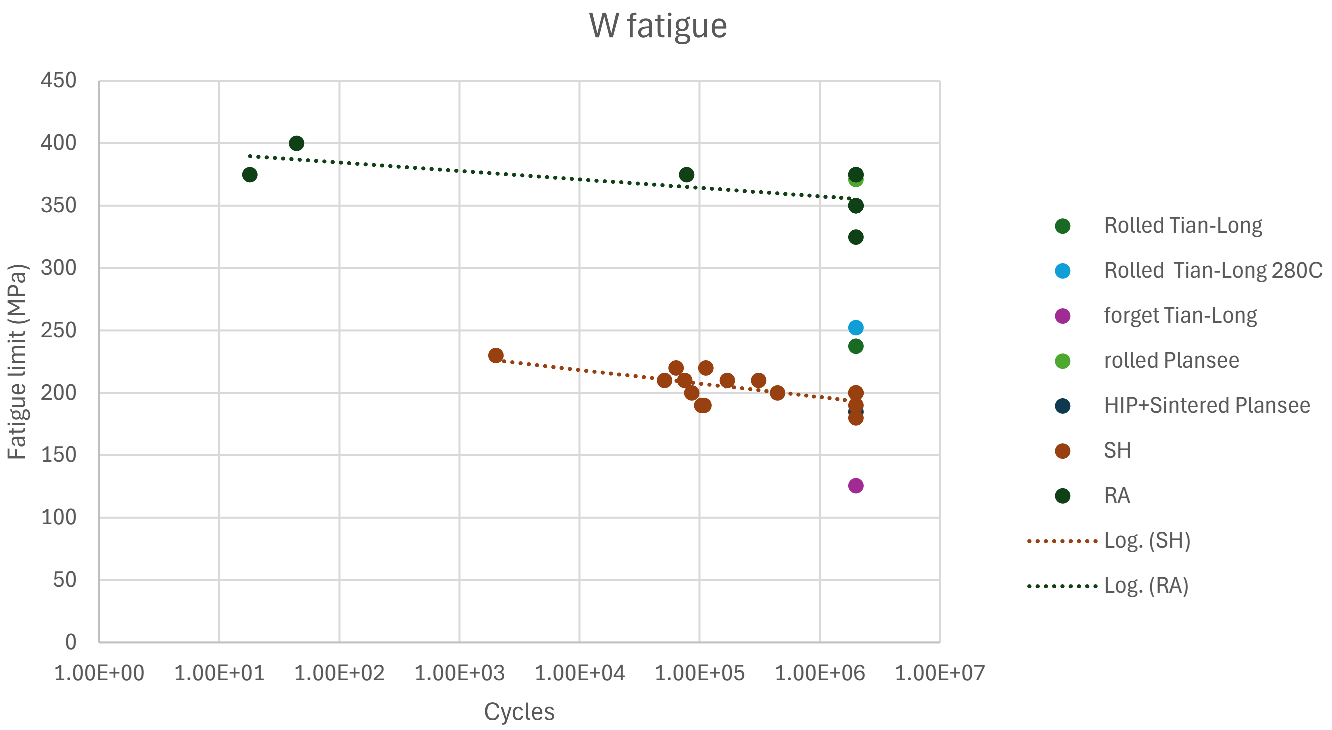


**Fig. 9.** Wöhler diagram for rolled and forged tungsten at 280° and 480 °C.

# Ongoing and required material R&D to meet the project requirements



**Axial forging is possible but there is a limitation:**

- Maximum of 110 mm heigth with 260 mm diameter
- From this dimensions reduced mechanical properties as no more axial nor radial deformation can be done.

**Rolled tungsten:**

- Shows superior fatigue properties than forged and PM HIPed tungsten
- However, it has nearly zero ductility at room temperature and is highly anisotropic
- The orientation of the rolled tungsten bricks with respect to the proton beam needs to be carefully considered.
- The post-pulse maximum stress should be below 100 MPa, and the post-pulse peak stress amplitude lower than 50 MPa (see J. Habainy, Y. Lee, Y. Dai, S. Iyengar, https://doi.org/10.7566/JPSCP.28.031004)

# Palette of tests for the material target – and why

## Mechanical testing:

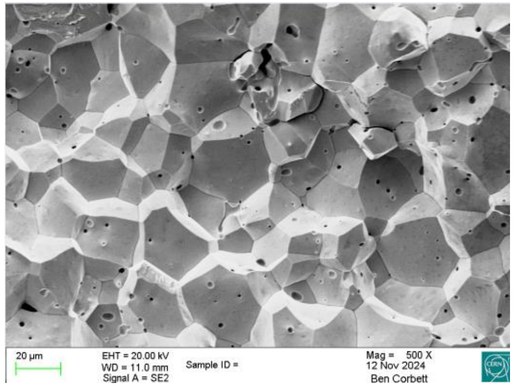
- Charpy impact toughness testing of the base material, from RT to 600 ºC
- RT & high T tensile testing with possibility of an inert or vacuum atmosphere
- As above, fatigue testing
- Tensile testing of the adhesion strength of the HIP bonded plates W-W & W-Ta-W.
- Material hardness (as a function of T?)

## Ongoing in house on HR plates:

- A complete grain size analysis
- Grain orientation analysis
- Recast layer analysis & post cut processing
- Density evaluation
- Microstructural changes of the base material during the heating exposure/HIPing process

## Oxidation studies:

- in relation to NDT
- and operating environment



## Material characterization

## Metrology & NDT

- Immersion UT of all incoming plates EN 4050-4
- Flatness evaluation ASTM B760-07
- Roughness evaluation

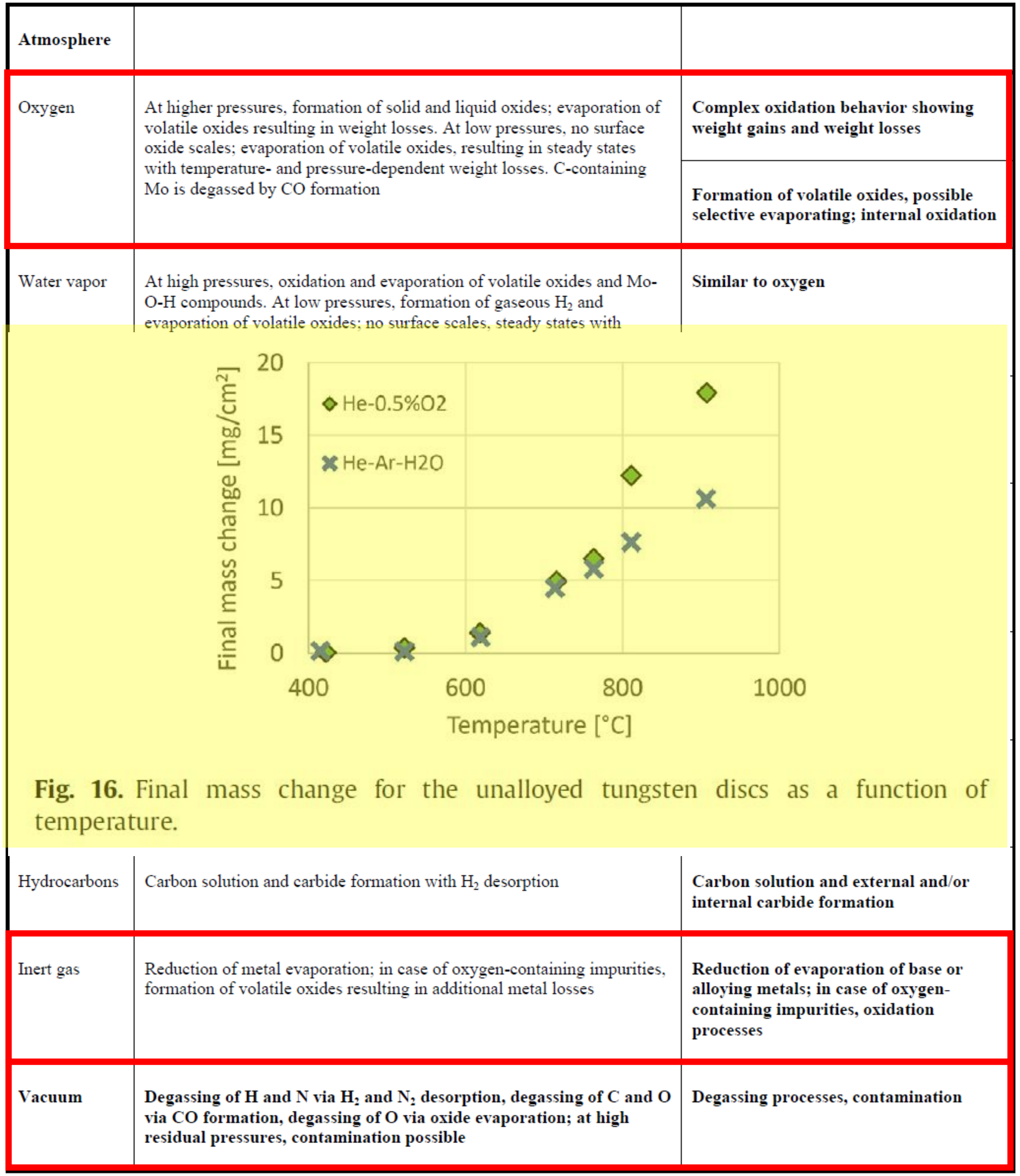
# Palette of tests

### Oxidation studies vs. operating environment

- similar behaviour expected as reported for Mo ⇒
- cleaning of W is desirable to remove compounds that could cause carbon contamination during exposure to a heat cycle
- a variety of cleaning agents may be used to remove oils and hydrocarbons (vapor degreasing and hand or automatic washing with detergent solutions)
- chemical cleaning only needed for heavily oxidised surfaces

*See J. Habainy et al., Formation of oxide layers on tungsten at low oxygen partial pressures:*

- **In Ar gas with a maximum oxygen partial pressure of 5 ppm, a thin and adherent oxide film was observed to form on the surface of tungsten specimens even at 500 °C**
- For the operation of the ESS spallation facility, it is important to note **that tungsten can be oxidized in environments with low oxygen partial pressures at T as low as 400 °C**
- **Below 500 °C it is expected that the oxide formed will be of the protective type**
- **However**, considering that the tungsten will be cooled by a massive helium flow with a flux of 3 kg/s at 1.1 MPa, **surface erosion of the oxide scale was a concern**
- Erosion experiments were performed to study the adhesion of the oxide formed on tungsten at 500 °C
- The sample, pre-oxidized for 1 h in a He-0.5%O2 gas mixture, showed no signs of erosion caused by the helium jet
- Still, the **spalling of the oxide layer** due to beam pulse and beam trip induced thermal cycling, and fatigue, during five years of target lifetime, **remains an issue**
- Also of concern is the possibility of tungsten oxide sublimation in accidental cases such as over-focused beam combined with loss of helium confinement.
- **To minimize such risks, the target primary cooling loop will be purified and the impurity levels will be monitored during operation.**



| **Atmosphere** | | |
|---|---|---|
| Oxygen | At higher pressures, formation of solid and liquid oxides; evaporation of volatile oxides resulting in weight losses. At low pressures, no surface oxide scales; evaporation of volatile oxides, resulting in steady states with temperature- and pressure-dependent weight losses. C-containing Mo is degassed by CO formation | **Complex oxidation behavior showing weight gains and weight losses**<br>**Formation of volatile oxides, possible selective evaporating; internal oxidation** |
| Water vapor | At high pressures, oxidation and evaporation of volatile oxides and Mo-O-H compounds. At low pressures, formation of gaseous $H_2$ and evaporation of volatile oxides; no surface scales, steady states with | **Similar to oxygen** |
| Hydrocarbons | Carbon solution and carbide formation with $H_2$ desorption | **Carbon solution and external and/or internal carbide formation** |
| Inert gas | Reduction of metal evaporation; in case of oxygen-containing impurities, formation of volatile oxides resulting in additional metal losses | **Reduction of evaporation of base or alloying metals; in case of oxygen-containing impurities, oxidation processes** |
| **Vacuum** | **Degassing of H and N via $H_2$ and $N_2$ desorption, degassing of C and O via CO formation, degassing of O via oxide evaporation; at high residual pressures, contamination possible** | **Degassing processes, contamination** |

**Fig. 16.** Final mass change for the unalloyed tungsten discs as a function of temperature.

# Palette of tests for the material target – and why

| | Tensile testing | | | | | |
|---|---|---|---|---|---|---|
| | Fatigue testing | | | | | Charpy testing |
| | **CERN** | **NLR** | **Lucideon** | **SincoTec** | **Amentum** | **Nordmetall** |
| **Country** | Switzerland | Netherlands | United States | Germany | United Kingdom | Germany |
| **Test types** | Tensile test & Fatigue test | Tensile, Fatigue & Density | Fatigue & Tensile | Fatigue | Fatigue | Charpy impact |
| **Samples** | Open | 6 Samples<br>2x Tensile 2x Fatigue 2x Density | 6 Samples<br>2x Tensile (RT &HT), 6 x Fatigue (3x air 3x argon) | 30 samples<br>RT & HT, spread TBD by CERN | 20 samples | 46 Samples<br>6x Reference<br>40x Room –> high temperature (~600˚C) |
| **Sample geometry** | Fatigue- L- 135 mm, W 100 mm | Tensile - L100 mm, G 25 mm, W 6 mm<br>Fatigue - L 134 mm, Density- 10 mm x 10 mm x 5 mm (L x W x T) | TBD | L 160 mm, W 30 mm<br>16 per plate | L- 134 mm, W30 mm | 10 mm x 10 mm x 55 mm |
| **Machining** | EDM-CERN | EDM-CERN | EDM-CERN | Machined-SincoTec | EDM-CERN | EDM-CERN |
| **Machine parameters** | Testing up to 20 Hz | Testing up to 100 Hz | Frequency to be determined | Testing up to 80Hz | Testing up to 20 Hz | Testing in increasing increments from room temperature to 600 ˚C |
| **Heating & atmosphere** | Room temperature only in atmosphere | Furnace heated in argon oven<br>(Experienced in this testing) | Information not given | Induction heating in argon test chamber.<br>(Experience in this testing) | Furnace heated (including grips) Static argon during test (no experience in this testing) | Information not given |
| **Duration** | 6 days per sample fatigue | 12 days | 11-12 weeks | ~ 6-7 weeks | 17 weeks | 4 weeks |
| **Price** | EDM cost only | €40, 400.00 | £23,280.00 | €51,786.00 | £104,681.11 | €4,600.00 |

# Palette of tests for the material target – and why

## Previous work: Cladding

- HIP has been proven as a valid technique to bond W to Ta and W to W (through a Ta interfoil): erosion-corrosion resistant claddings in representative geometries of the final target

## Homogeneous bonding

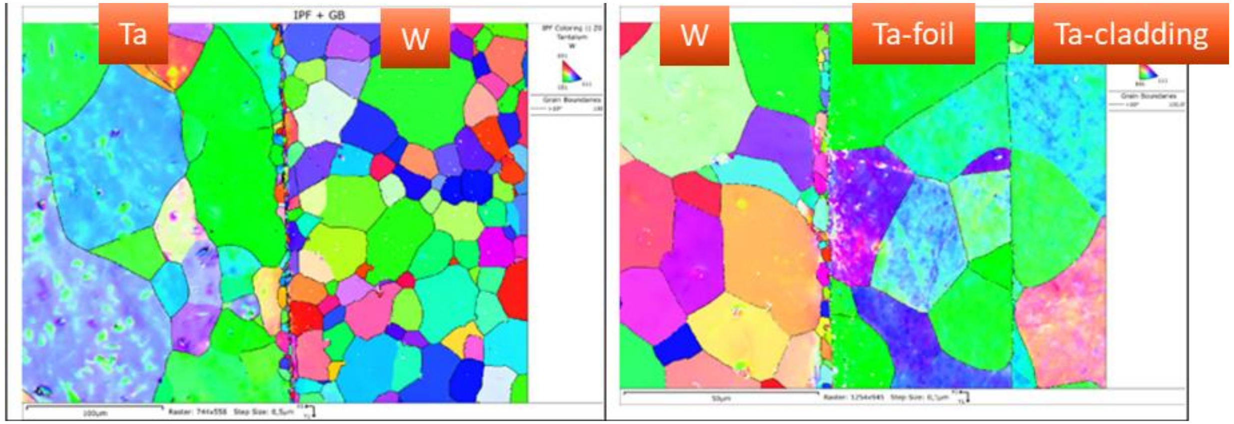
- With stronger interfaces and theoretical thermal conductivities were achieved in Ta-TZM, Ta-W, and Ta2.5W-TZM. Ta2.5W-W showed 70% of the cladding material's strength [1] [2]
- Checked by NDT, microstructural and mechanical characterization on unirradiated and irradiated components

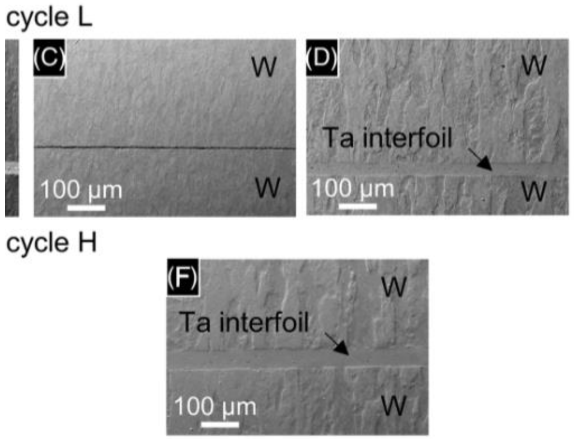
HIP cladding ⇑
Other methods like CVD and sleeve-in were unsuccessful

Ta-cladding by HIPing exhibited reliable and good bonding quality (Ta to W with and without foils and W/Ta/W)

Robust heat transfer from core to cooling water

More studies are needed to complete assessment mechanical strength



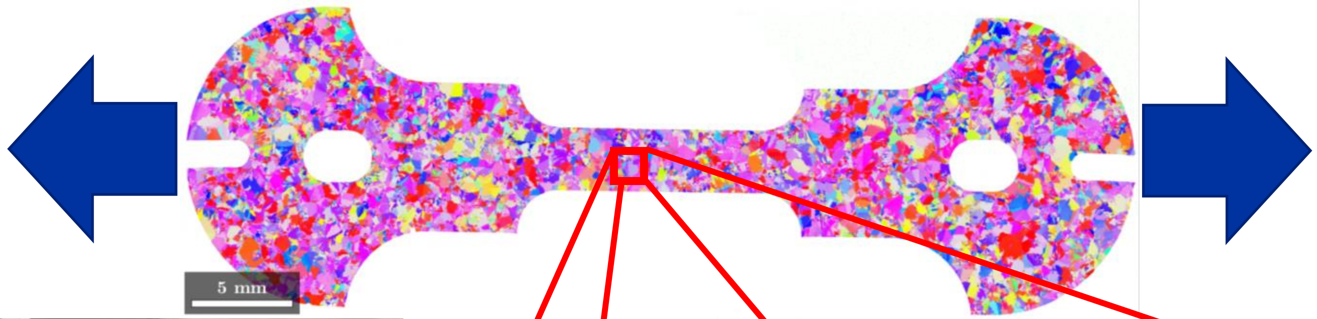


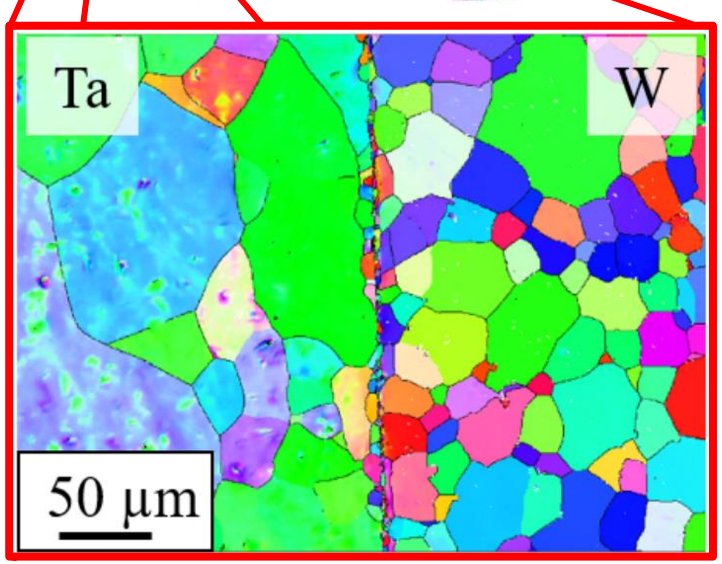
*[1] 2018 → Recent developments on the application of Hot Isostatic Pressing (HIP) technologies for proton beam targets at CERN with Fraunhofer J. Busom et al.*
*[2] 2024 → PIE of a prototype tantalum-clad target in collaboration with Framatome T. Griesemer et al.*

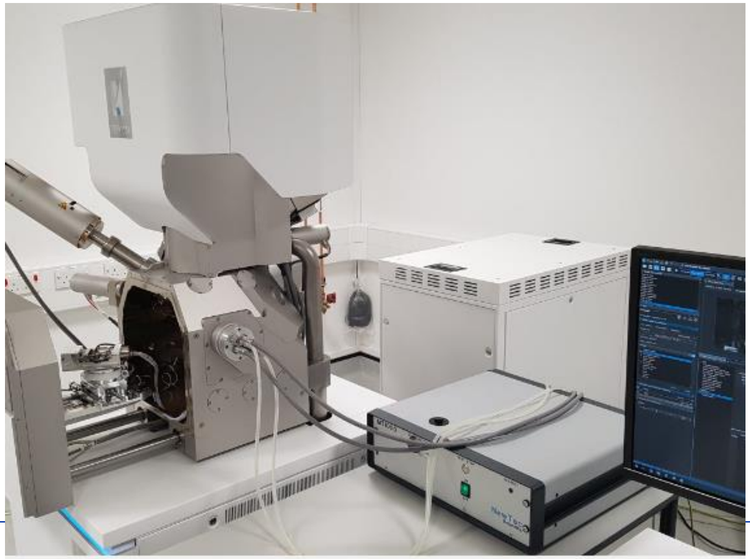
# Palette of tests for the material target – and why

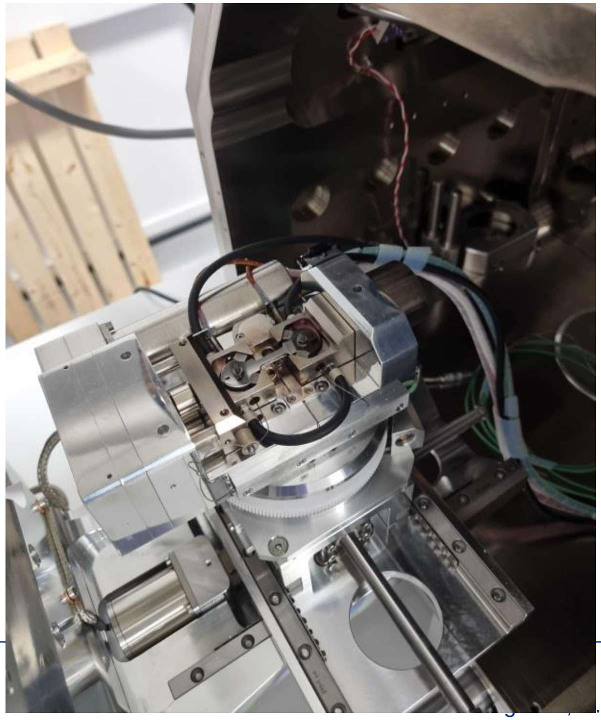
## In-situ proposal

- Collaboration with the University of Manchester, experts in this field
- Mechanical testing inside SEM
- Well adapted to test interfaces (W/Ta/W)
- **RT and high temperature in-situ**
- **SEM vacuum environment**
- Cost: ≈ 6000 CHF per test









# Palette of tests for the material target – and why

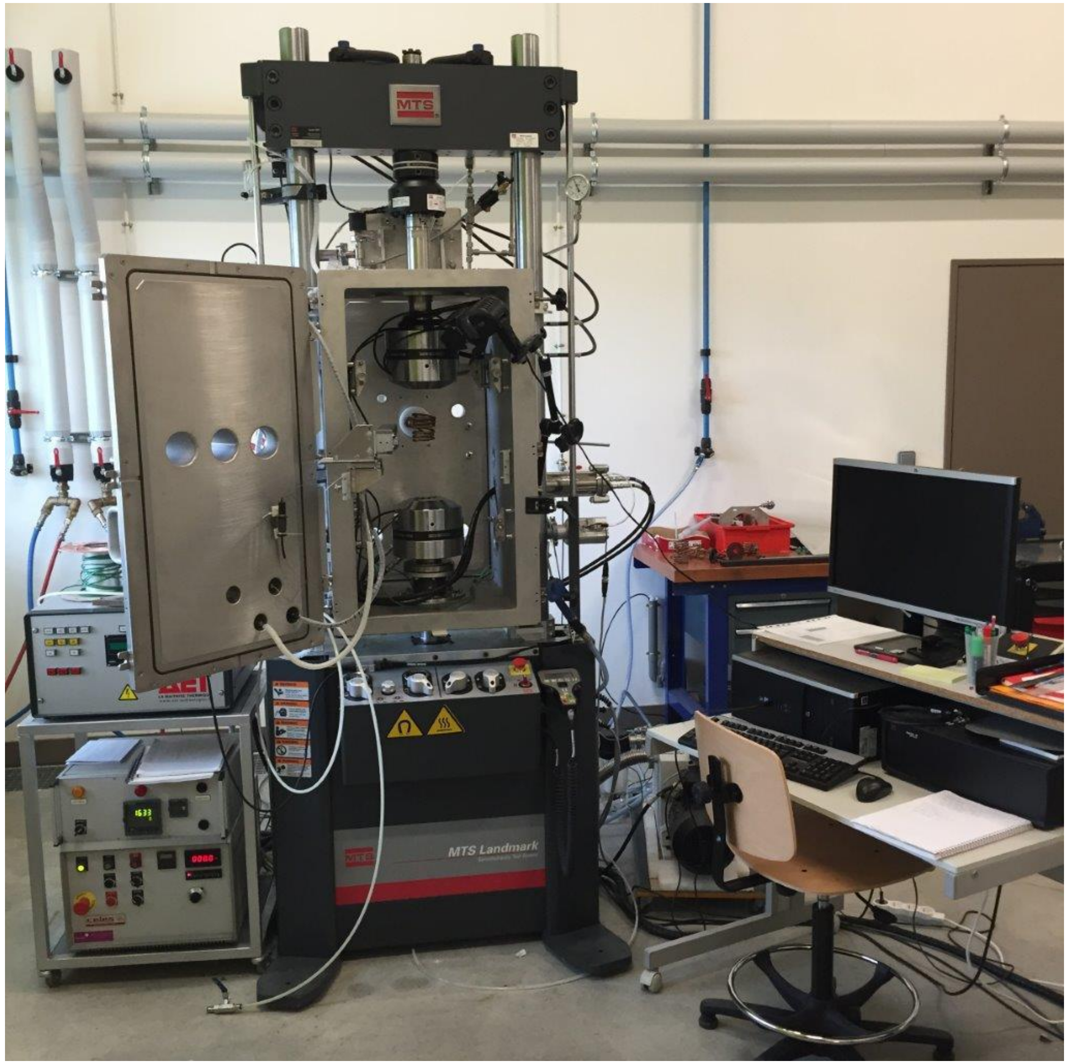
## Profilometry – based indentation plastometry

- The system allows obtaining stress–strain curves (up to uniform elongation) **based on indentation + profilometry data**
- We (EN-MME) have benchmarked it with a ‘blind test’ on a variety of materials (stainless steel P506, Nb RRR 300, electroformed Cu) with very consistent results (difference in $Rp_{0.2}$ and Rm < 10%)
- The HT option has been validated for pure tungsten up to 800°C
- **Estimated 131 kCHF**
- In-SEM also being evaluated for specific tests (collaboration Prof. Kermouche / Ecole des Mines de Saint Etienne) and own equipment (200 kCHF)

# Palette of tests for the material target – and why

**High T (1200°C) + vacuum Universal Testing System**

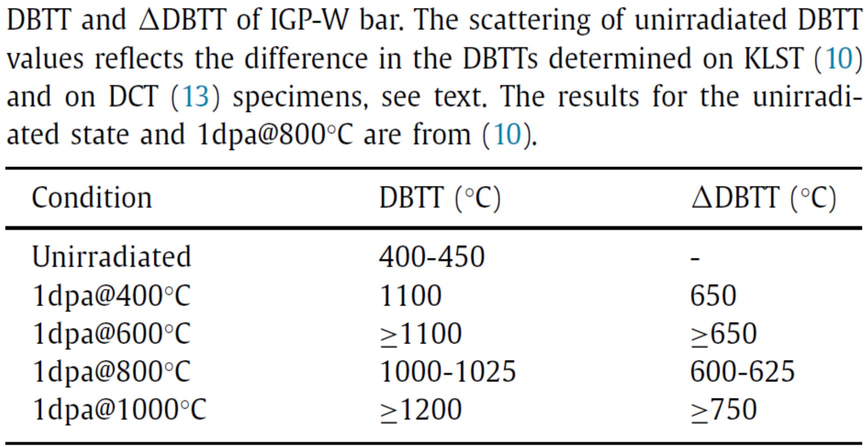
- Scarce availability
- High (and highly scattered) cost of high cycle fatigue testing at high temperature under vacuum or protective atmosphere
- Equip ourselves with state–of–the–art HT fatigue testing device?
- Two potential suppliers: Instron /UK & MTS/USA
- Both suppliers work with a French partner which is a reference of vacuum furnaces: AET
- Seamless integration with the unit, vacuum environment to avoid oxidation, and the whole specimen is at HT
- The system could eventually be installed in an extension of our current mechanical testing laboratory
- Both machine and vacuum furnace would be in the range of **550 – 600 kCHF**, including grips and extensometers



# Radiation damage considerations on materials – do we care?

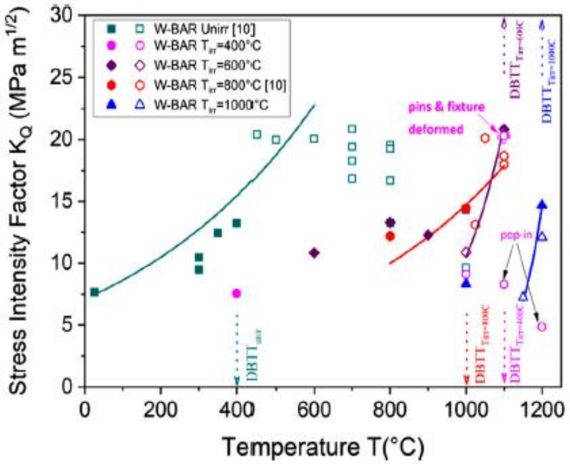
## General outcome: increase in the DBTT of irradiated samples

- The increase of the DBTT depends on fluence and irradiation temperature & it is pronounced even for doses as low as ~1 dpa
- Early works report DBTT of sintered unirradiated W ~ 400°C and of irradiated W ~ 600°C (ITER Materials Assessment Report (MAR), ITER Doc. G 74 MA 10 01-07-11 W0.3)
- Recent works confirm that irradiation strongly impacts the fracture-mechanical behaviour of wrought W irradiated to 1 dpa
- Depending on the irradiation temperature, the DBTT increases by about 650 °C or even higher



DBTT and ΔDBTT of IGP-W bar. The scattering of unirradiated DBTT values reflects the difference in the DBTTs determined on KLST (10) and on DCT (13) specimens, see text. The results for the unirradiated state and 1dpa@800°C are from (10).

| Condition | DBTT (°C) | ΔDBTT (°C) |
|---|---|---|
| Unirradiated | 400-450 | - |
| 1dpa@400°C | 1100 | 650 |
| 1dpa@600°C | ≥1100 | ≥650 |
| 1dpa@800°C | 1000-1025 | 600-625 |
| 1dpa@1000°C | ≥1200 | ≥750 |



*Gaganidze E., et al (2021). Effect of irradiation temperature on the fracture-mechanical behaviour of tungsten irradiated to 1 dpa, Journal of Nuclear Materials, 556 https://doi.org/10.1016/j.jnucmat.2021.153200*

- Tungsten wires irradiated at 0.2, 1, and 10 dpa and tested at RT. No significant change in the ductility of both irradiated and non-irradiated wires was found - Lürbke, R. et al. (2025), https://doi.org/10.1016/j.nme.2024.101858

# Conclusions

- The selected metallurgical route, form of product (HR plates), HIP diffusion bonding techniques are promising, based on previous assessments and ongoing tests
- However, an extensive material characterisation and assessment of mechanical properties at intermediate temperature is still needed to support this material choice
- Testing campaigns are extensive, complex and costly → consider developing in-house test facilities
- Critical points are the limitation of the thickness: a HIP cycle required, equivalent to an annealing, that might raise the DBTT
- Irradiation hardening and embrittlement are potential concerns (primary degradation phenomena of W):
    - hardness and yield strength increase, ductility loss at high doses, shift of DBTT
    - Large DBTT shift expected even at a low dose of 1 dpa
    - Brittle regime in all temperature range eventually expected, no self-recovery
- Thermomechanical processing techniques, such as rolling and forging and/or additives/dopants can reduce the DBTT of W, even down to RT. Nevertheless, both approaches have proven to be less effective when W is subjected to high-temperature annealing or irradiation

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