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International tungsten development efforts and the ~~German~~ gas cooled divertor design

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CONTENTS (→ PRE-DEFINED BY LANCE)

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- **Introduction (or focusing on the not quite hopeless problems)**
- **Gas cooled divertor designs**
- **Identification of issues (fabrication, properties, environment, irradiation effects)**
- **Material system mapped to design window (Where do we look good, where are still gaps?)**
- **Summary and path forward**

1 INTRODUCTION

TUNGSTEN AND ITS USE AS ARMOR MATERIAL

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The life time of a power plant divertor is TWO years – hopefully!

High heat flux	→ High operating temperatures (peaks>1800°C) → Microstructural stability, aging, … → Thermo-shocks, cyclic loading, fatigue, …
Heavy ion bombardment	→ Sputtering, cracking/fracturing → Surface interactions and modifications → Microstructural changes
Neutron load 15 dpa/year (in W)	→ 30 dpa (in W) until end of service → Transmutation effects (Re, Os) → Swelling (order of magnitude: 3% for pure W)

QUESTION: What can we do about this? How can we improve **ARMOR** materials?

ANSWER: There is not much we can do now! We have to live with most properties and effects. A final assessment would require real in-service conditions.

“Reasonable” Alloying Elements for W

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M_2W Be	Mg	MW B	MW_2 C $M_{1-x}W$	M_4W Al		Y	La	
Ti >3wt.% >300°C	V	MW_3 Cr	Mn	MW, M_7W_6 Fe	M_7W_6 Co	MW Ni	Cu	
MW_2 Zr	Nb	Mo		Ru < 3 wt. %	Rh < 2 wt. %	M_3W Pd	Ag	Cd
MW_2 Hf	Ta		MW Re < 26 %	Os < 5 %	MW Ir	MW Pt	Au	

Insoluble | **Intermetallic Phases** | **Line Compounds** | **Solid Solution**

Tungsten Materials

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Pure Tungsten

Grain Stabilized Tungsten „ODS Tungsten“

Potassium Doping

e.g. WVM, WVMW
→ Bulb Wire

Oxides & Carbides

- La_2O_3 (e.g. WL10, WL15, WL20)
- CeO_2 (e.g. WC20)
- ThO_2 (e.g. WT20)

→ Weld Electrodes
- Y_2O_3, ZrO_2, TiC, HfC, etc.

„Heavy Metals“ (Two Phases)

- W-Ni-Fe (e.g. Densimet, Inermet)
- W-Cu

→ Functional Applications

Alloys (Solid Solution)

- W-Re (<26%)

→ only commercial alloy

- W-V
- W-Ta
- W-Mo
- W-Ti
- (W-Nb)

→ Even more brittle as pure tungsten !!!

Not suitable for structural divertor applications

Production Routes

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Powder Metallurgy

- Blending
- Pressing
- Sintering
- Hot Forming

This is so far the only large-scale production route which could handle the 500 tons of W needed for one divertor !

- Blending with Bin
- Injection Moldi
- Debindering/S ng
- HIP

+ Mass ction
+ Ne ished
ts
ogenous
crostructure

→ *S. Antusch, KIT*
→ *J. Opschoor, ECN*

Functional Applications

- Ball Milling
- Encapsulati
- HIP/Hot Formi

+ Na cture
+ D y
all Scale
roduction Route

→ *H. Kirushita, IMR*
→ *N. Baluc, PSI*
→ *A. Muñoz, CIEMAT*

Still Under Investigation

COMMERCIAL SEMI-FINISHED W PRODUCTS

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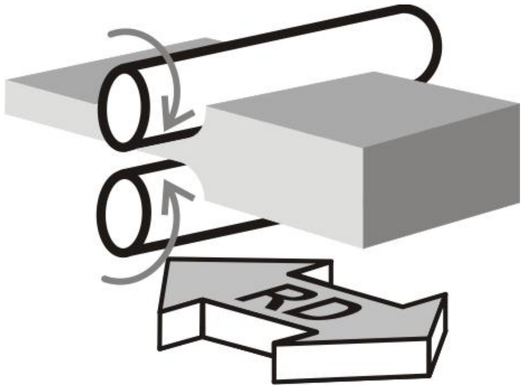
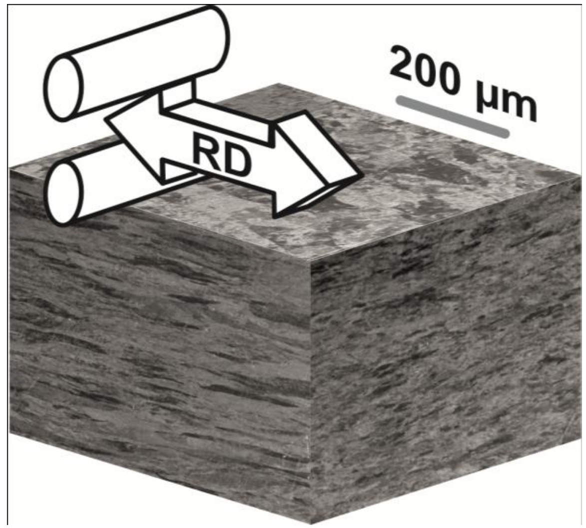
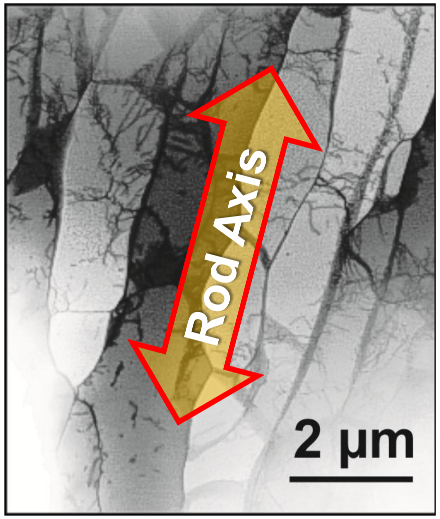
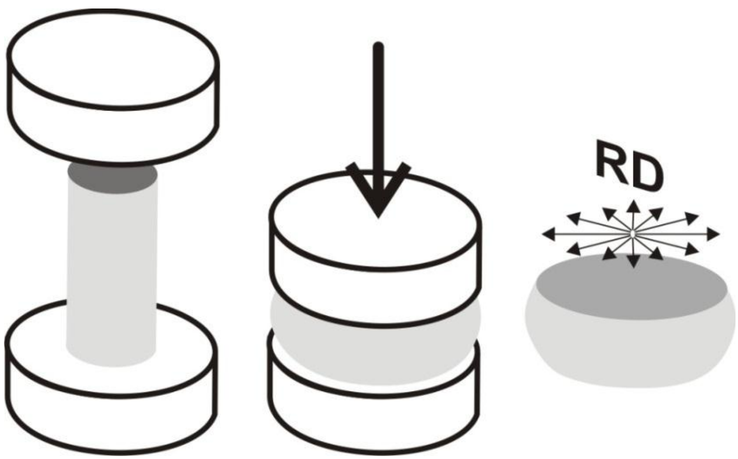
Rolling Plates



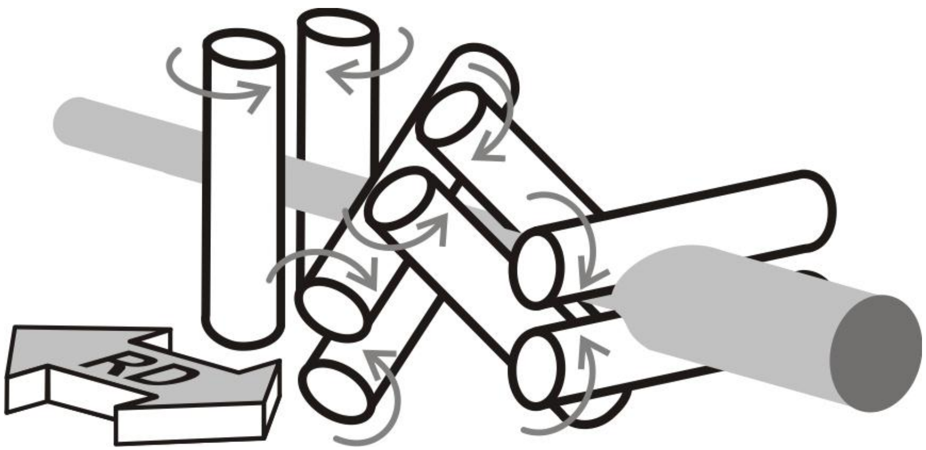




Forging Round Blanks



Rolling/Swaging Rods



MICROSTRUCTURE AND RELATED PROPERTIES

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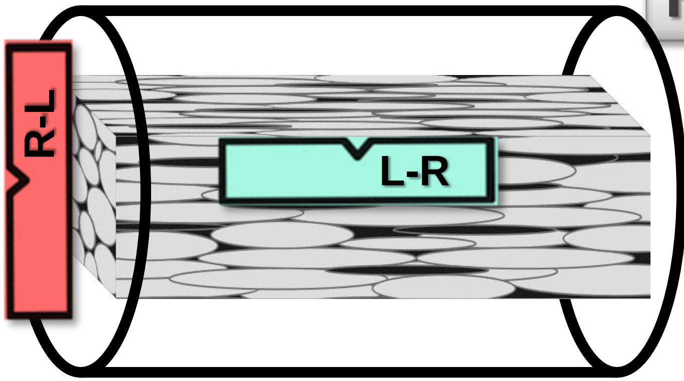
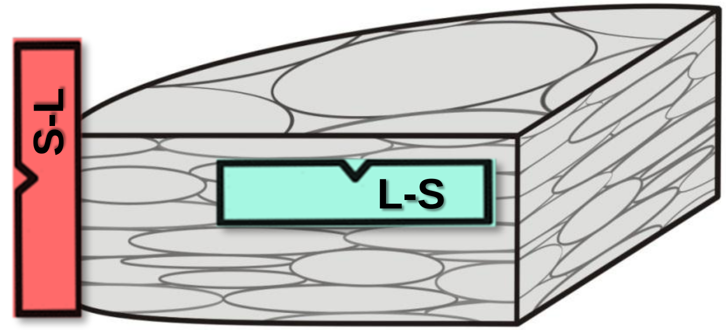
Rods

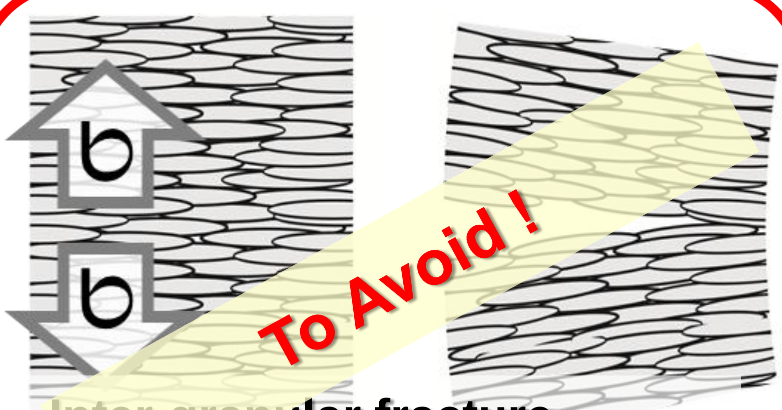


Bundle of „Fibres“

Plates **Round Blanks**



Stack of „Pancakes“



Inter-granular fracture,
enhanced by oxide particles !

Partly ductile fracture,
improved by deformation !

Structural Tungsten Materials Summary

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So far, the best suitable tungsten materials for structural applications (divertor or other large scale components) are

Thin Plates, Thickness < 4 mm

Produced by Sintering (Hydrogen Atmosphere) and Cross-Rolling

Pure Tungsten (maybe small amounts of grain stabilizers, like La_2O_3)

Costs for 500 t → over 100 Mio. US $

based on PLANSEE online catalogue, September 2011, including discount

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HELIUM COOLED DIVERTOR DESIGNS

FINGER DESIGN, JET COOLING

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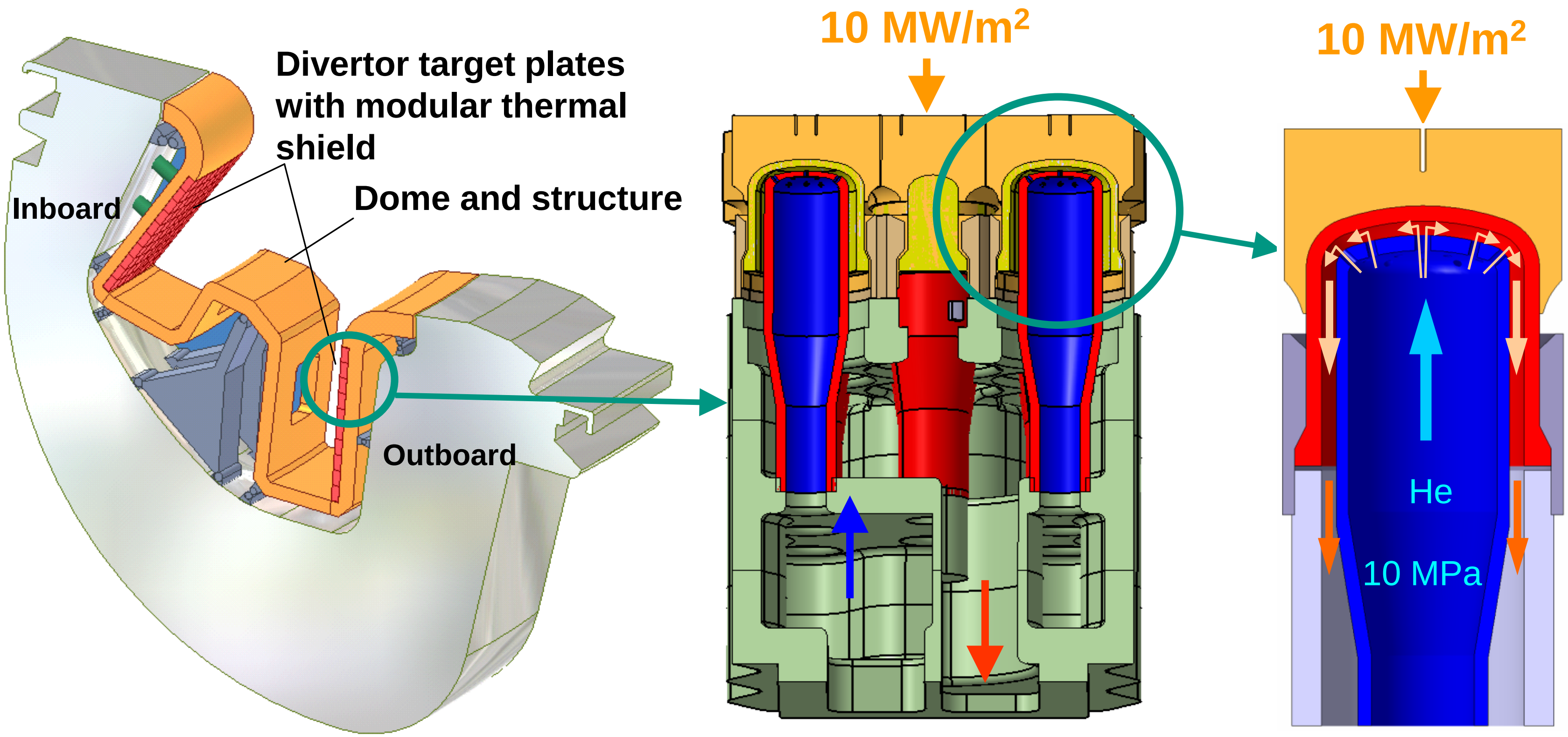


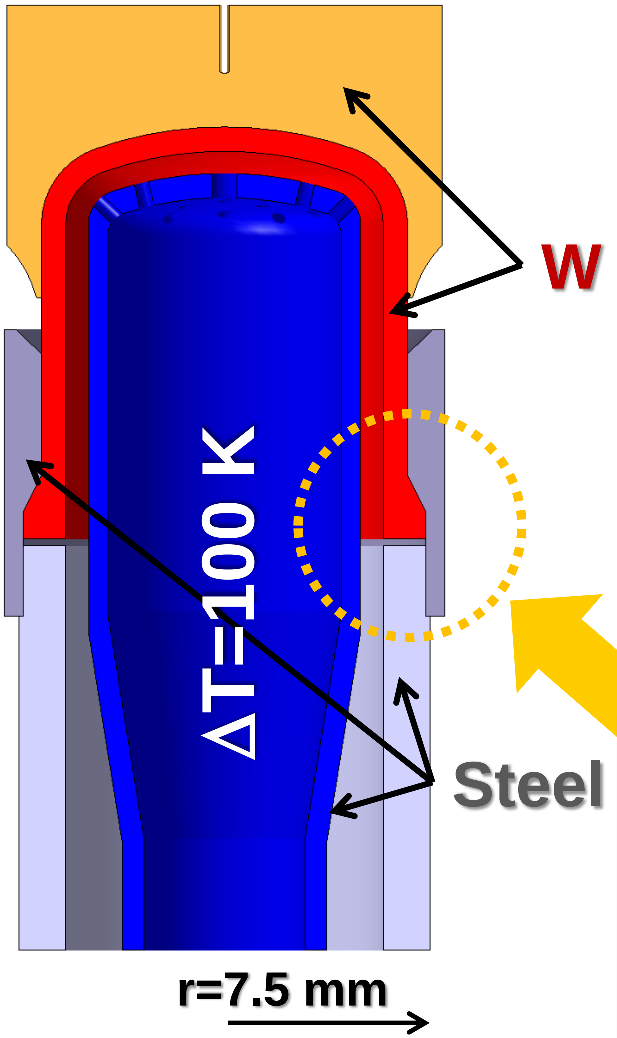
Divertor Cassette

9-Finger Module

Finger

→ P. Norajitra, T. Ihli *et al.*, 2003-2009

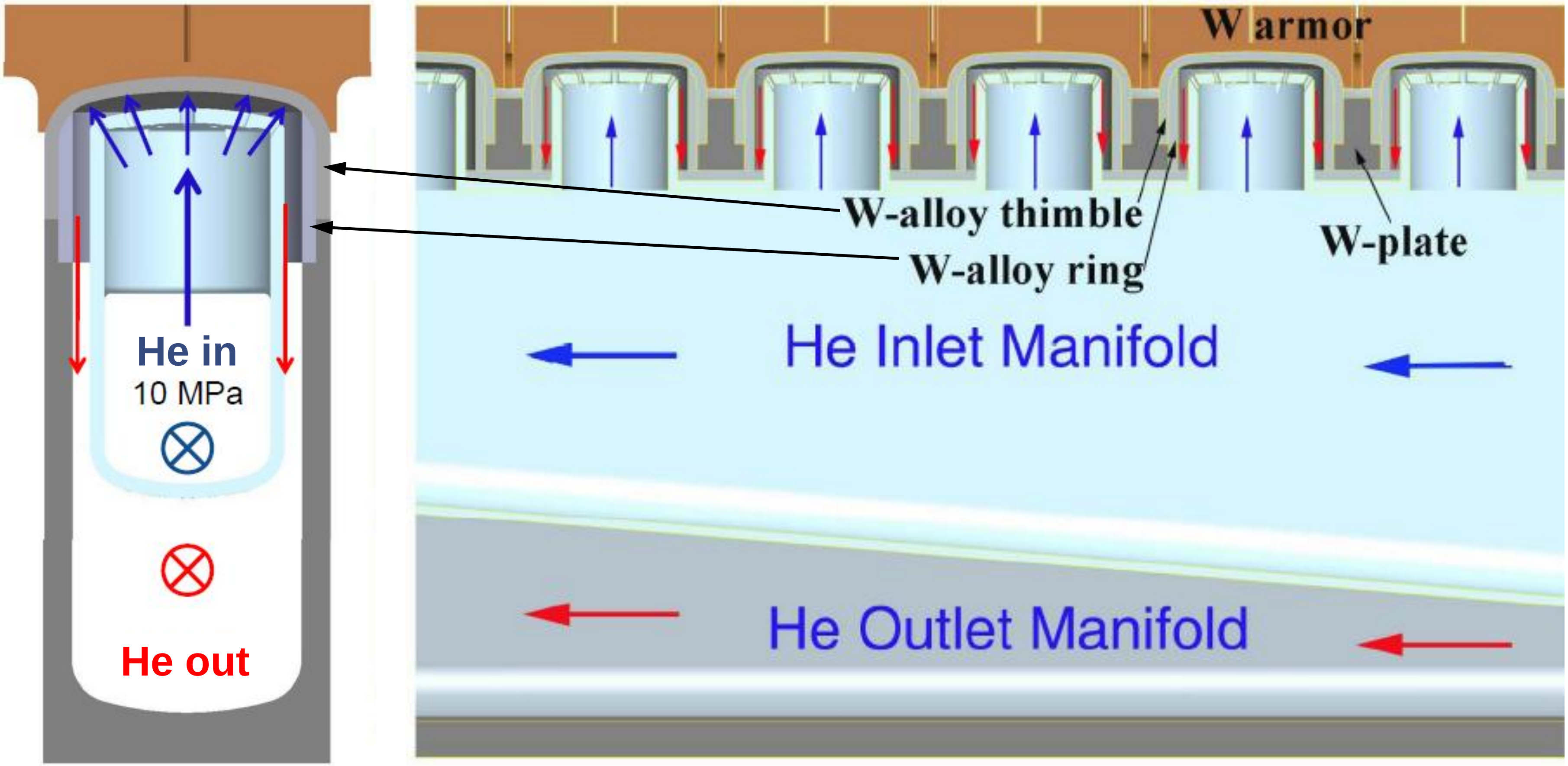
FINGER DESIGN, JET COOLING



- + High heat flux: >10 MW/m²
- + Small Size, Thin Walls
- − Large Numbers: ~500 000
- − Joints between W and Steel

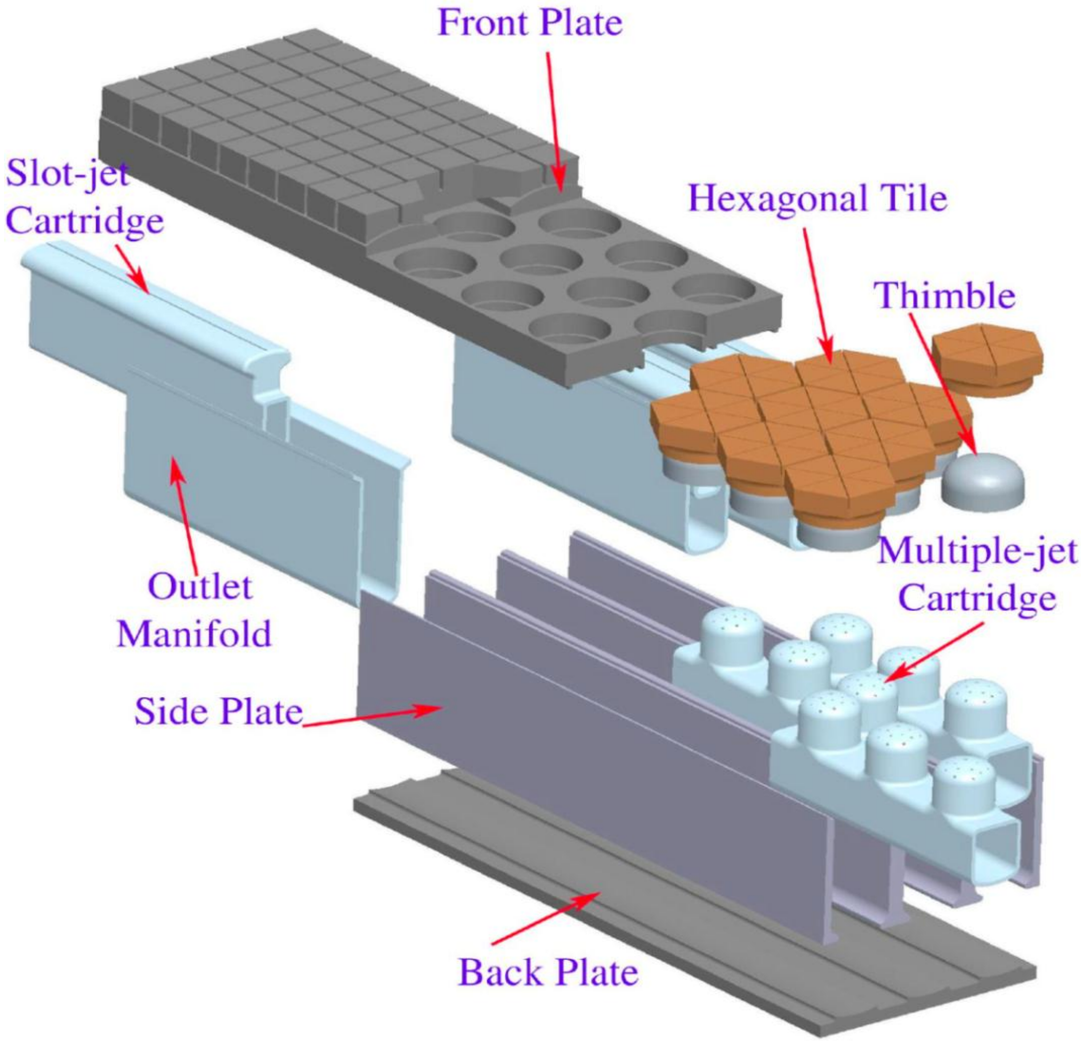
He and W temperature limited by steel
Ferritic ODS → 750°C ???
Eurofer ODS, 9Cr ODS → 650°C
Eurofer 97, F82H → 550°C

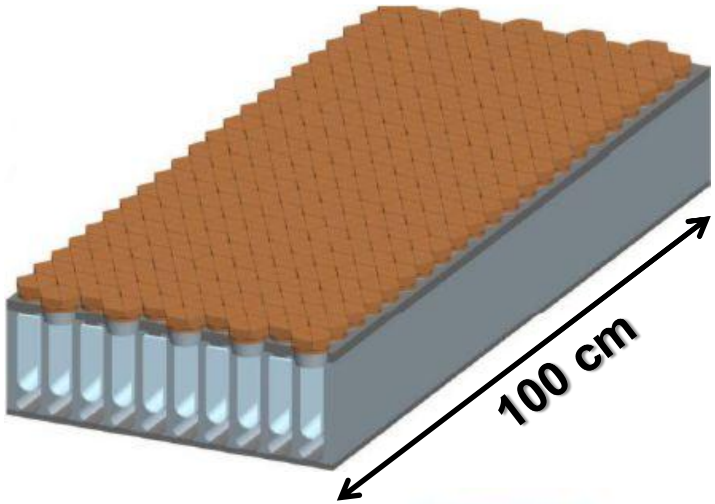
PLATE DESIGN (ARIES), JET COOLING



X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

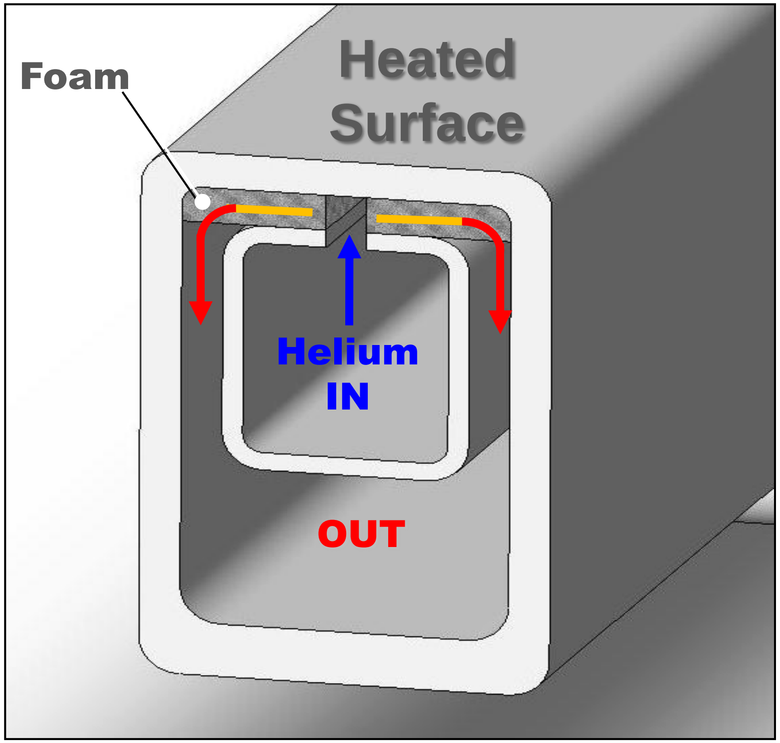
PLATE DESIGN (ARIES), JET COOLING

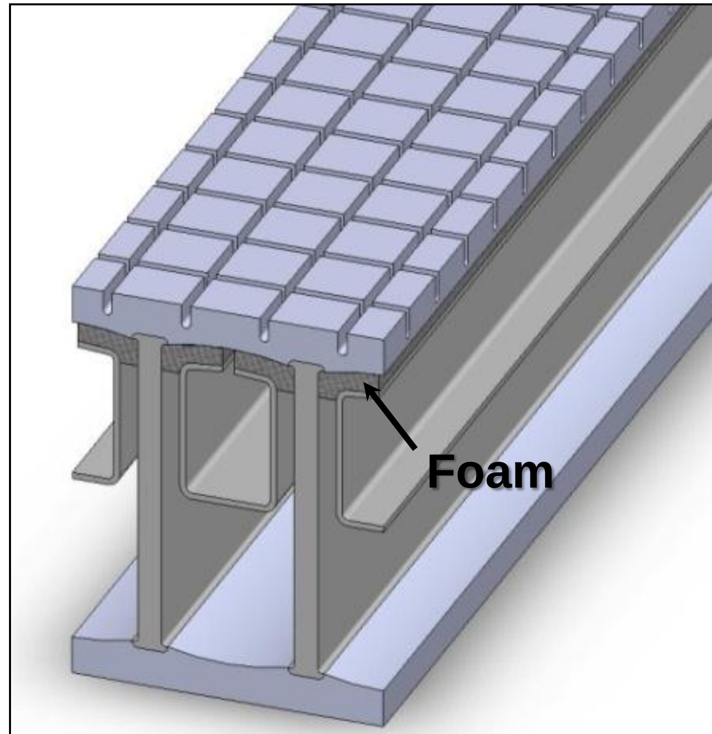


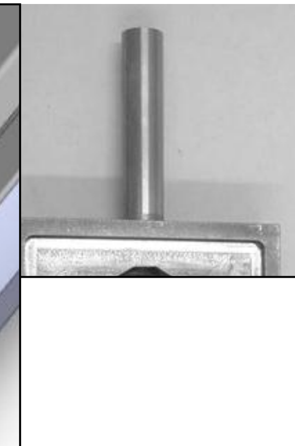


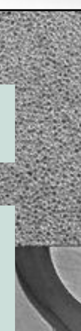
X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

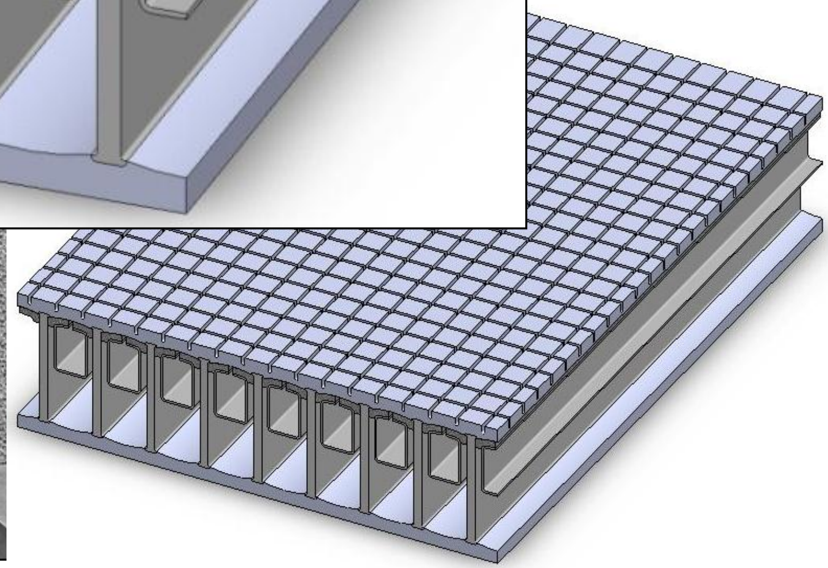
PLATE DESIGN, FOAM PROMOTER







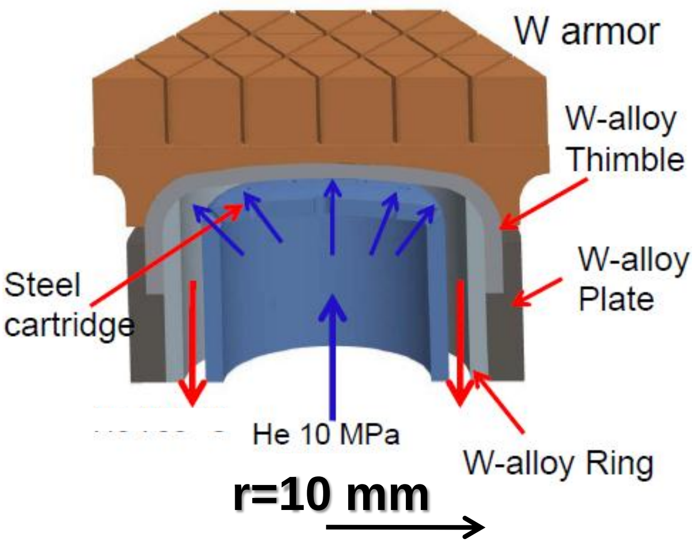




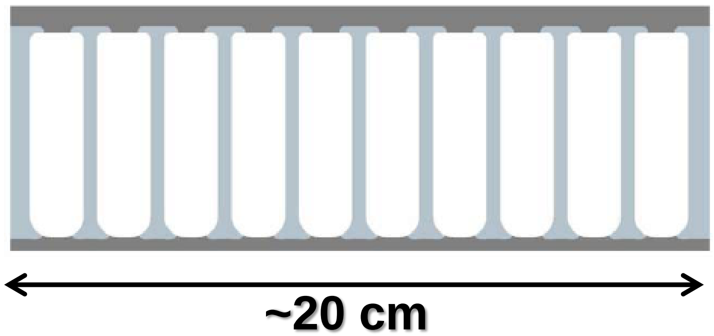
→ S. Sharafat *et al.*, UCLA, 2005-2009

→ Mo, Nb, SiC Foam:
D. Youchison *et al.*, SNL,2011

Plate Design (ARIES), Jet Cooling



- + High heat flux: ~15 MW/m²
- + Small Size, Thin Walls
- + "Double Containment"
- − Large Numbers: ~300 000
- − Many/Long Struct. W-W Joints



He temperature limited by steel (multiple jet cartridges)
Ferritic ODS → 750°C ???
Eurofer ODS, 9Cr ODS → 650°C
Eurofer 97, F82H → 550°C

PIPE/MONOBLOCK DESIGN, JET COOLING

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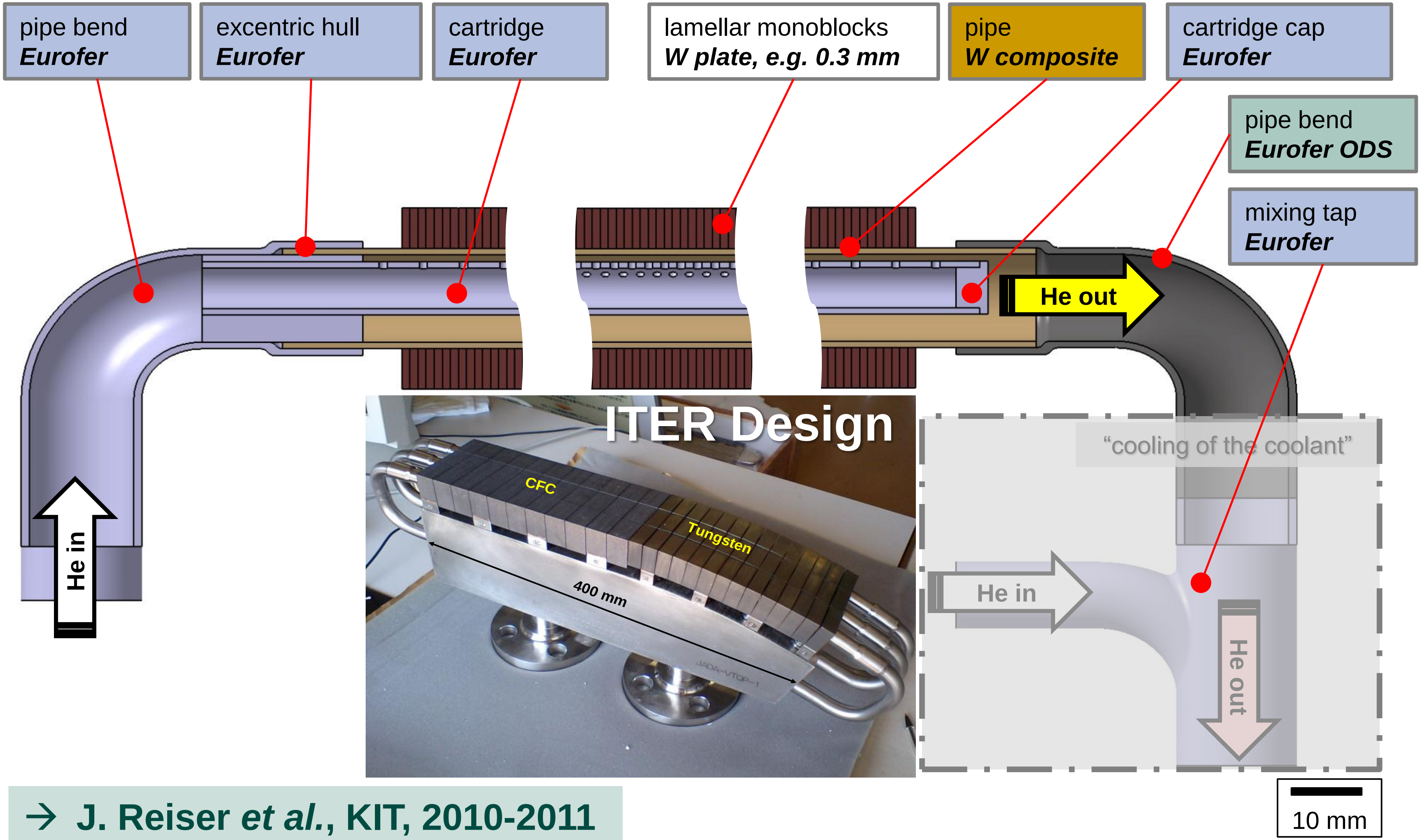
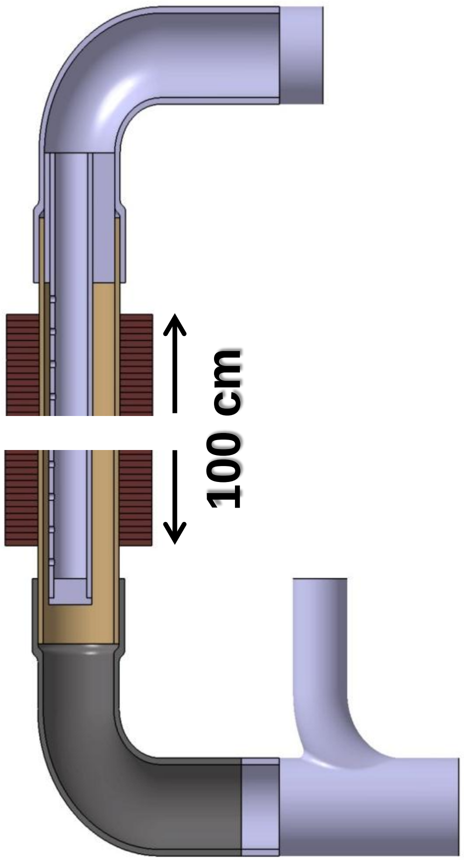


→ J. Reiser *et al.*, KIT, 2010-2011

PIPE/MONOBLOCK DESIGN, JET COOLING



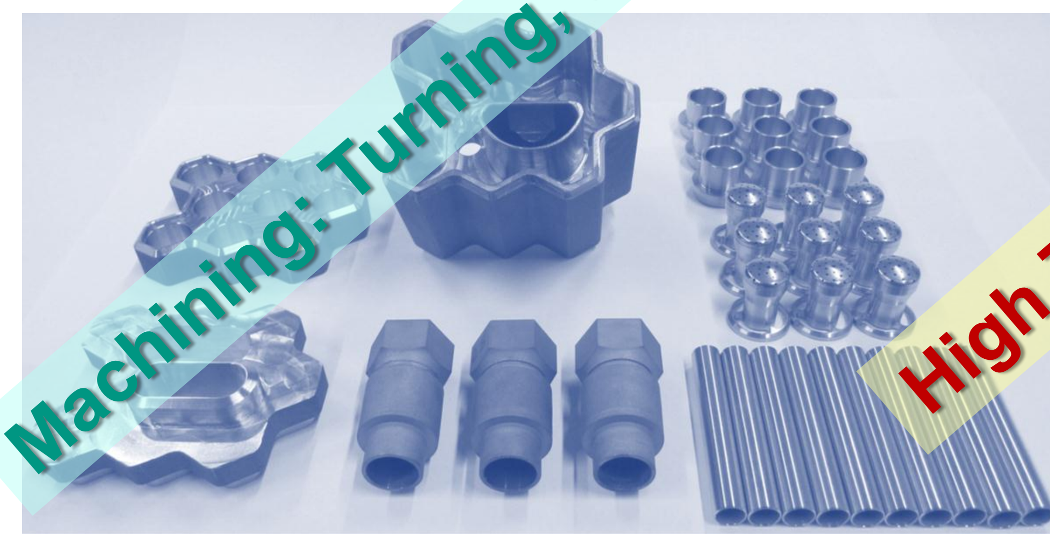
+ Simple Design
+ "Easy Joints"
+ "Small Number of Parts"
+ Inexpensive

− Low Temperatures for W
− Low Performance
− Speculative Pipe Material

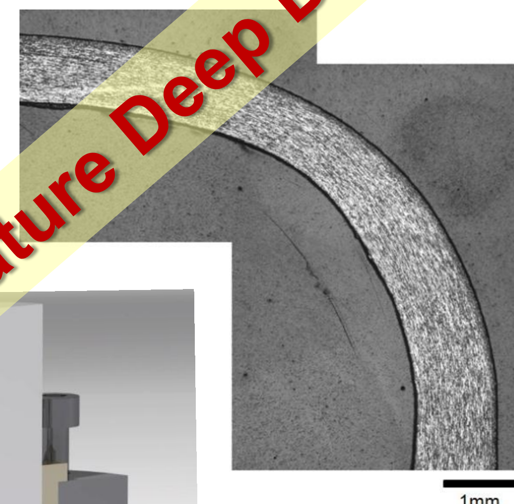
He temperature limited by steel
Eurofer ODS → 650°C (upper)
Eurofer 97 → 350°C (lower)

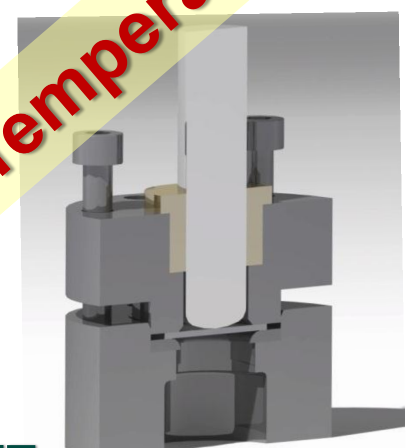
3 Identification of Issues

FABRICATION



Machining: Turning, Milling, Grinding, …

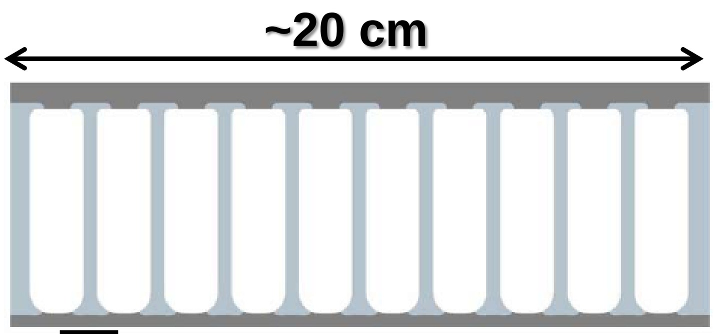


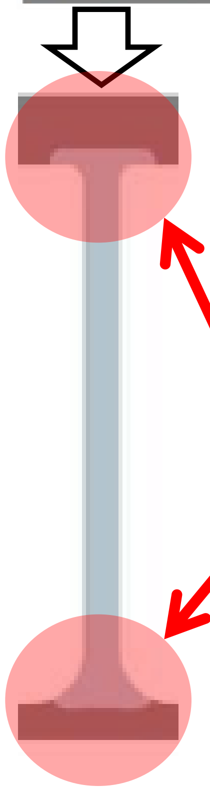


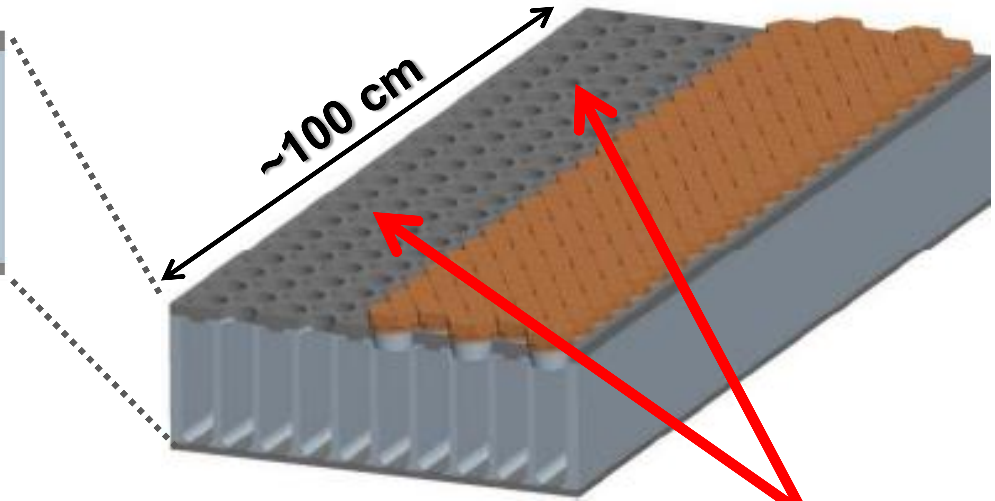
High Temperature Deep Drawing

P. Norajitra, J. Reiser, S. Baumgärtner *et al*., KIT

FABRICATION







Drilling Holes in 10 mm Plate → standard

High Temperature Plate Pressure-Forging → to be developed

JOINING → BRAZING

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IMPORTANT: We have to consider joints for STRUCTURAL applications!!!
Joining W tiles to W timbles is NOT considered as structural application!

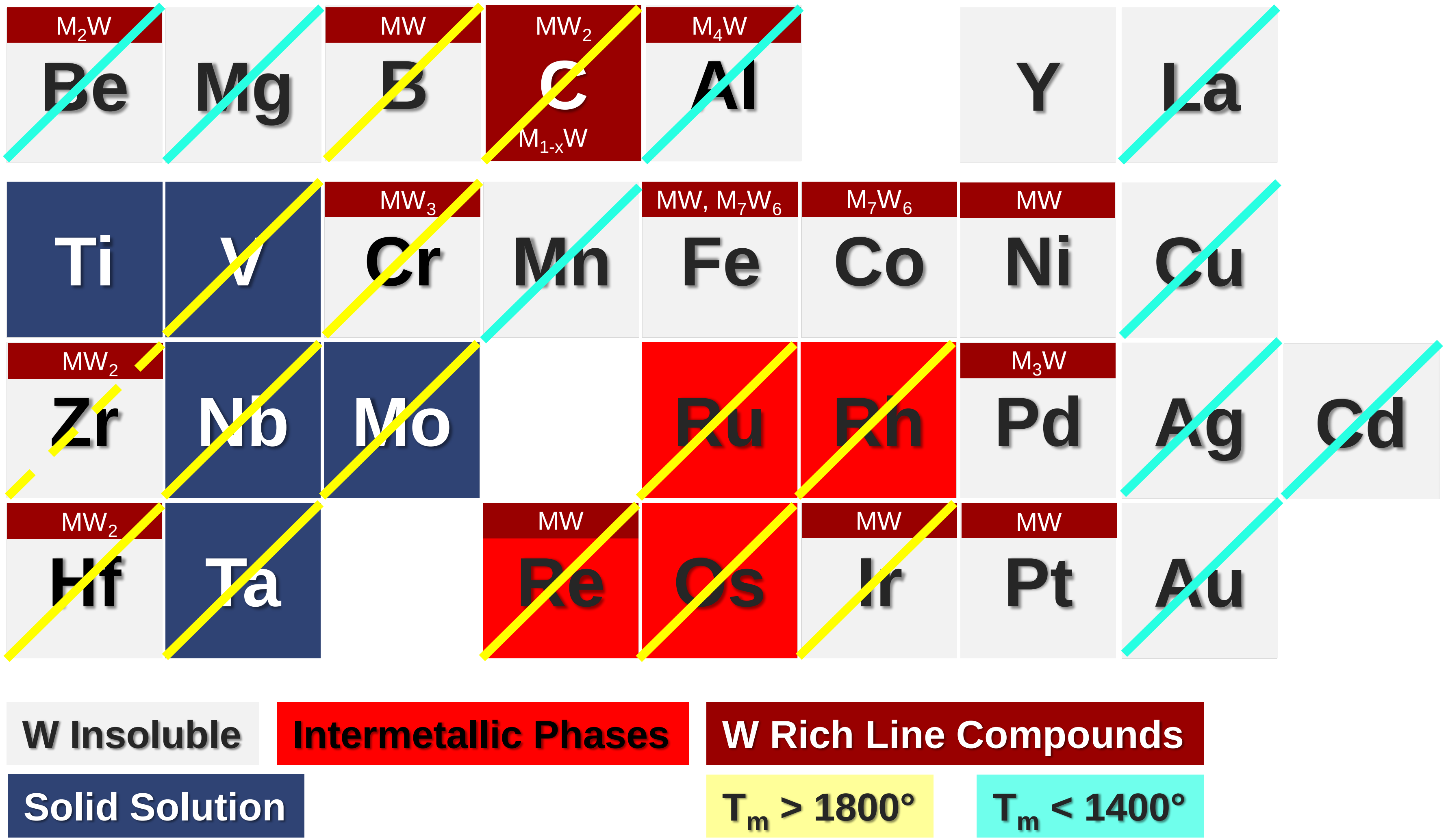
Brazing Material for W-W Joints

- Brazing temperature must be >>900-1200 °C (operating temp.)
- Brazing temperature must be <1800 °C → Grain growth
- Formation of brittle compounds cannot be tolerated

Brazing Material for W-Steel Joints

- Brazing temperature <1100 °C → Grain growth (in steel)
- Brazing temperature must be >>550-750 °C (operating temp.)
- Formation of brittle compounds cannot be tolerated

BRAZING W→W



M_2W
Be
Mg
MW
B
MW_2
C
$M_{1-x}W$
M_4W
Al
Y
La
Ti
V
MW_3
Cr
Mn
MW, M_7W_6
Fe
M_7W_6
Co
MW
Ni
Cu
MW_2
Zr
Nb
Mo
Ru
Rh
M_3W
Pd
Ag
Cd
MW_2
Hf
Ta
MW
Re
Os
MW
Ir
MW
Pt
Au
W Insoluble
Intermetallic Phases
W Rich Line Compounds
Solid Solution
T_m > 1800°
T_m < 1400°

BRAZING MATERIALS, W→W

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1670°C	Ti	<740°C:
1520°C	Y	Strong ... 40°C <1570°C ... 00°C: alpha-Y + Y_2O_3
1850°C	Zr	<2160°C: W→ ZrW_2 <1700°C ... % intermetallic ZrW_2 <860°C: Zr→ ZrW_2 ... tallic ZrW_2
1550°C	Pd	<1800°C: W→ ZrW_2 <900°C: intermetallic Pd_3W ???
1770°C	Pt	<24..°C: ... phase Pt_3W
1540°C	Fe	<1700°C: μ phase $Fe_7W_6(Fe,W)_4$ <1000°C: Laves phase Fe_2W
1500°C	Co	<1700°C: μ phase $Co_7W_6(Co,W)_4$ <1000°C: Laves phase Co_3W
1450°C	Ni	<1000°C: peritectoid intermetallics NiW <950°C: peritectoid intermetallic Ni_4W

Difficult, … ?

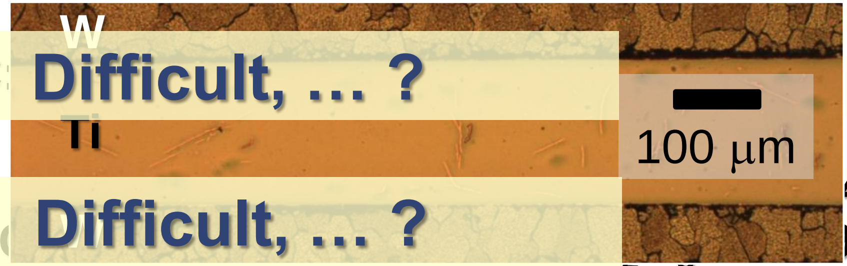
Difficult, … ?

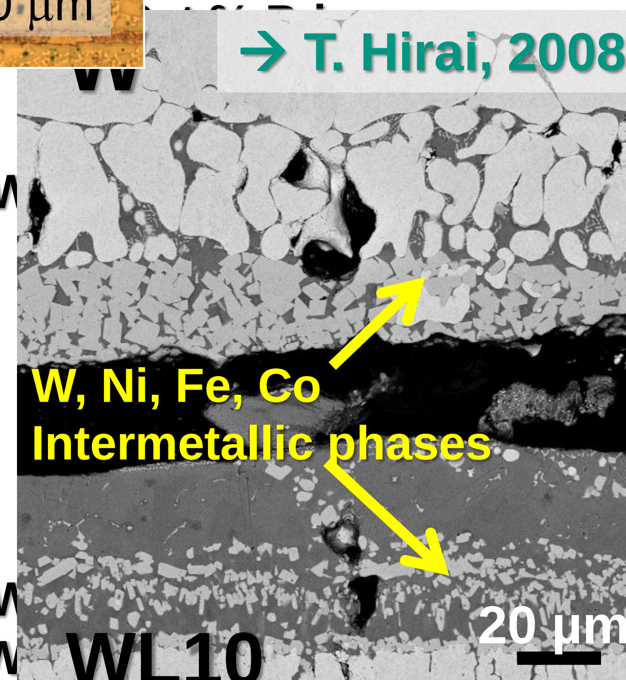
Brittle Joint

Expensive, … ?

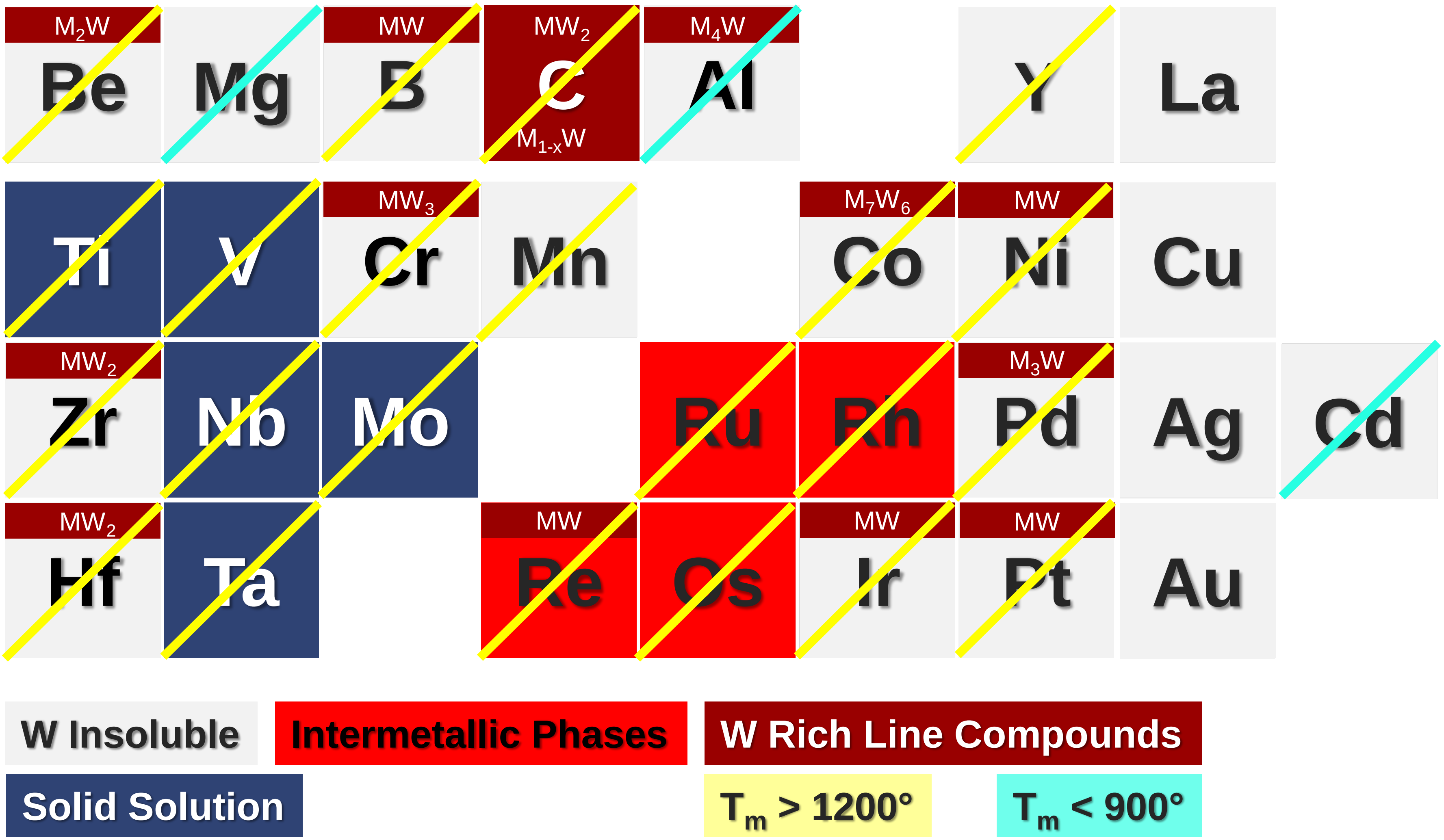
Very expensive, … ?

Brittle Joints



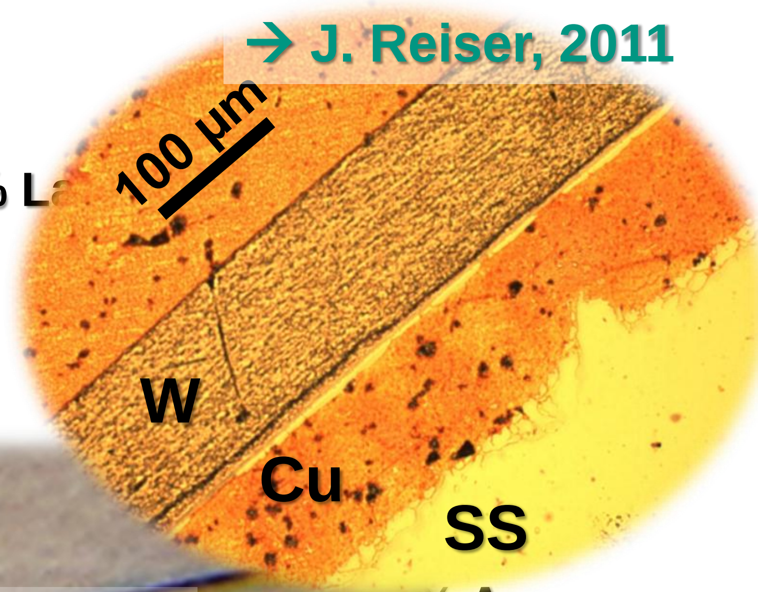


Brazing W→Steel



BRAZING MATERIALS, W→STEEL

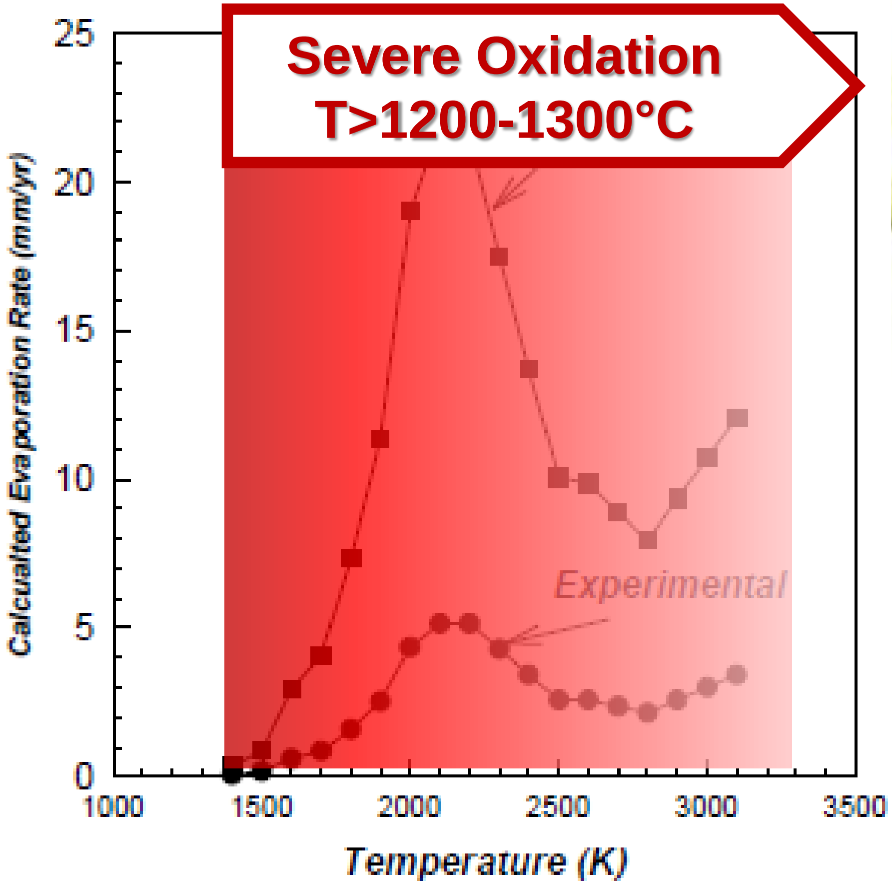
920°C	La	<790°C: eutecticum → 93at.% La
1080°C	Cu	✓ … but strength ???
960°C	Ag	
1060°C	Au	< < … % Au



CONCLUSION: Copper has to be used as sealing rather than as a braze material !!!

ENVIRONMENT → OXIDATION

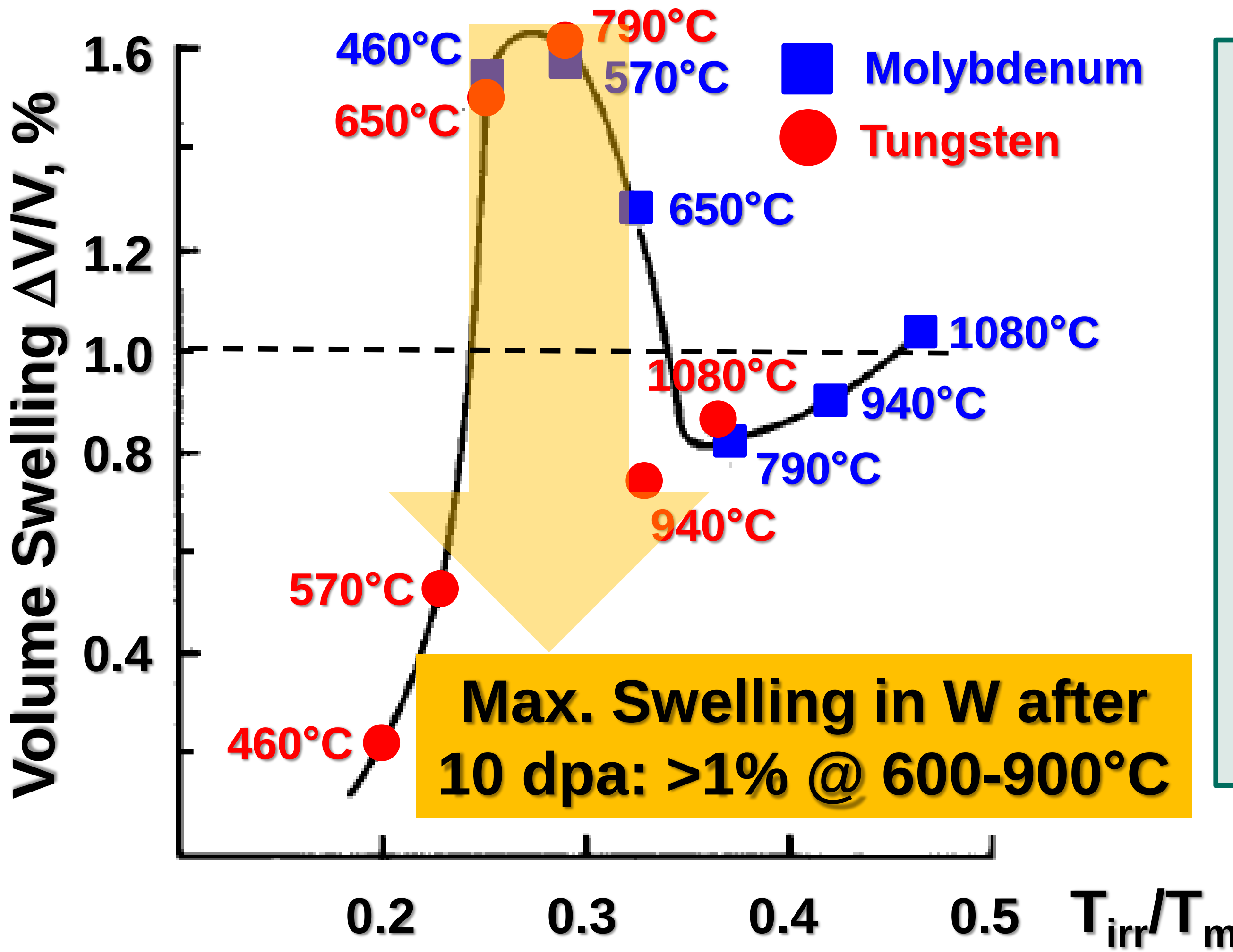
WO_3 yellow, T_m=1470°C, 7200 kg/m³, volatile in vacuum



→ N.M. Ghoniem, 1998

CONCLUSION
For tungsten operating at 50 atm. He coolant, at 0.1 ppm oxygen, the upper temperature is estimated at 1200-1300°C.

IRRADIATION EFFECTS → SWELLING



Max. Swelling in W after 10 dpa: >1% @ 600-900°C

EBR-II

E_n > 1 MeV
1 x 10^{22} n/cm²

E_n > 0.1 MeV
1.6 x 10^{22} n/cm²

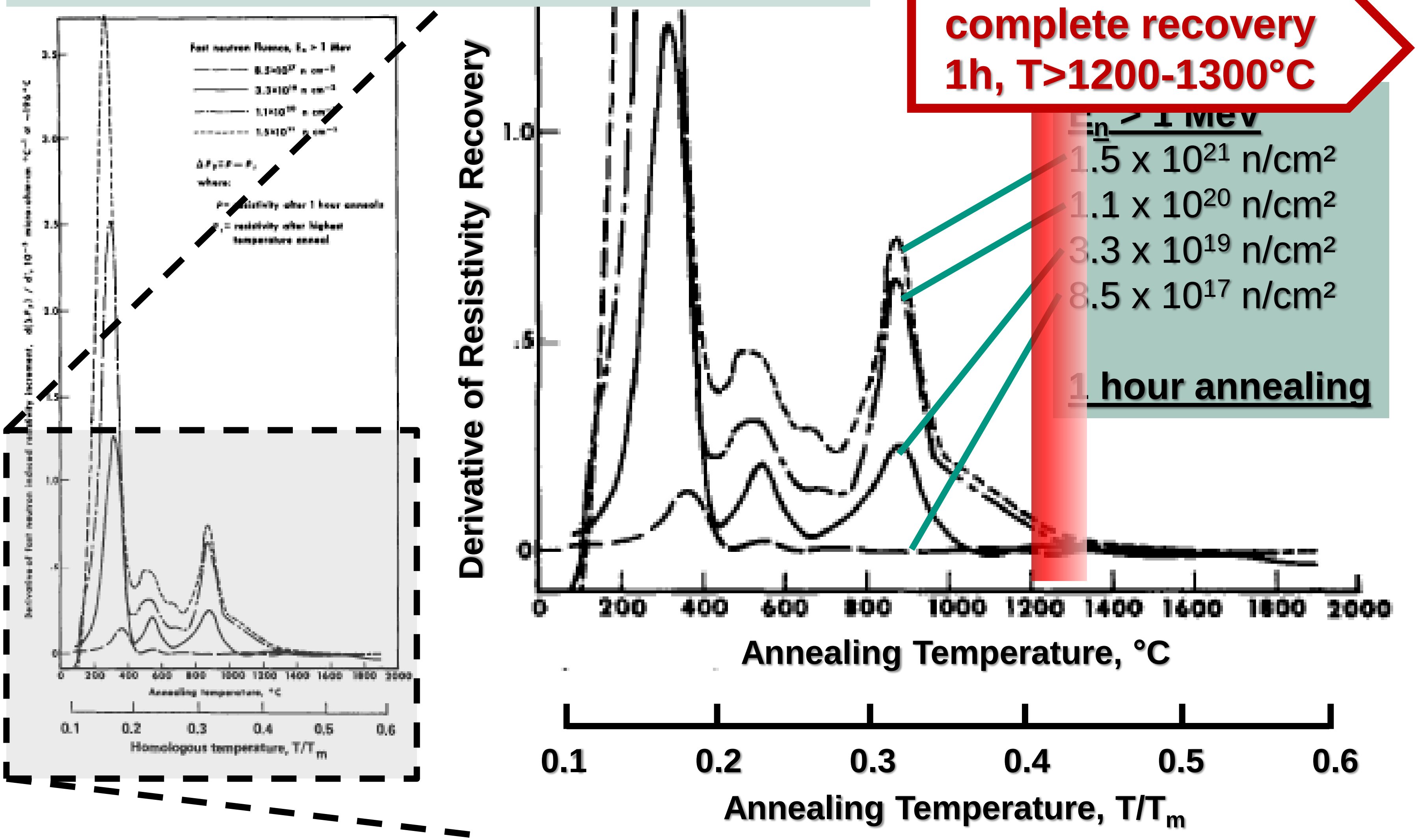
→ **29 dpa in Mo**

→ **9.6 dpa in W**

→ F. Lee, J. Matolich, J. Moteff, JNM 62 (1976) 115-117

IRRADIATION EFFECTS → RECOVERY

→ L.K. Keys, J. Moteff, JNM 34 (1970) 260-280



IRRADIATION EFFECTS → EMBRITTLEMENT

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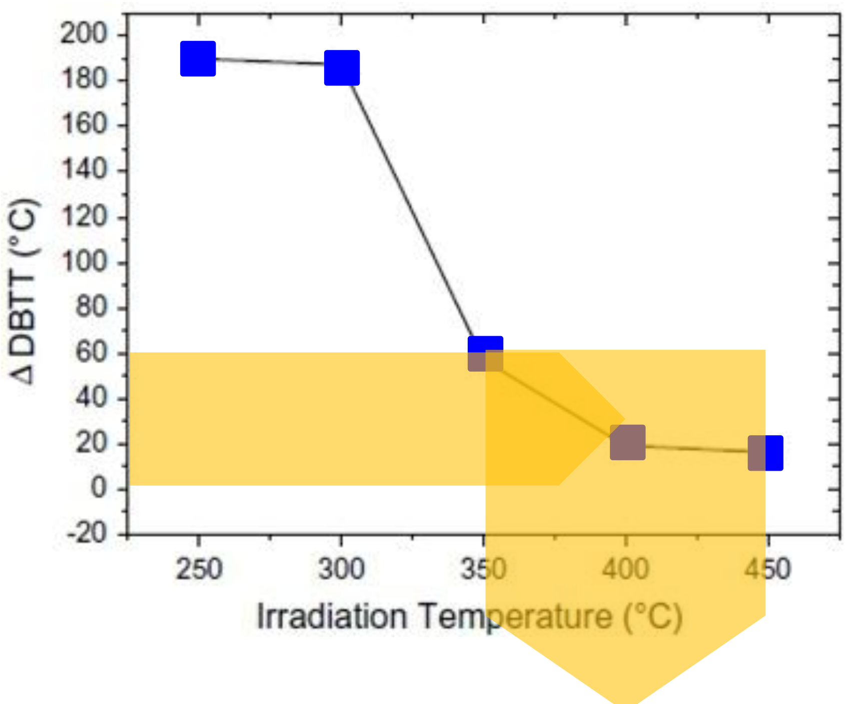
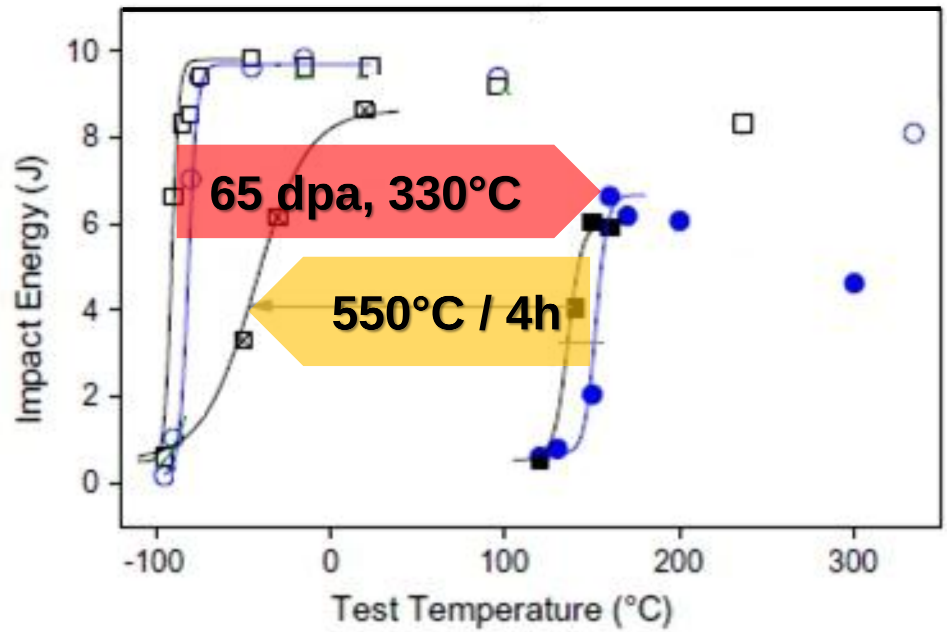
EUROFER: In-service irradiation embrittlement after ~10 dpa



Possible Operating Temperature T_{op} > 350°C

EUROFER: Recovery of 65 dpa irradiation embrittlement



Possible Recovery Temp. T_{rec} > 550°C

→ E. Gaganidze *et al.*, KIT

IRRADIATION EFFECTS → EMBRITTLEMENT

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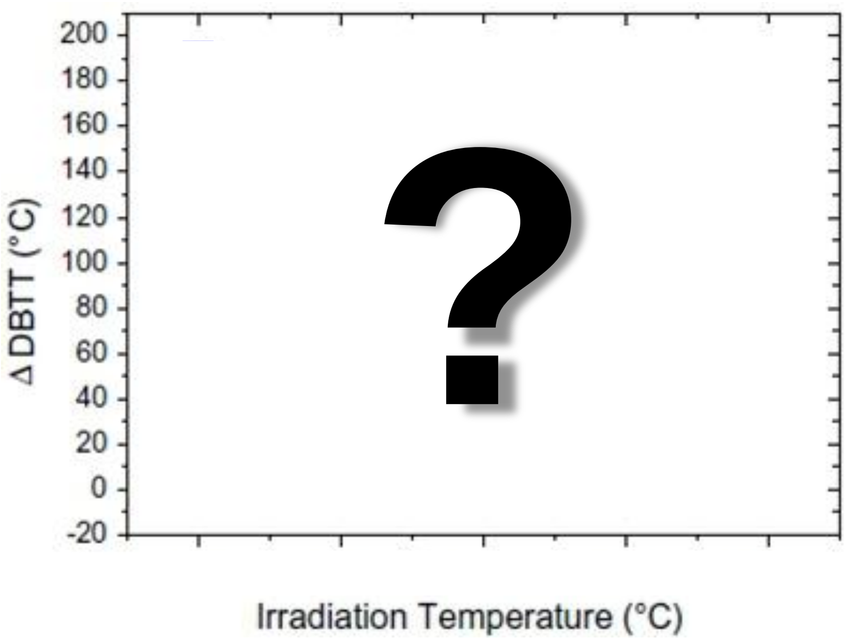
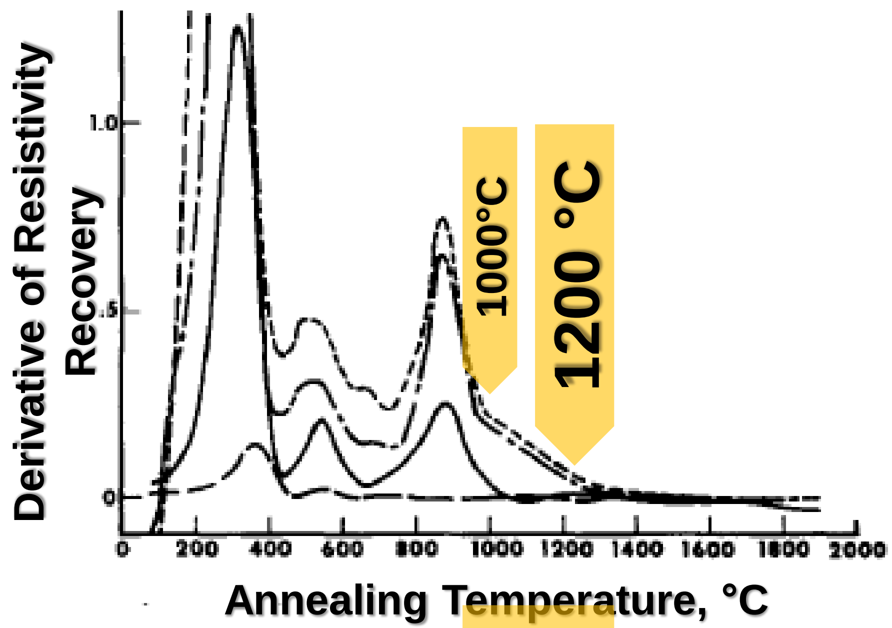
TUNGSTEN: In-service irradiation embrittlement after 10-20 dpa



Tungsten: Recovery of ~2 dpa stage IV irradiation hardening

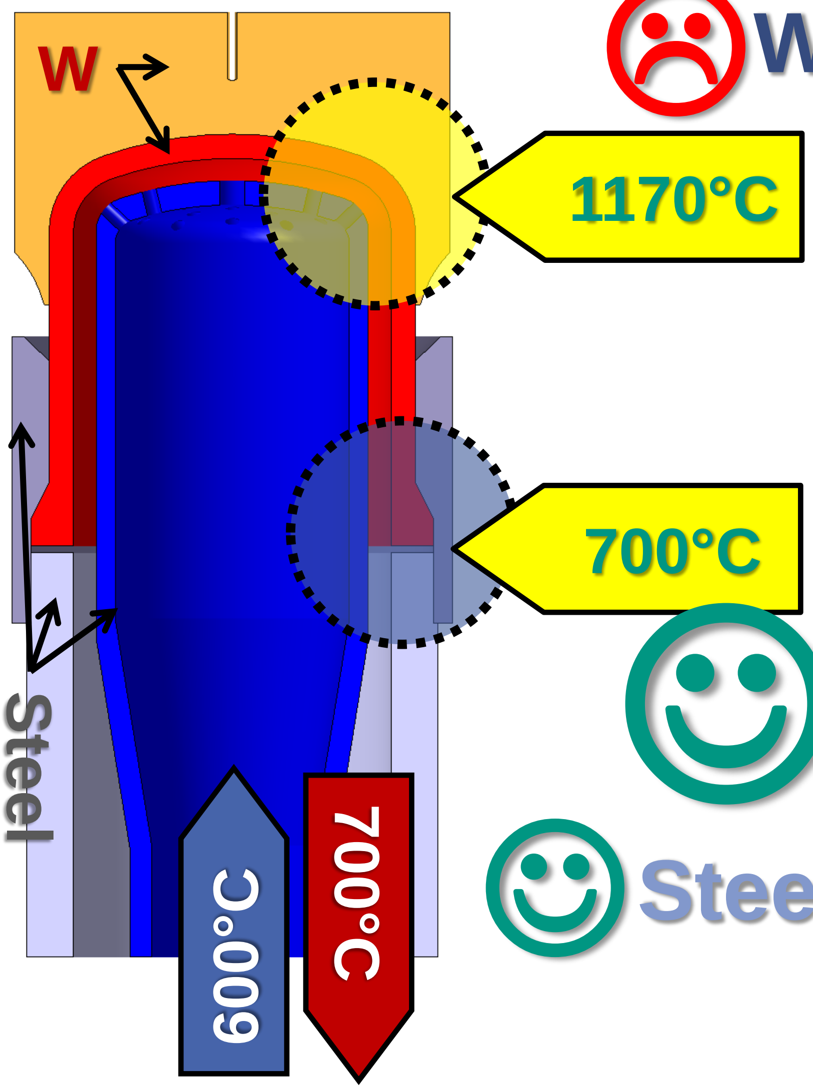


Possible Operating Temp.
T_{op} > 800°C … 1000°C

4

MATERIAL MEETS DESIGN

MATERIALS / DESIGN WINDOW → FINGER



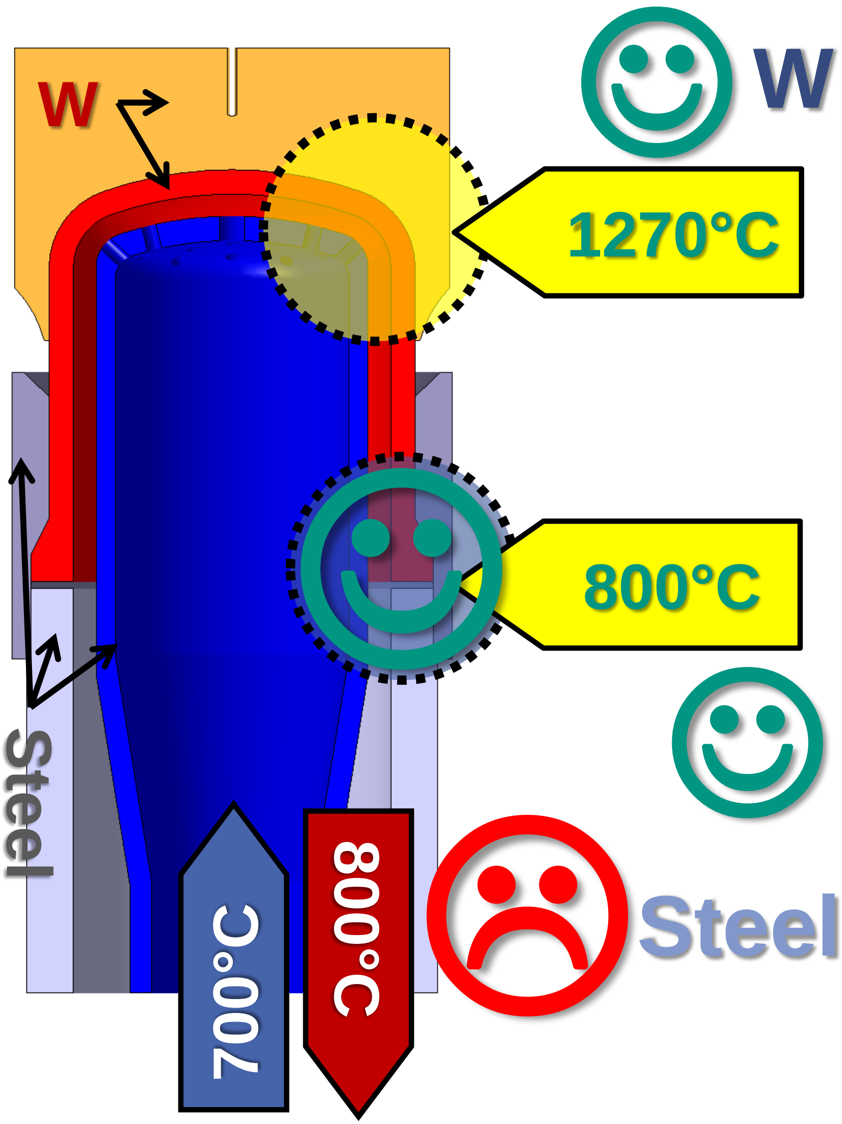
W

Oxidation →	OK
Swelling ~3% →	?
Embrittlement →	OK
Grain Growth →	? (ODS)

Steel

Swelling ~5% →	?
Embrittlement →	NO GO (?)
Brazing (Cu) →	OK (…)
Embrittlement →	OK
Strength, … →	? (ODS)

MATERIALS / DESIGN WINDOW → FINGER



Oxidation	→	OK
Swelling ~3%	→	?
Embrittlement	→	OK
Grain Growth	→	ODS

Swelling ~5%	→	?
Embrittlement	→	OK (tbc)
Brazing (Cu)	→	OK (…)
Embrittlement	→	OK
Strength, …	→	ODS ???

MATERIALS / DESIGN WINDOW → FINGER

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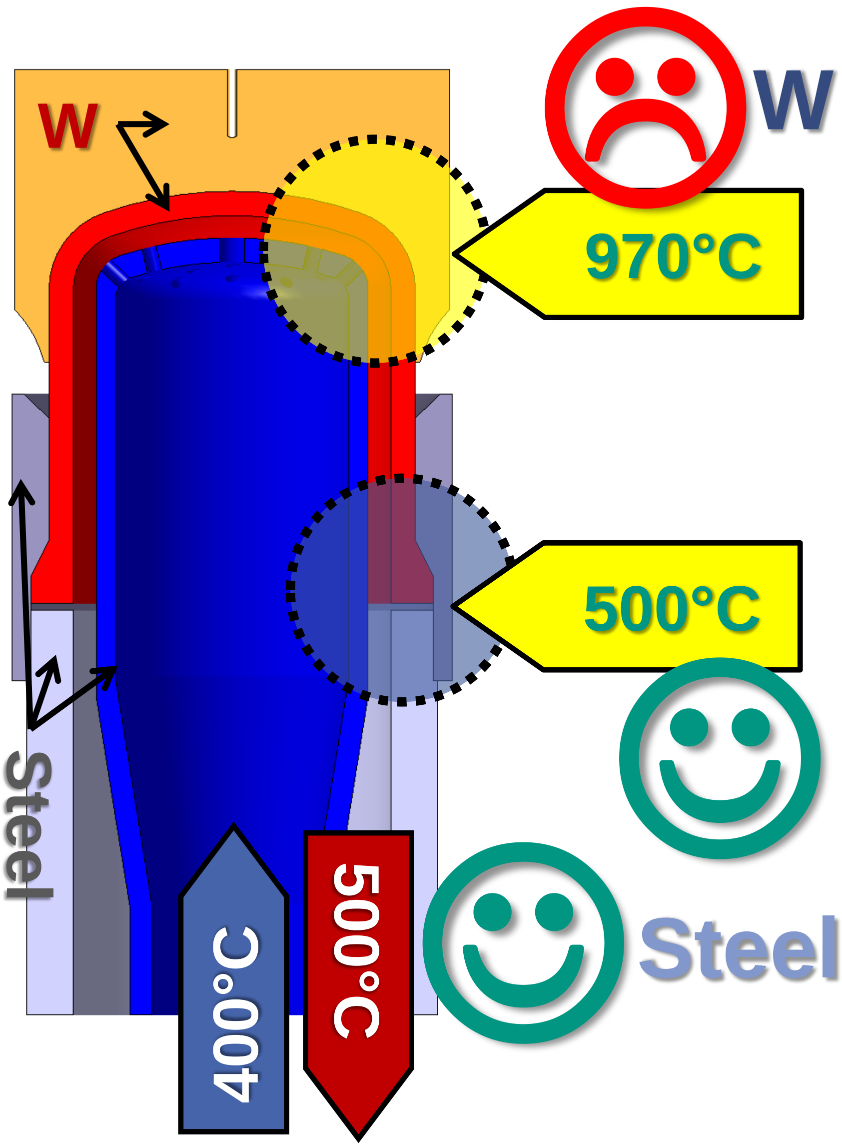
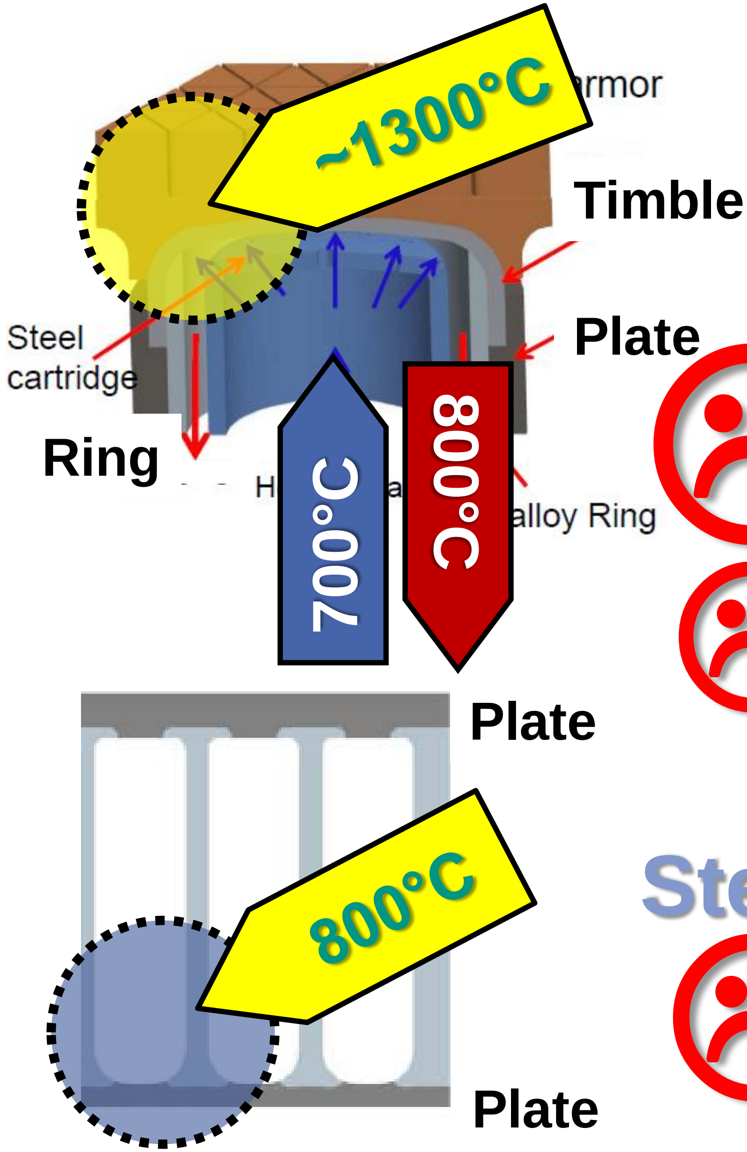


Oxidation	→	OK
Swelling <3%	→	OK (?)
Embrittlement	→	OK
Grain Growth	→	OK
Swelling <2%	→	OK (?)
Embrittlement	→	NO GO
Brazing (Cu)	→	OK (…)
Embrittlement	→	OK
Strength, …	→	OK

Materials / Design Window → Plate



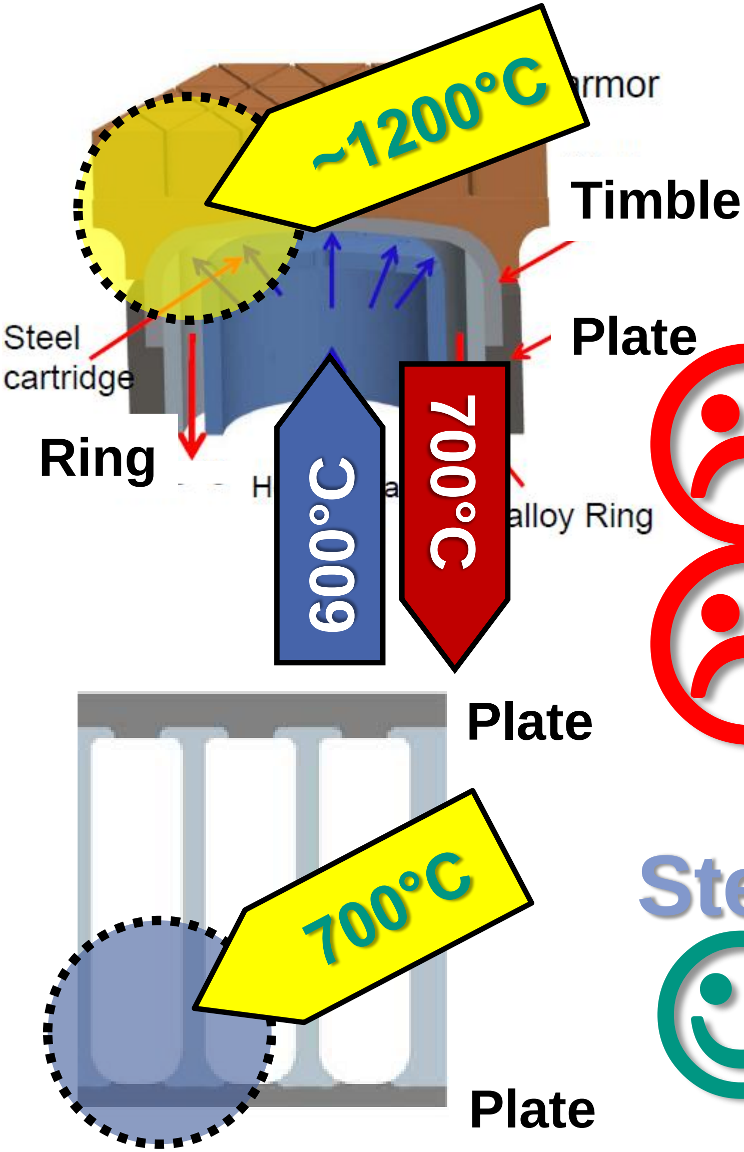
W

Oxidation →	OK
Swelling ~3% →	???
Embrittlement →	OK
Grain Growth →	ODS
Brazing W→W →	Pd, Pt ???
Swelling ~5% →	?????
Embrittlement →	OK (tbc)

Steel

Embrittlement →	OK
Strength, … →	ODS ???

Materials / Design Window → Plate



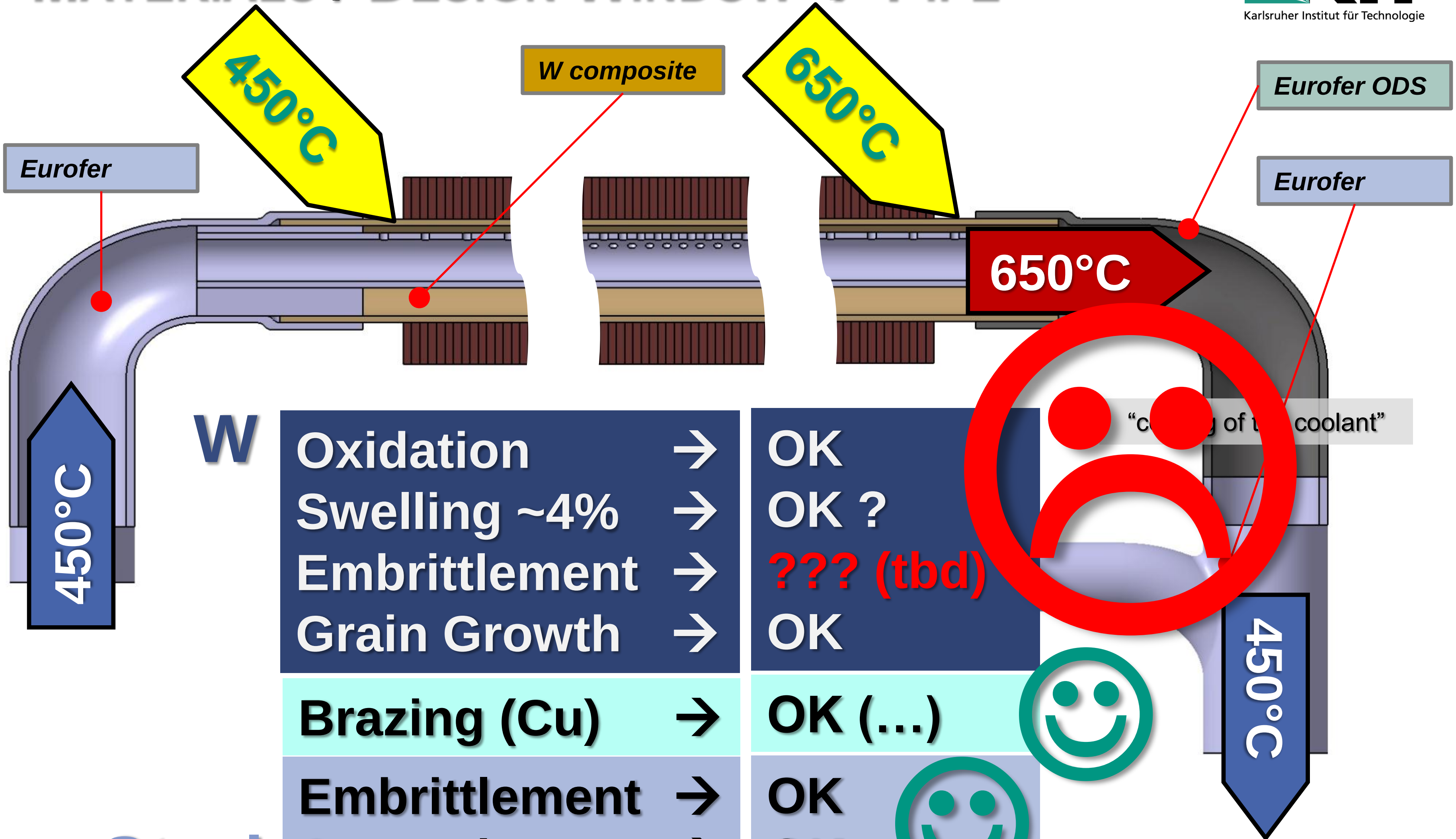
W

Oxidation →	OK
Swelling ~3% →	???
Embrittlement →	OK
Grain Growth →	? (ODS)
Brazing W→W →	Pd, Pt ???
Swelling ~5% →	?????
Embrittlement →	NO GO (?)

Steel

Embrittlement →	OK
Strength, … →	? (ODS)

MATERIALS / DESIGN WINDOW → PIPE



W	Oxidation →	OK
	Swelling ~4% →	OK ?
	Embrittlement →	??? (tbd)
	Grain Growth →	OK
	Brazing (Cu) →	OK (…)
Steel	Embrittlement →	OK
	Strength, … →	OK

5 SUMMARY AND PATH FORWARD

SUMMARY

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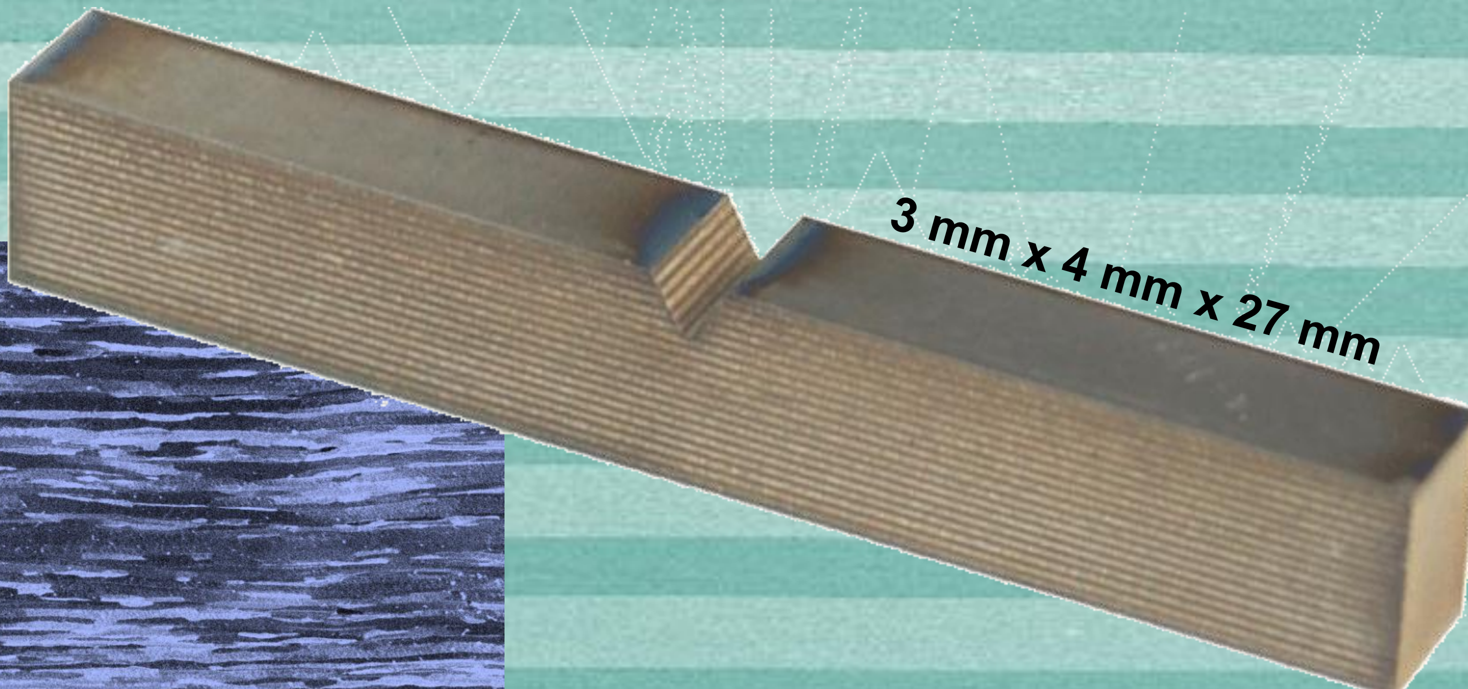
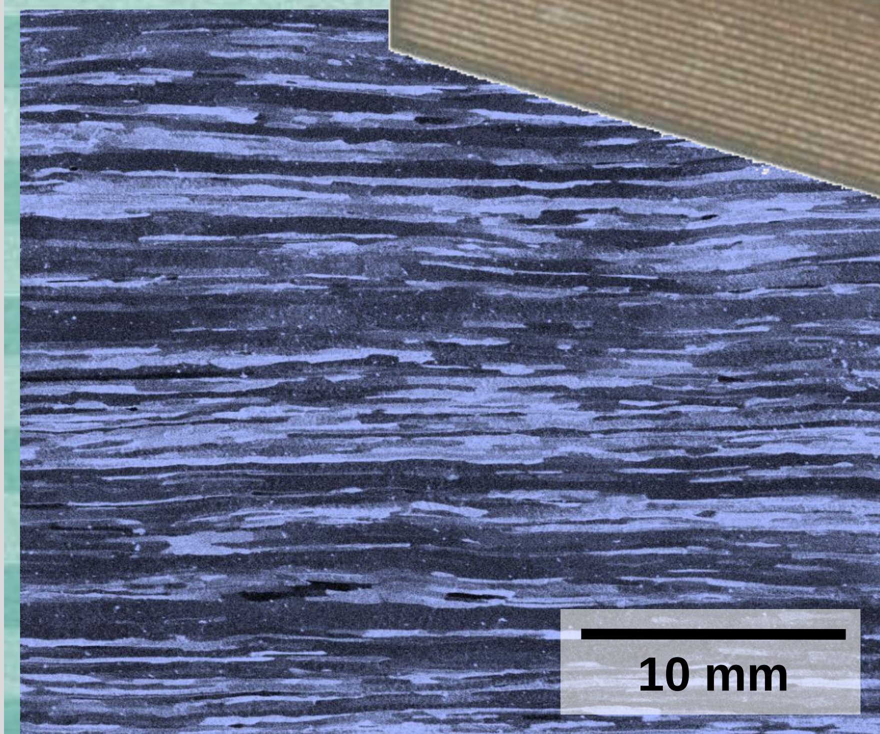
- → Thin plates (<4 mm) of pure W (including small amounts of grain stabilizers, if necessary) are the most suitable sem… d products for structural applications !
- → The microstructure … contour of the accord… ome fabrication pr… be developed) !
- → Co… an be used as brazing material for W-steel joints, but needs additional strengthening by desing !
- → Suitable structural W-W joints are not yet demonstrated and characterized ! → Pt, Pd, …?
- → W irradiation data needed for design (determination of lowest possible operating temperature) !!!

Specific Design Rules for Structural Tungsten Components

Path Forward → Tungsten Alternatives

W Laminate Material





→ J. Reiser, KIT, 2010-2011

PATH FORWARD → TUNGSTEN ALTERNATIVES

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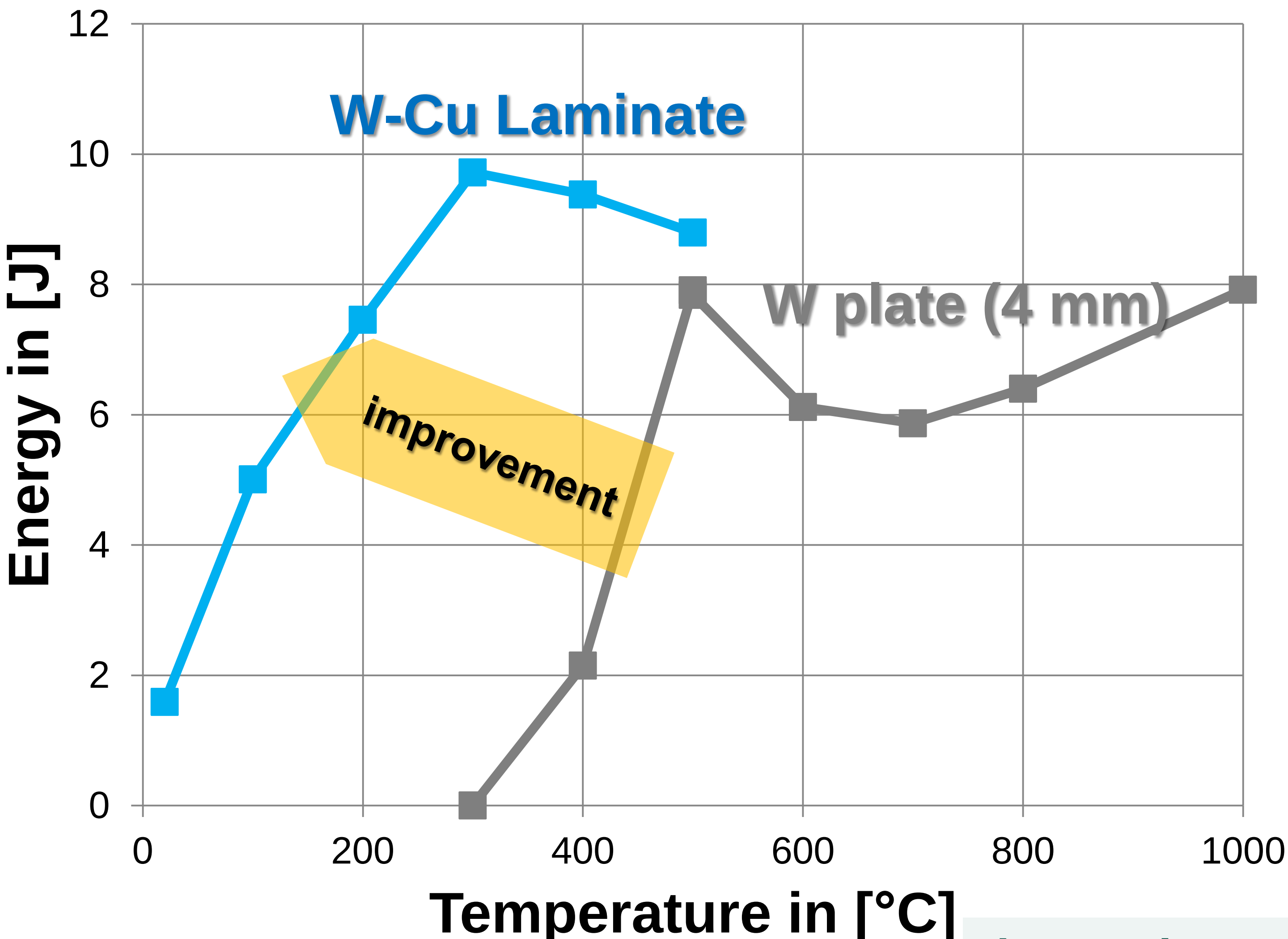
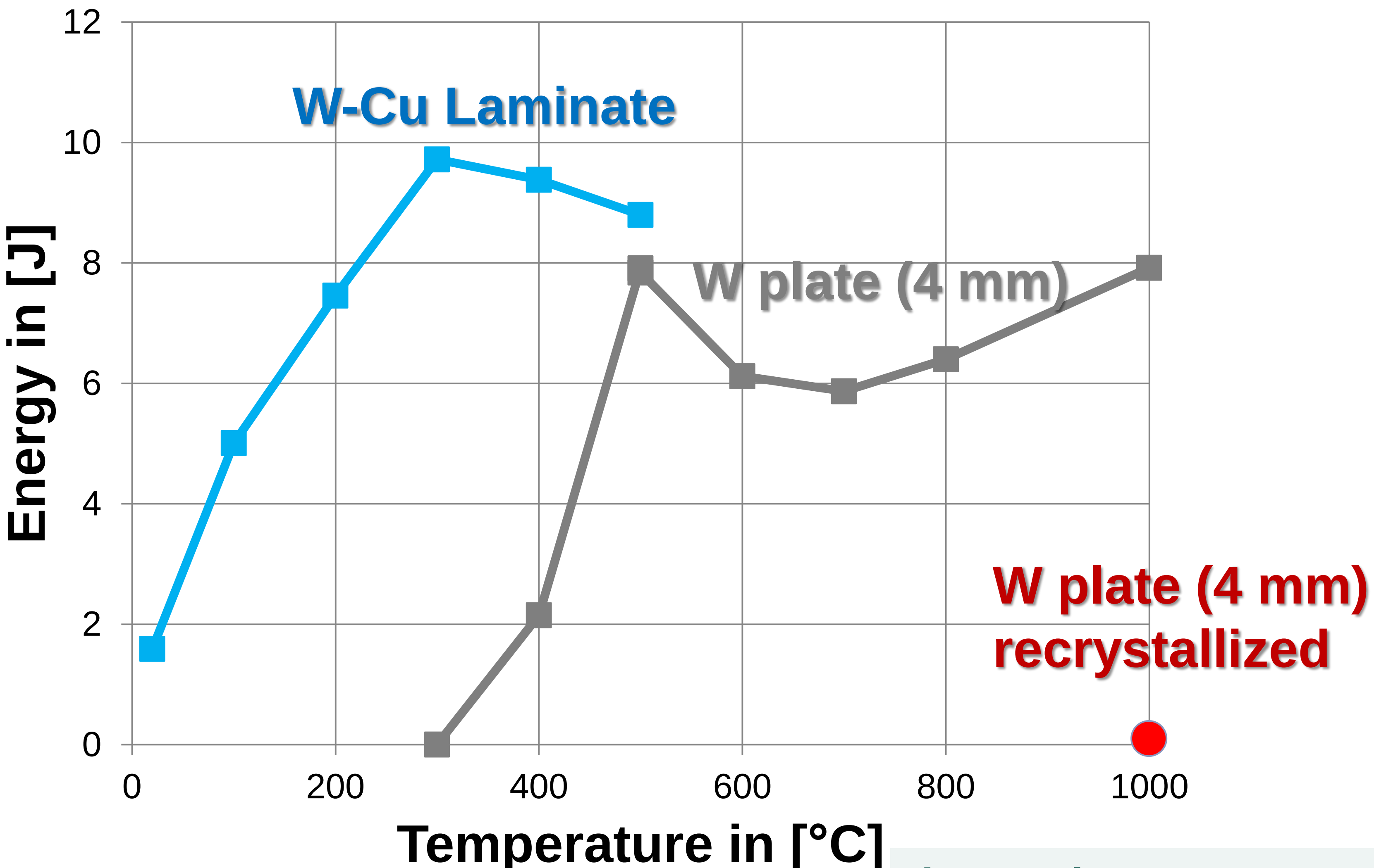


→ J. Reiser, KIT, 2010-2011

PATH FORWARD → TUNGSTEN ALTERNATIVES



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PATH FORWARD → TUNGSTEN ALTERNATIVES

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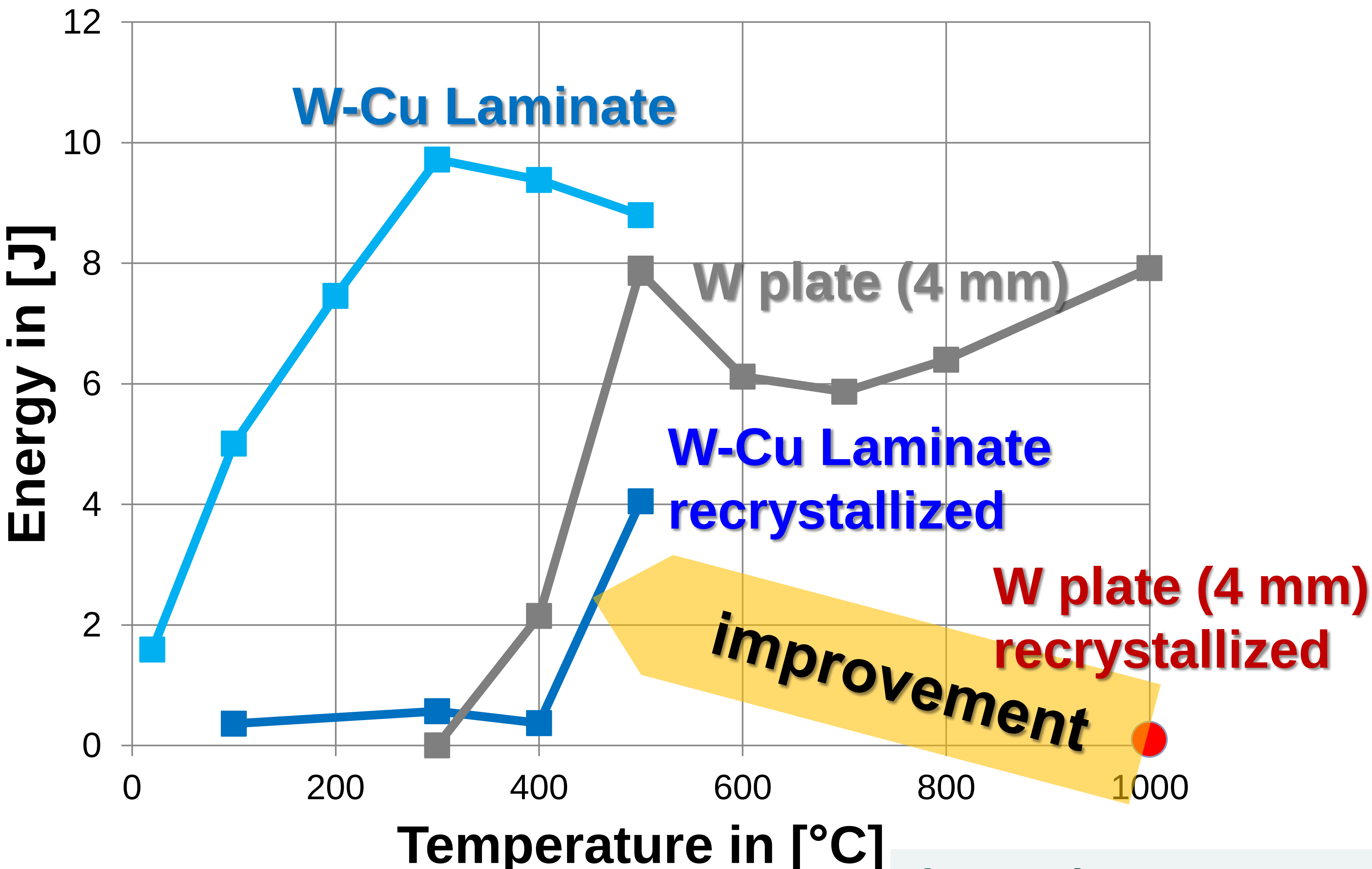

→ J. Reiser, KIT, 2010-2011

PATH FORWARD → TUNGSTEN ALTERNATIVES

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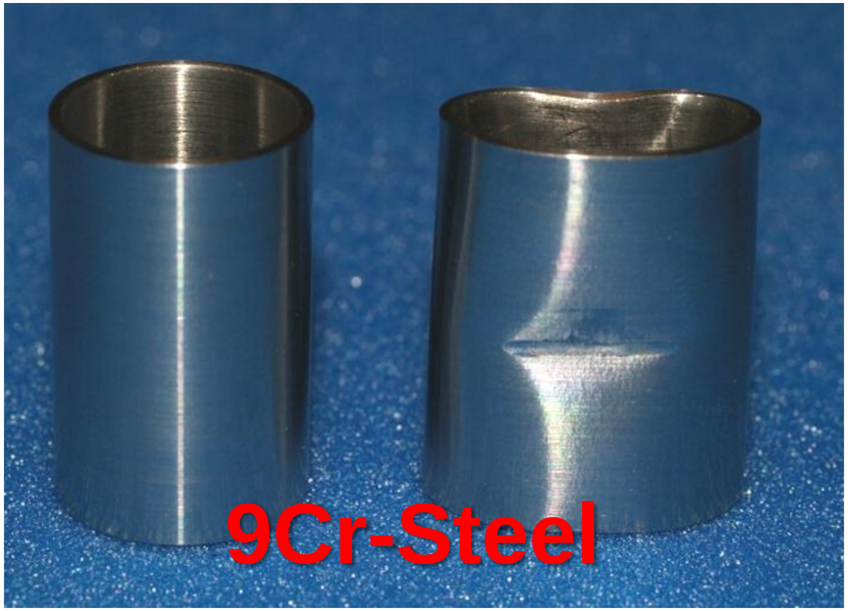

→ J. Reiser, KIT, 2010-2011

THE ULTIMATE DIVERTOR → GENERIC DESIGN