The European Fusion Materials Research Program - Recent Results and Future Strategy

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Outline

- **Introduction**
  - **The EU Breeding Blanket Concepts**
  - **The EU Strategy for Materials Development**
- **EUROFER RAFM (Reduced Activation Ferritic Martensitic) Steel**
  - **The Candidate for TBM and Breeding Blankets in Early DEMO Operation**
- **ODS Steels for High Temperature Demo Application**
- **SiC_f/SiC**
- **Tungsten Alloys**
- **Conclusions**

Introduction:
The EU Breeding Blanket Strategy

'Near term'

The EU DEMO Breeding Blanket program is focused in a first step on two reference breeding blankets:

(A) the Helium-Cooled Lithium-Lead (HCLL) blanket which uses Pb-17Li as both breeder and neutron multiplier,

(B) the Helium-Cooled Pebble-Bed (HCPB) blanket using ceramic pebbles as breeder and beryllium pebbles as neutron multiplier.

TBMs (Test Blanket Modules) of both concepts are to be tested from day one in ITER operation.

"Very long term"

In the EU Power Plant Conceptual Studies (PPCS) two alternative concepts are considered with higher efficiency and higher availability:

(C) The "dual coolant" concept, i.e. a self-cooled Li-Pb blanket with a helium cooled first wall and a helium cooled divertor (called Model C)

utilizes RAFM "type" steels and SiC_f/SiC ceramic composites for insulating flow inserts.

(D) A self-cooled Li-Pb blanket with SiC_f/SiC as structural material.

Introduction: The EU Strategy for Materials Development

Materials Fully Developed and Code Qualified

EUROFER 2
Optimised mechanical properties

ITER-HH | ITER-D T | *DEMO* | *DEMO* | *DEMO*

HCLL & HCPB
EUROFER

HCLL or HCPB
EUROFER

EUROFER3
Low level waste after 100y,
Impurity Control

SiC/SiC as structural material

Self Cooled
SiC/SiC

SiC/SiC as functional material

ODS – Eurofer type

Dual Coolant
EUROFER, ODS, SiC

ODS – Ferritic

Tungsten alloys

High performance divertor
Tungsten, Ferritic ODS

E. Diegele, R. Andreani, R. Lässer, B. van der Schaaf

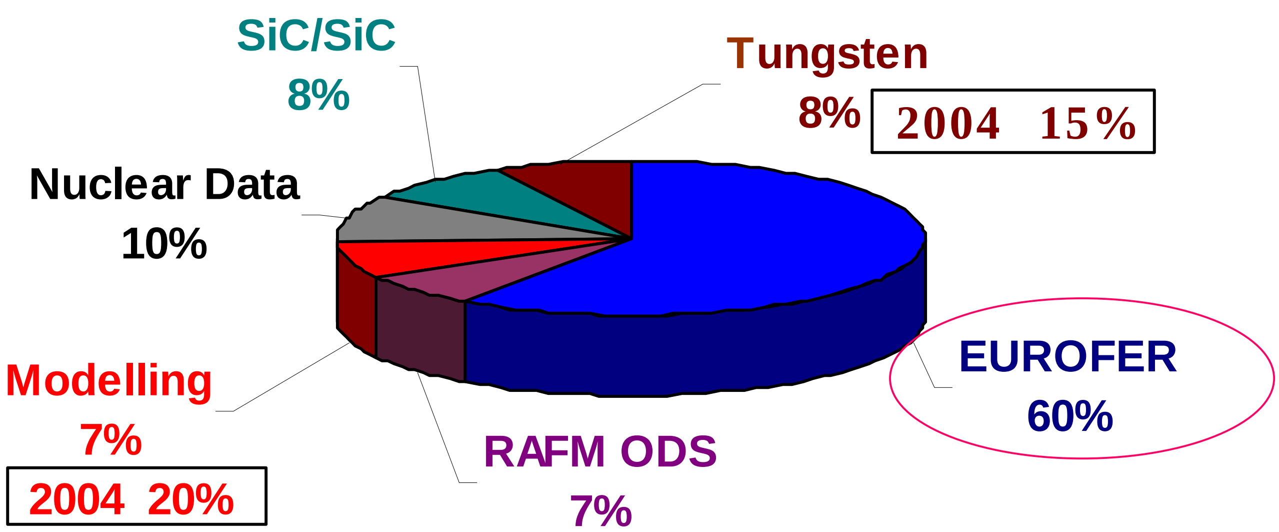
16th ANS TOFE, Madison, 16th September, 2004

The Materials Development Strategy

- **EUROFER, a 9 Cr *WVTa* Reduced Activation Ferritic Martensitic steel**
  - ❑ **The reference structural material for the DEMO blanket concepts.**
  - ❑ **Used in the TBMs to be tested in ITER.**
  - ❑ **The operational temperature window ranges from 300°C to 550°C.**
- **ODS (oxide dispersion strengthening) steels**
  - ❑ **Target is to improve the (creep) strength at high temperatures.**
  - ❑ **The primary candidate structural material for "advanced" breeding blankets, replacing EUROFER.**
  - ❑ **Back bone material for gas-cooled divertor concepts.**
  - ❑ **Increase in the operating temperature up to 650°C for *EUROFER type ODS material* or 750°C nano-composited ferritic steels (NFS or NCF).**
- **SiC_f/SiC ceramic composites**
  - ❑ **Material for the HT operation of "advanced" blankets in the very long-term (self cooled LiPb).**
- **Tungsten alloys**
  - ❑ **The candidate structural material for He divertor concepts (which require extremely high temperatures of 700-1350°C at the 'high heat flux removal units')**

Annual Budget

Materials Development R&D 2002-2004



Budget:	**7 M€/year total**
	2 M€/year EC *plus 5* ***M€/year*** *national programmes*

EUROFER – Critical Issues

- The key issue is the characterisation and understanding of degradation under neutron irradiation. The EU is progressing with irradiations to a wide range of radiation damage.
  - ❑ Lowest level irradiations (up to ~1 dpa) support the analytical study of the build–up of radiation damage in the associated modeling program.
  - ❑ Medium damage level irraditions (~3-15 dpa) to constitute an engineering database for design activities and licensing procedure,
    - ➢ Focusing also on specific manufacturing processes or joining techniques like EB-weld and HIP.
  - ❑ High dose level irradiation experiments (300 specimens) to 70-80 dpa at 320°C–350°C in view DEMO application.
- Technological issues
  - ❑ Compatibility issues with breeding materials:
    - ➢ Flowing LiPb and solid ceramic breeder materials.
  - ❑ Development of reliable joints.
  - ❑ Development of corrosion and permeation barriers.
  - ❑ In support of future licensing procedures high temperature creep-fatigue-interaction rules have to be formulated and validated.

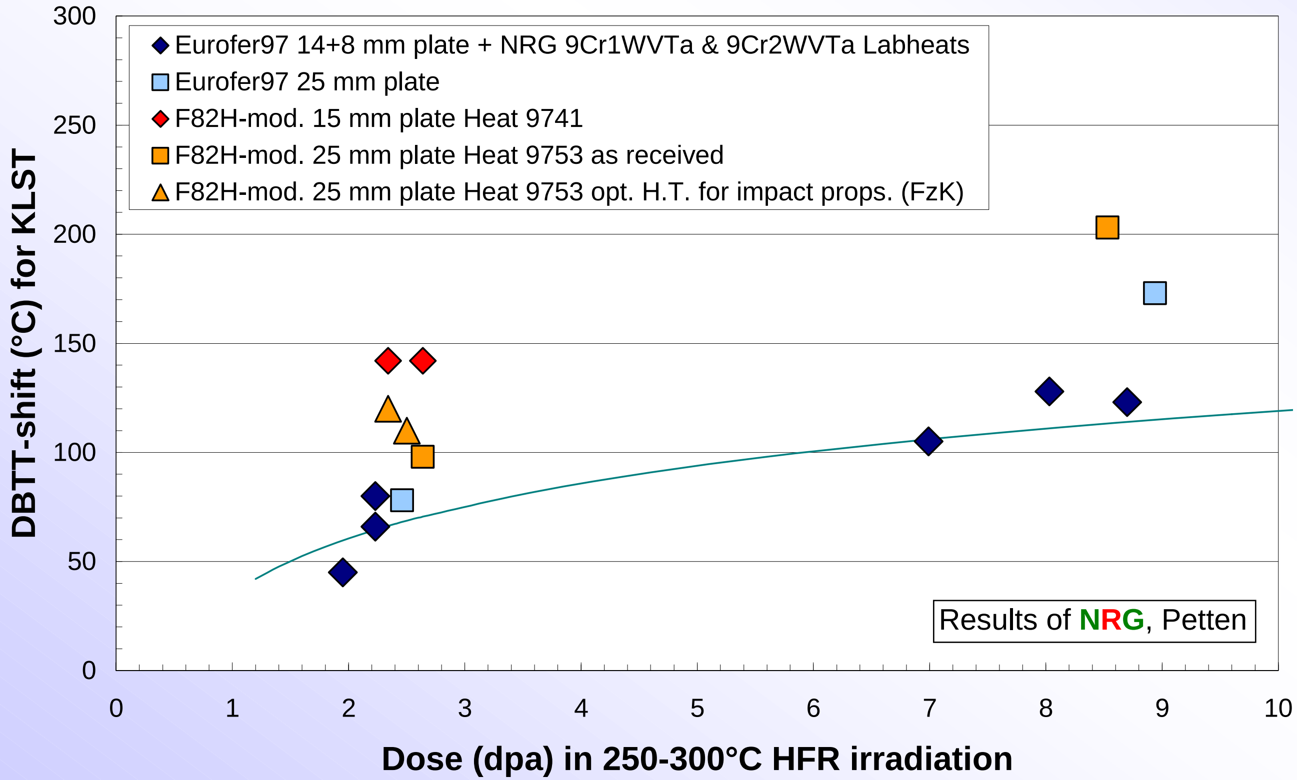
EUROFER - Status and Recent Achievements

- **Full qualification of EUROFER "97 " (first heat)**
  - ❑ **Nearly completed in unirradiated conditions, including also qualification of various joints and welds (solid HIP, EB and TIG welds).**
  - ❑ **The data are assessed and stored in a data base. Data for use by designers and engineers are available in a qualified documents following the standard of Appendix A of the ISDC (ITER Interim Structural Design Criteria)**
  - ❑ **First results (on joints) from irradiation campaigns in HFR and in Mol promising**

- **A second heat of 7.5 t is ready for delivery (partially completed)**
  - ❑ **The material is dedicated to technological issues as for example mock-up fabrication, optimization of joining techniques (at industrial scale) and to analyze any particular TBM design issues.**

Status and Recent Achievements
Example: DBBT of Irradiated EUROFER

Shift of the Ductile-Brittle Transition Temperature as a function of dose –
(T_0 unirradiated is -70 °C)



F82H

EUROFER

Issue: is there a ‚saturation‘ ?

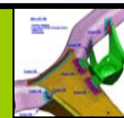
Irradiation campaigns up to 35 - 80 dpa are underway.

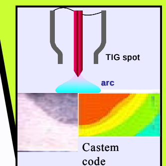
PIE expected in 2005-2008.

2005 | 2006 | 2007 | ?

SIMULATION

- FEA/Design
- Brazing
- Heterog.-welding
- Distorsions
- Stresses



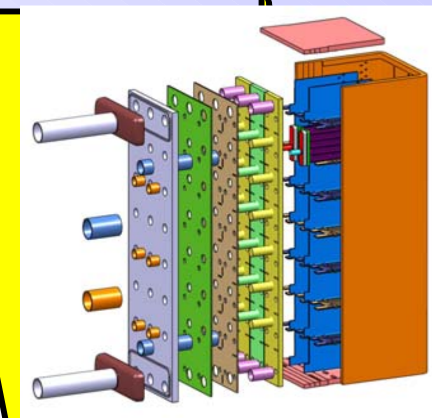


Welding developments

- EUROFER laser welding (8mm) (even both side welding)
- 40 mm EUROFER welding
- Dissimilar tubes welding

?

Final Mock-up

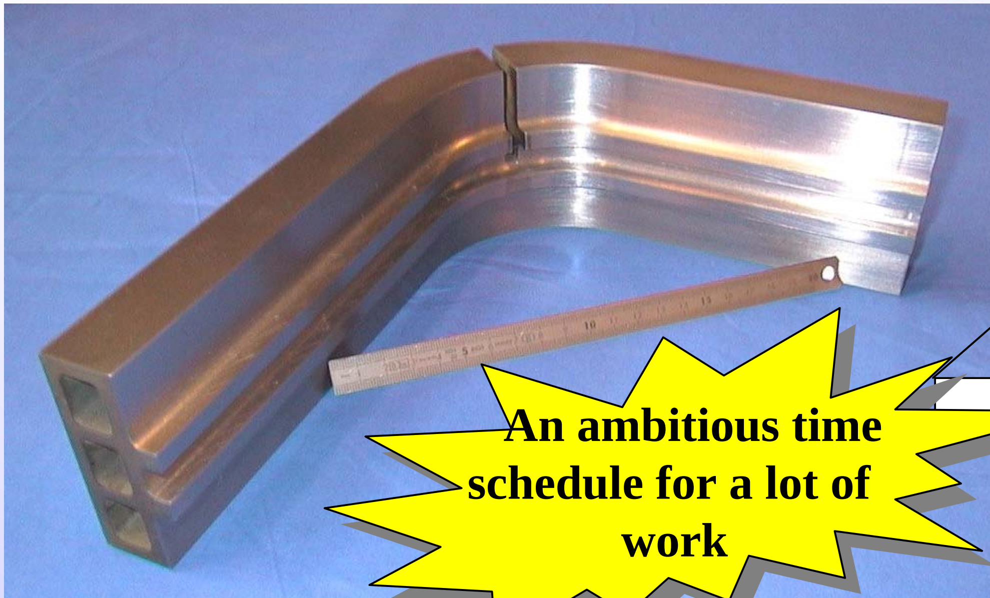


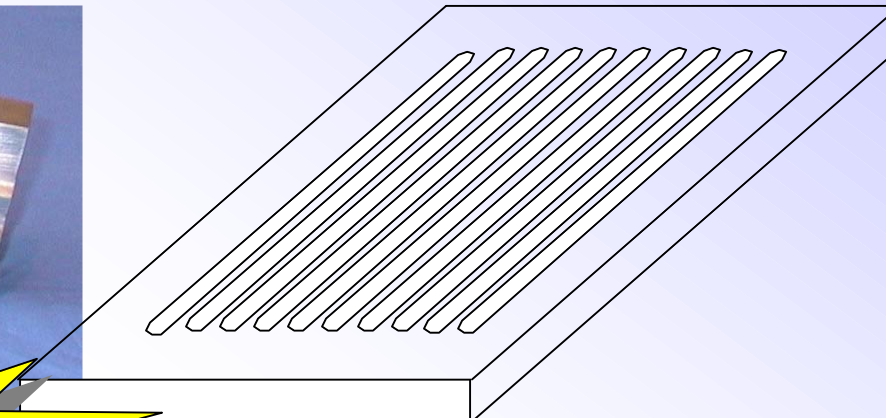
Mock-up's

- Stress and distorstion Demonstrator

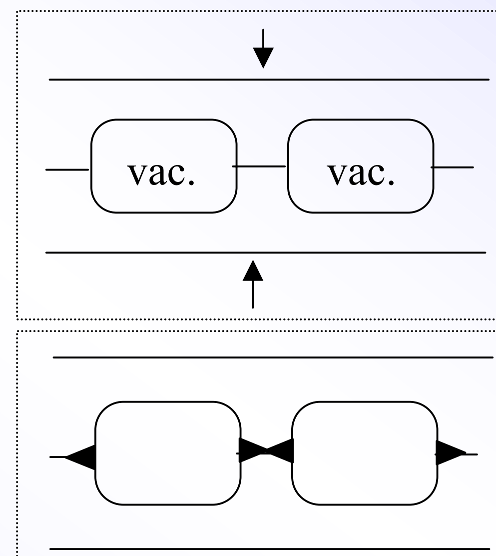
Road map to a qualified TBM mock-up Philippe Aubert, CEA, France

EUROFER – Status and Recent Achievements
HIP Processes for the First Wall





An ambitious time schedule for a lot of work



<u>Basic manufacturing sequence for a First Wall</u>

First, consider the design and split the component into simple parts:

plates (grooved or smooth), tubes.

Currently 9 different options (e.g. diffusion welding, two-step HIP)

EUROFER – Future Work and Development Strategy

Development Strategy

EUROFER-2 (optional)

- **Aiming at further improvement of mechanical properties after irradiation (DBTT), on the basis of the results of the PIE on material irradiated up to 40 dpa, 320-350°C (PIE results available in 2005) and 80 dpa (PIE 2006-2008)**

EUROFER-3

- **Aiming at providing a real low activation material with re-cycling times within 100 years.**
- ***From the EUROFER specification this seems to be technically feasible but has to be proven in industrial heats where the impurity control is extremely difficult to manage unless special clean production lines are available.***

Future Work (about 30 individual tasks in 2005)

- **He/dpa effects: ^{54}Fe enriched EUROFER will be produced in 2004 using small-scale specimens and irradiated in 2005. (The use of Fe-54 leads to higher He production.)**
- **In-pile relaxation experiments on EUROFER**
- **Compatibility: Concentrate on corrosion modelling and its verification in loops with temperature gradients.**
- **Qualification fabrication processes: Welding technologies in support of TBM design) and the qualification of sub-components including joints.**
- **Rules for design, fabrication and inspection: For TBMs licensing high temperature design rules have to be developed and validated – *including development of SSTT.***
- **…**

Irradiation Modeling - Objectives

IFMIF will be the facility needed to provide the basic required engineering data on the structural materials to be used for DEMO construction.

A programme of theoretical investigation focussed on the radiation effects in the EUROFER-RAFM steel under fusion relevant conditions has been launched in 2002 with the

Mission

- **to increase the understanding of irradiation effects on the microstructure with the final goal to quantify the influence of neutron irradiation on mechanical properties.**
- **to establish correlations among the irradiation effects produced in RAFM steel (EUROFER) in different irradiation facilities: fission reactors, fast neutron reactors, spallation sources, IFMIF and fusion devices.**

The programme is understood as a synthesis of modeling, simulations and experimental verification.

Irradiation Modeling – Program

The main activities to be carried out are:

- **Ab-initio inter-atomic binding energy and PKA evaluations;**
- **Molecular Dynamics calculations (displacement cascades, defect accumulation, interaction with impurities and precipitates, transmutations, grain boundaries and dislocations);**
- **Kinetic Monte-Carlo calculation (time and temperature dependent evolution of microstructure and defect accumulation);**
- **Dislocation Dynamics-Finite Element Models (evolution of the plasticity and of the fracture properties).**

Emphasis is given to guide the program towards problems inherent in alloys. In particular the development of Fe-Cr potentials has priority.

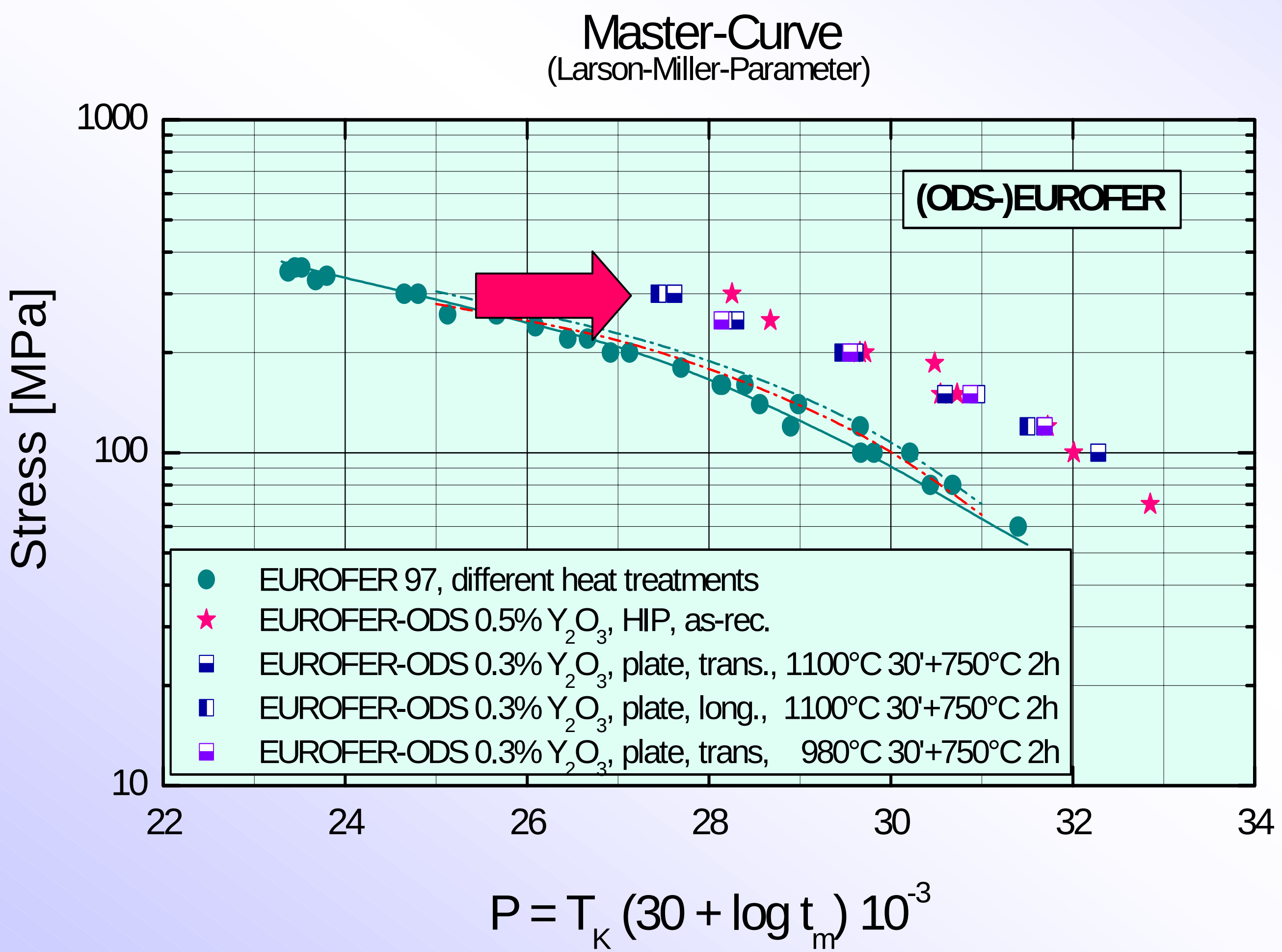
To compare and qualify these models, specific ion irradiation experiments leading to high He and H production at clearly defined temperature and damage levels are foreseen.

ODS Steels – Key Issues and Achievements

The R&D during 2001 to 2004 was focused in producing at laboratory scale reference ODS European steel

- **Research groups at CEA, CRPP and FZK follow different fabrication procedures and combinations of thermal and mechanical treatment.**
- **EUROFER based RAFM-ODS exhibits higher irradiation creep resistance with respect to conventional RAFM steels and could be used at temperature up to 650°C – 700°C .**
- **The main problem is the embrittlement at low temperature (higher DBTT) and reduced fracture toughness compared to conventional steels.**
- **The fabrication processes are still to be optimized, e.g. with respect to mechanical and thermal treatments.**

ODS Steels – Achievements: Creep Strength

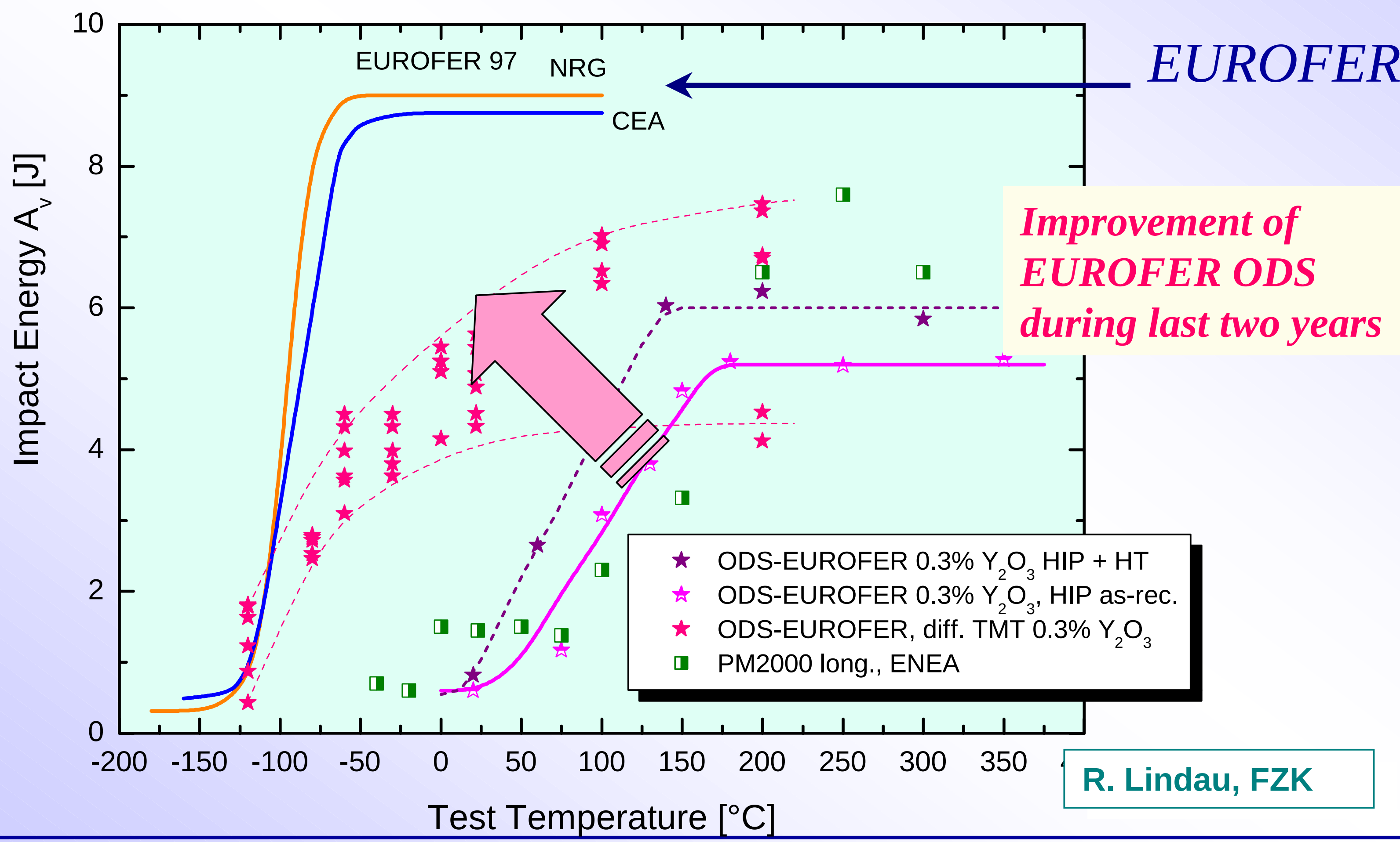


- ***EUROFER***
- ***ODS***
- ***HIPped ODS***

Gain in creep strength

R. Lindau, FZK

ODS Steels –Achievements: Impact Properties



R. Lindau, FZK

ODS Steels – Future Development

EUROFER-ODS

- **A batch of ODS material at industrial scale (about 50 kg) will be produced in 2004 – and characterized in 2005.**

Ferritic ODS steels

- **For higher temperature application, ferritic ODS steels are studied starting this year to meet design requirements for gas-cooled divertors.**

- ***In the frame of the IEA implementing agreement: An exchange of information, exchange of materials and limited investigations of such materials is proposed for the future (discussion started during the last IEA FM meeting, December 2003 in Kyoto).***

It is acknowledged, that protection of property rights might be a concern.

Critical Issues of SiC_f/SiC Ceramic Composites

Primary Basic Issues

- **Nuclear transmutation products,** ***i.e gaseous He and H production due to (n,p) and (n,a) reactions.***
- **Radiation stability of physical properties (in particular thermal conductivity) and mechanical properties.**

The properties depend on the qualities of the fibres, the fabrication process (e.g. fibre preforms and infiltration techniques), fibre coating and in particular on a stable fibre-matrix interphase.

Technological Issues

- **High Porosity and High Permeability (->Coatings),**
- **Fabrication, Joining (Brazing) of 'large components',**
- **Development of guidelines for designing component** ***(inherent brittleness and anisotropy).***

SiC_f/SiC Composites – Status of EU 2D and 3D 'Reference Materials'

Objective: ***manufacturing of composites with advanced fibres, with stoichiometric SiC matrix, improving thermal properties, keeping enough mechanical strength, explore alternative manufacturing routes in addition to CVI (Chemical Vapor Infiltration).***

2D materials have been manufactured with 30 and 40% fibre volumetric percentage.

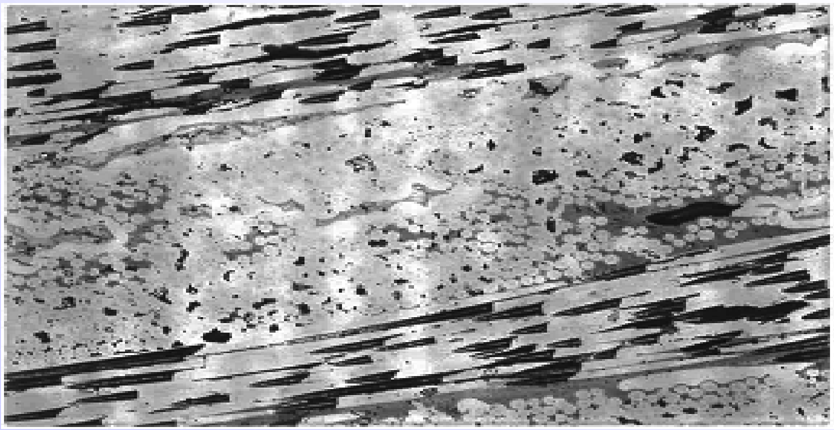
Reference material: ***Eight 2D-plates, 200x200x3,5 mm^3 were SiC CVI- infiltrated and CVD-coated without PIP (Polymer Impregnation and Pyrolysis).***

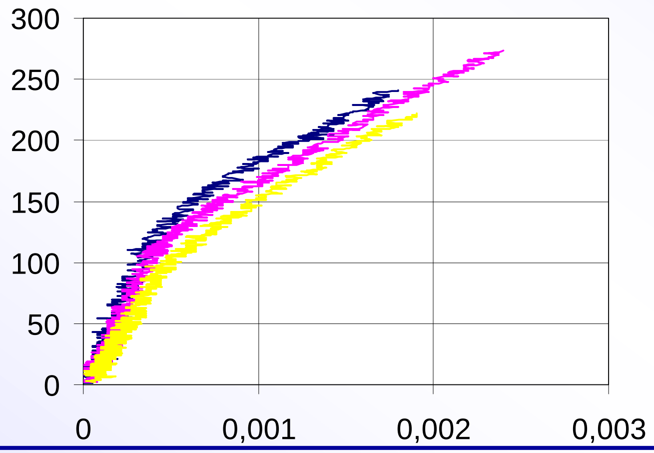
- **The 2D composites mechanical properties satisfy the specifications *(with some minor exceptions).***
- **30% fibre composites exhibited lower performances compared to 40% composites. Tensile strengths up to 270 MPa were obtained.**
- **PIP process on CVI composites, aimed at improving density and thermal-mechanical properties, showed no substantial improvement.**

SiC_f/SiC Composites – Status of EU 2D and 3D 'Reference Materials' – Cont.

Japan and the US developed material with significantly better mechanical and physical properties. The EU approach is unique in the sense that it aims for fabrication at 'industrial scale'. (Companies involved are MAN Technologie, Germany and FN, Italy).

3D preforms were first manufactured at Techniweave Company (USA) (40% volumetric fibre, T-type texture with few-% fibre through the thickness). However, the CVI densification on these preforms *was not yet successful*. New preforms (from US and Japanese companies) have been ordered and are going to be infiltrated (Aug. 2004).





SiC_f/SiC Strategy - International Collaboration

Activities

- **Japan, to develop and provide advanced SiC_f/SiC composites and in particular those based on the LPS/NITE *(Liquid Phase Sint/Nano-infiltration and transient eutectic-phase)* process.**
- **EU, to provide JA with SiC_f/SiC composite samples produced by industry.**
- **Japan, to characterise the samples provided by EU.**
- **EU, to characterise the SiC_f/SiC composites after neutron irradiation at 600-1000°C,**
- **EU, to test their compatibility vs. Pb17Li and to assess their joinability.**

Time schedule

- **Duration of JA-EU collaboration: 2003-2006**
- **Material supply: 2003 (JA), 2004 (EU)**
- **Irradiation: October 2005**

(Information as presented by B. Riccardi)

SiC_f/SiC – Low Activation Brazing

Brazing technique uses eutectic compositions of silicon and titanium and chromium (Si-16Ti, Si-18Cr (at%) eutectic, melting temperature 1330°C and 1305°C).

- **Advantage of lower melting point; Less composite fibre-interface degradation.**

Characteristics of joints obtained

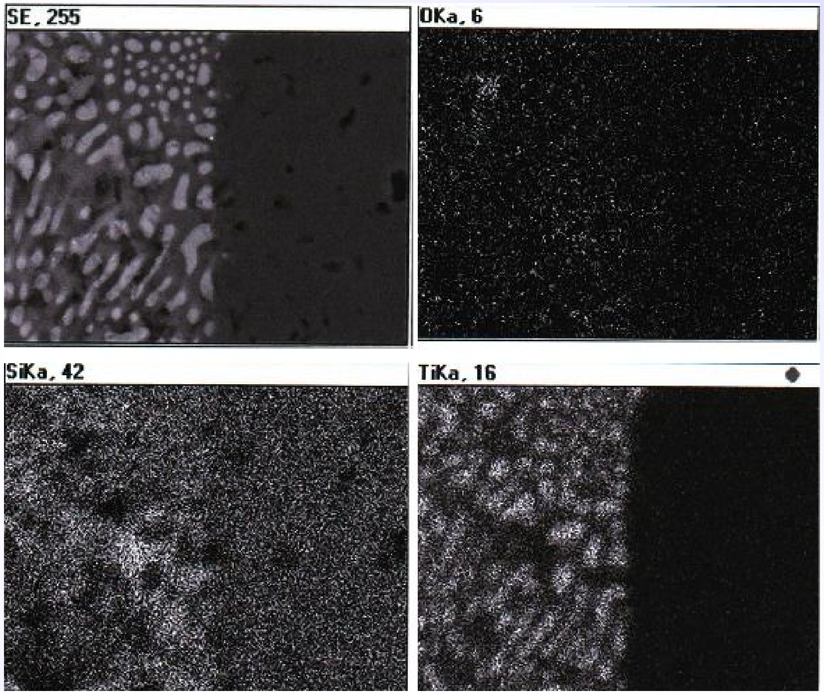
- **High operating temperature,**
- **Reduced residual stresses,**
- **High shear strength (70-80 MPa),**
- **Really Low Activation.**

Disadvantage

Surface preparation and tight tolerances requested.

Critical issue

Stability of the joints under irradiation.



B Riccardi, ENEA, in collaboration with University Cluj-Napoca, Romania and MPI Halle, Germany

SiC_f/SiC Strategy – Future Activities

***Compatibility* with Pb-17Li at temperatures 800-1000°C under flowing conditions.**

***Development* of 'New' Material(s)**

- **With advanced/alternatives manufacturing concepts.**
- **With low through-tickness thermal conductivity and high 2 D in-plane strength for the use as *functional material* (insulation in dual coolant concept).**

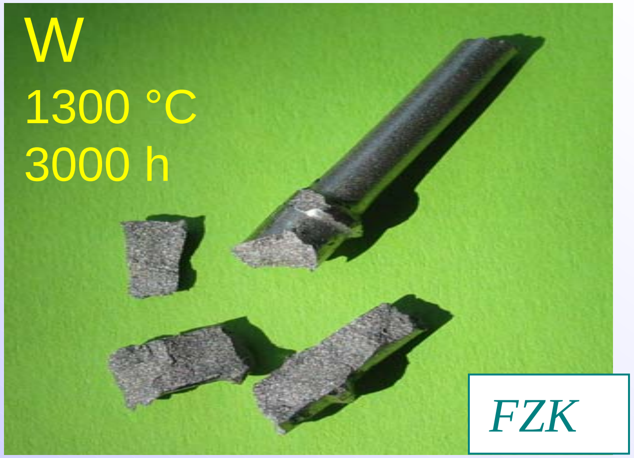
Modeling

- **Micro-mechanical modeling using multi-scale localisation/homogenisation approaches *with the final aim to calculate the thermo-mechanical properties of large SiC_f/SiC structures*.**
- **Numerical modeling of mechanism of radiation damage under fusion relevant neutron spectra in SiC-crystals *(atomic-scale modeling of displacement cascades in monolithic SiC in presence of extended defects such as dislocations and grain boundaries)*.**

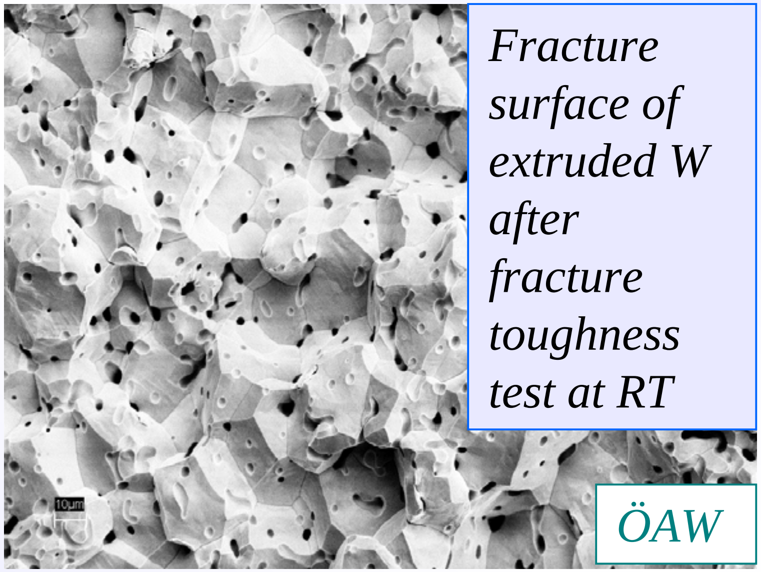
Tungsten Alloys – Issues: a Long List of Major Problems

- **The Low Ductility (deformability)**
  - Sensitivity to production history, alloying elements, exposure to temperature (re-crystallisation), loading direction, irradiation dose and irradiation temperature.
  - Only few systematic studies.
- **Inherent Low Fracture Toughness at Low Temperature**
  - High DBTT,
  - Shift in DBTT under neutron irradiations is not well known.

W specimen after creep test at 1300°C



FZK



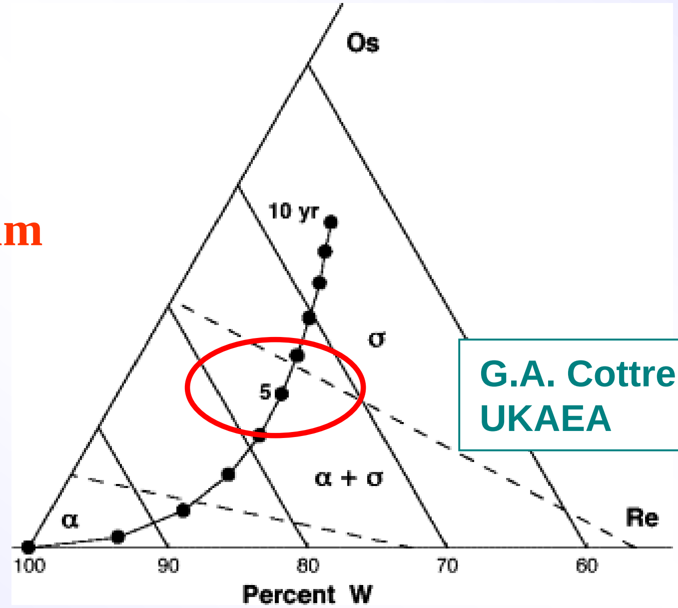
Fracture surface of extruded W after fracture toughness test at RT

ÖAW

Tungsten Alloys – Issues (continued)

- **No experience in pressurized large components at industrial scale with the high reliability requirements set-up in fusion power plants.**
- **Concepts, guidance and rules on damage-tolerant design.**
- **Irradiation effects**
  - **The knowledge (degradation of mechanical properties, shift in DBTT, swelling) is limited.**

Transmutations are a key problem:
Considerable amount of Osmium and Rhenium are produced in service causing the formation of brittle σ phase.



G.A. Cottrell, UKAEA

Tungsten Development Strategy - SPD

W based materials

fracture toughness tests above and below DBTT
(effect of production route)

severe plastic deformation
(SPD)

characterization of the **microstructural evolution** during SPD

thermal stability

mechanical &
fracture mechanical
testing of SPD material

Materials investigated:

Tungsten alloys (1% La_2O_3) or K-doped (called WVM)

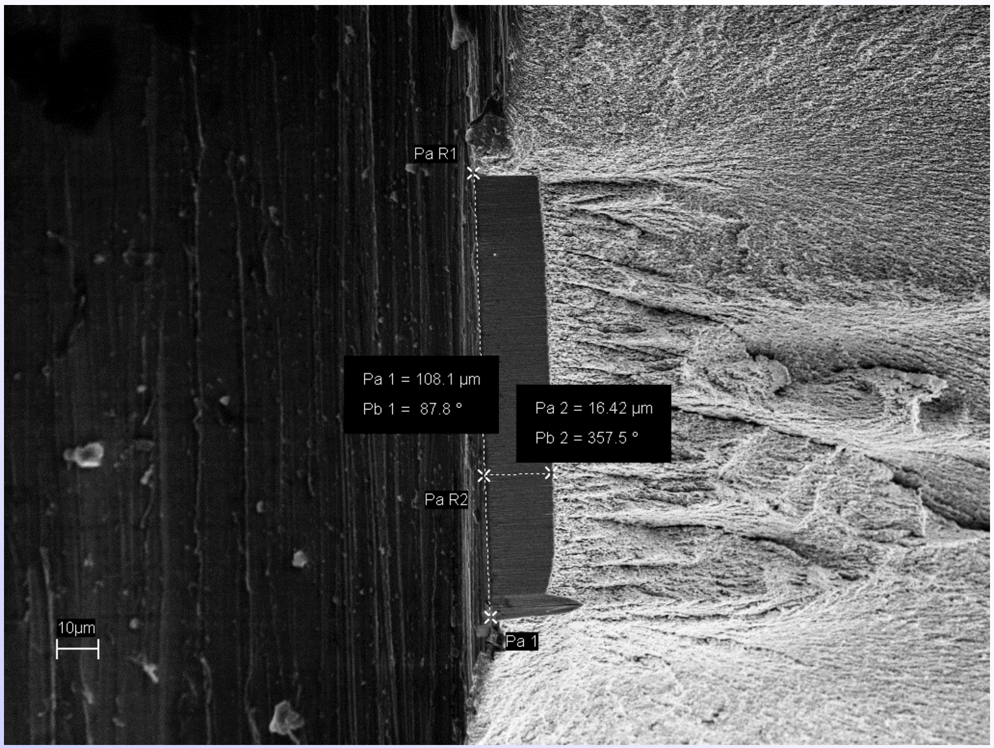
W-5%Re and W-25%Re no longer considered

(poor recrystallization behaviour)

Pure tungsten for comparison

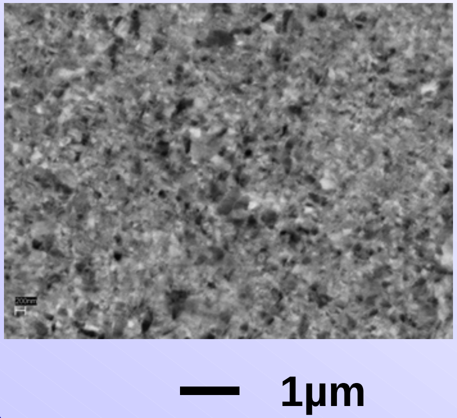
The Good News of SPD (HPT) Deformed Tungsten

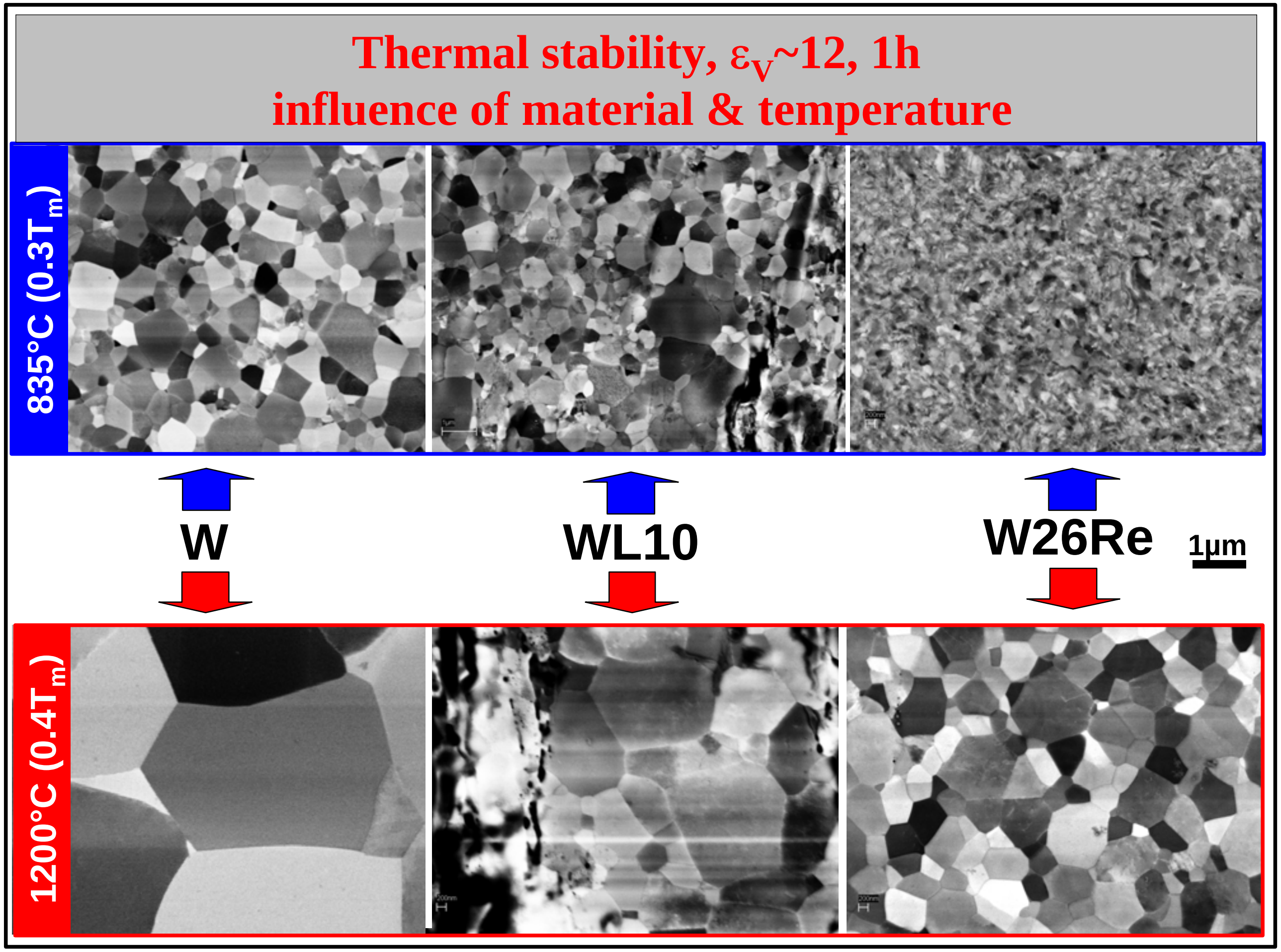
- High Pressure Torsion leads to significant improvement of ductility at room temperature. Deformed tungsten (Total elongation e=20) shows a fracture toughness of about 40-45 MPa √m compared to 6-7 MPa √m of sintered material.



HOWEVER ...

BUT… Lacks of Thermal Stability





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Tungsten - (*near term*) Future Development

In the next future the following activities are considered to have priority:

- **Investigations to improve ductility and the radiation resistance of W alloys. Emphasis will be put on nano-structured materials, with low interstitial content (*produced by 'severe plastic deformation'*). *(The major issue is the thermal stability of the small grains).***
- **Medium and high temperature irradiation tests (600/1000°C) will be performed up to 5 dpa in the OSIRIS reactor, CEA, France, starting October 2005.**
- **Build a preliminary fusion relevant database to support divertor design activities.**
- **Perform missing mechanical characterization (e.g. creep, fracture).**

☞ **Experiments and modeling to increase the basic scientific understanding of the fracture process from RT to elevated temperatures are essential.**

☞ **Fundamental research to increase the understanding of irradiation effects on the microstructure (with the final goal to quantify the influence of neutron irradiation on mechanical properties).**

Results will give ideas how to cope with a material of reduced ductility.

❑ **Build up knowledge in EU research institutes and companies.**

Conclusions

The main objective of the European Long Term technology R&D program is to develop and test materials and fabrication technologies required for the in-vessel components of "DEMO" and beyond.

- **First priority is given to materials for TBMs to be tested in ITER.**
  - **RAFM steel (EUROFER):** ***the program conducted is very broad including various technological issues and is progressing on a good way which gives confidence to meet, at least, TBM requirements.***
- **Increasing effort is dedicated to the development of ODS-RAFM steel and SiC_f/SiC ceramic composite as well as tungsten alloys for high temperature applications.**
  - **EUROFER ODS materials:** ***Good progress, approach is promising (to be confirmed after irradiation).***
  - **SiC/SiC composites:** ***Promising new materials – (and techniques) - with favourable properties (to be confirmed after irradiation).***
  - **Tungsten alloys:** ***More questions than answers. A long way to go.***

The development of SiC/SiC and (even more) Tungsten alloys has high risks but a potential high pay off.