Hungarian Academy of Sciences
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Structural materials for Fusion and Generation IV Fission Reactors

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Content

Summary of the parameters of the innovative nuclear systems

	SFR	GFR	LFR/ADS	VHTR	SCWR	MSR	Fusion	
Coolant T (°C)	Liquid Na few bars	He, 70 bars 480-850	Lead alloys 550-800	He, 70 bars 600-1000	Water 280-550 24 MPa	Molten salt 500-720	He, 80 bars 300-480	Pb-17Li 480-700
Core Structures	Wrapper F/M steels Cladding AFMA F/M ODS	Fuel & core structures SiCf-SiC composite	Target, Window Cladding F/M steels ODS	Core Graphite Control rods C/C SiC/SiC	Cladding & core structures Ni based Alloys & F/M steels	Core structure Graphite Hastelloy	First wall Blanket F/M steels ODS SiCf-SiC	
Temp. °C	390-700	600-1200	350-480	600-1600	350-620	700-800	500-625	
Dose	Cladding 200 dpa	60/90 dpa	Cladding ~100 dpa ADS/Target ~100 dpa	7/25 dpa			~ 100 dpa + 10 ppmHe/dpa + 45 ppmH/dpa	
Other components		IHX or turbine Ni alloys		IHX or turbine Ni alloys				

F.Carré, NEA SMINS, 2007

Materials requirements

- **Mechanical and thermophysical properties:**
  - **acceptable creep resistance, tensile strength, fracture toughness after ageing**
- **Chemical compatibility, corrosion resistance**
- **Material availability, cost of fabrication, joining technology**
- **Safety, waste disposal aspects**
  - **Reduced activation materials**
- **Nuclear properties (neutron economy for claddings)**

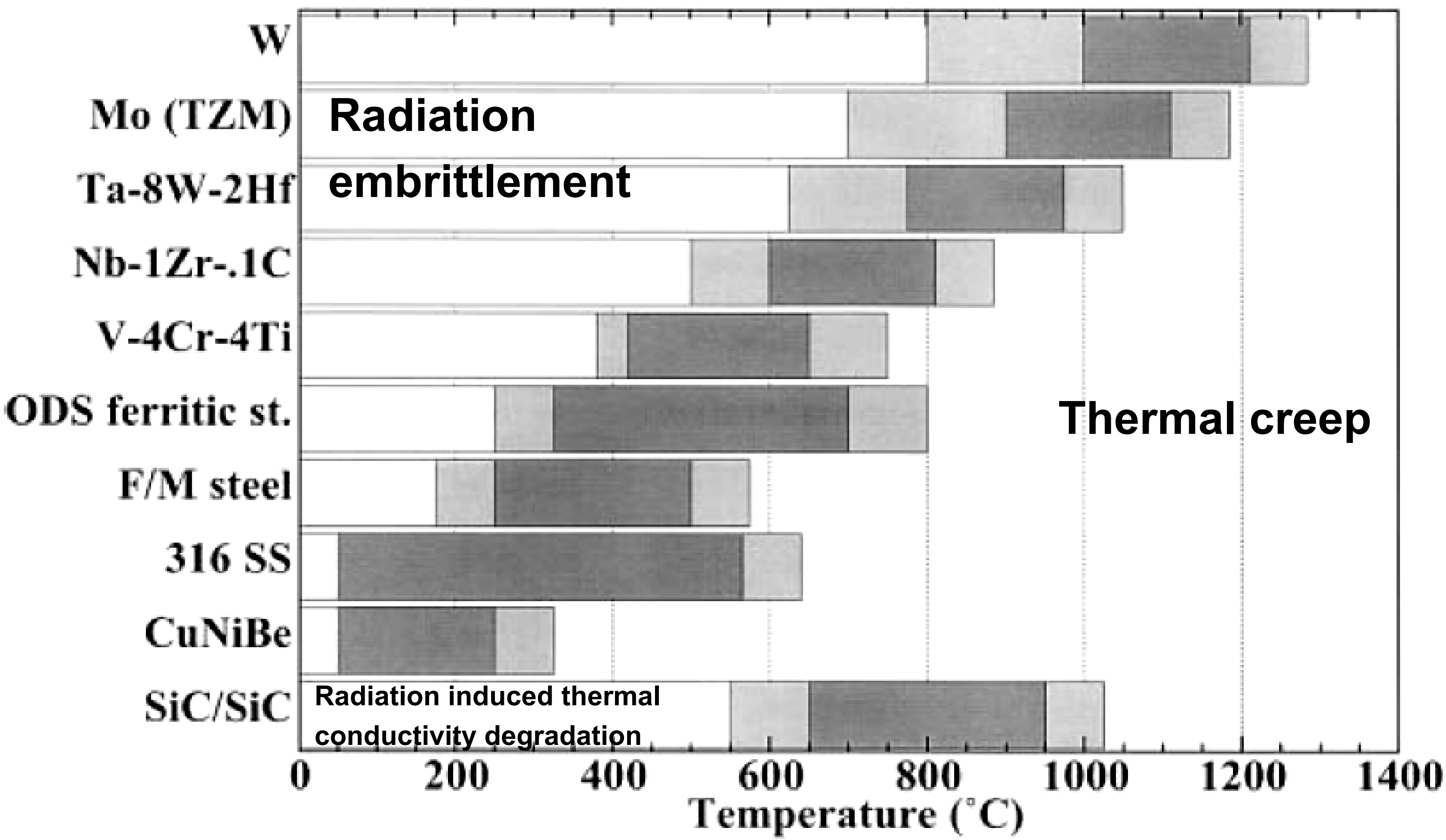
Classification of the materials according to the maximum allowable temperature

- **Low temperature (300-600°C) range: austenitic steels, ferritic / martensitic steels, and ODS alloys**

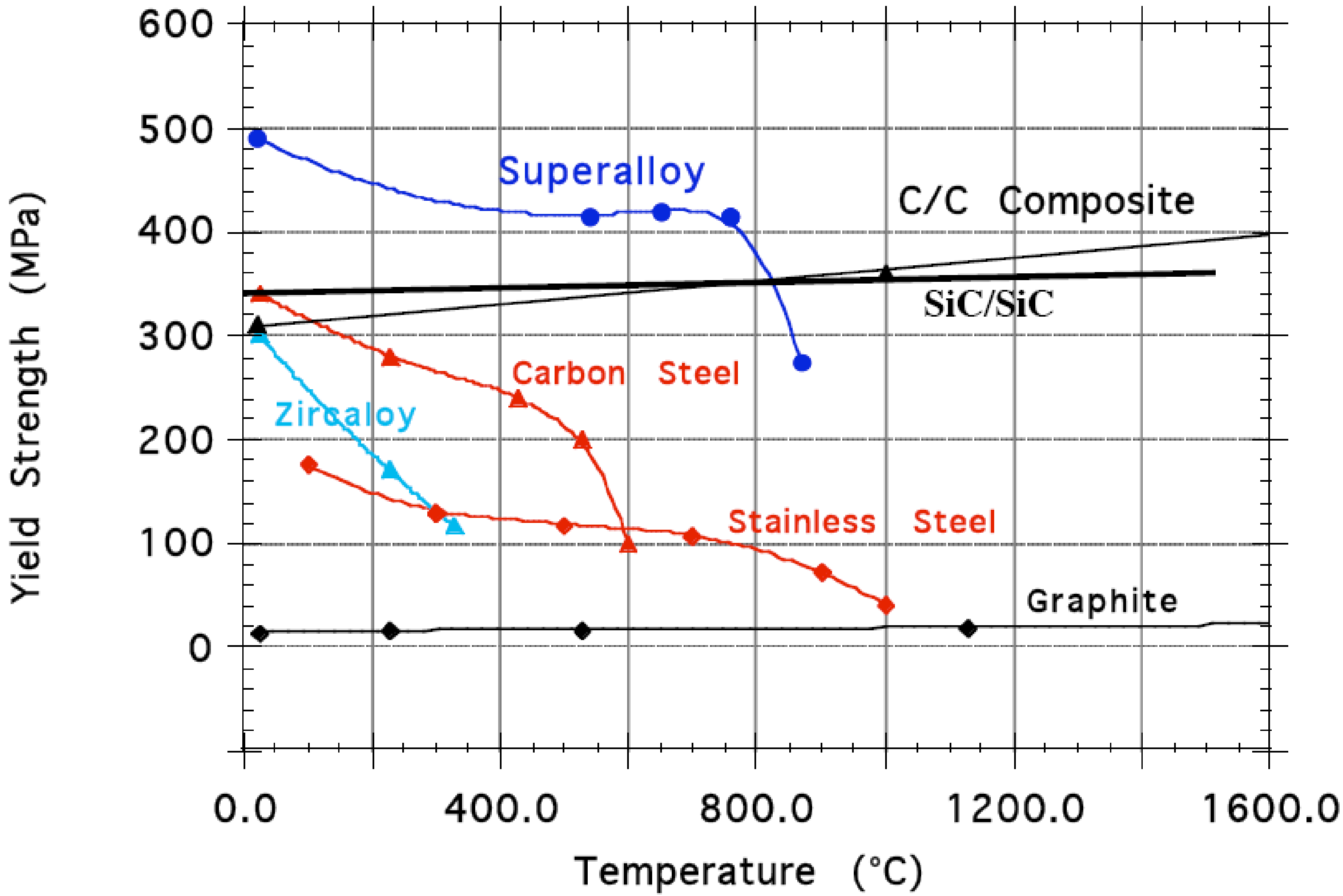
- **Intermediate temperature range (600-800°C): traditional and modified austenitic steels, ODS F/M steels, iron – or nickel-based super-alloys, refractory alloys**

- **High temperature (> 800°C) range: Ni- based alloys, advanced ODS and refractory based systems, ceramics (silicon carbide composites), graphite and carbon-carbon composite**

Operating temperature windows



Zinkle, Ghoniem, Fusion Eng. and Design, 2000



Compiled by L. Snead, ORNL

Metallurgy basics: Improving the strength of steels

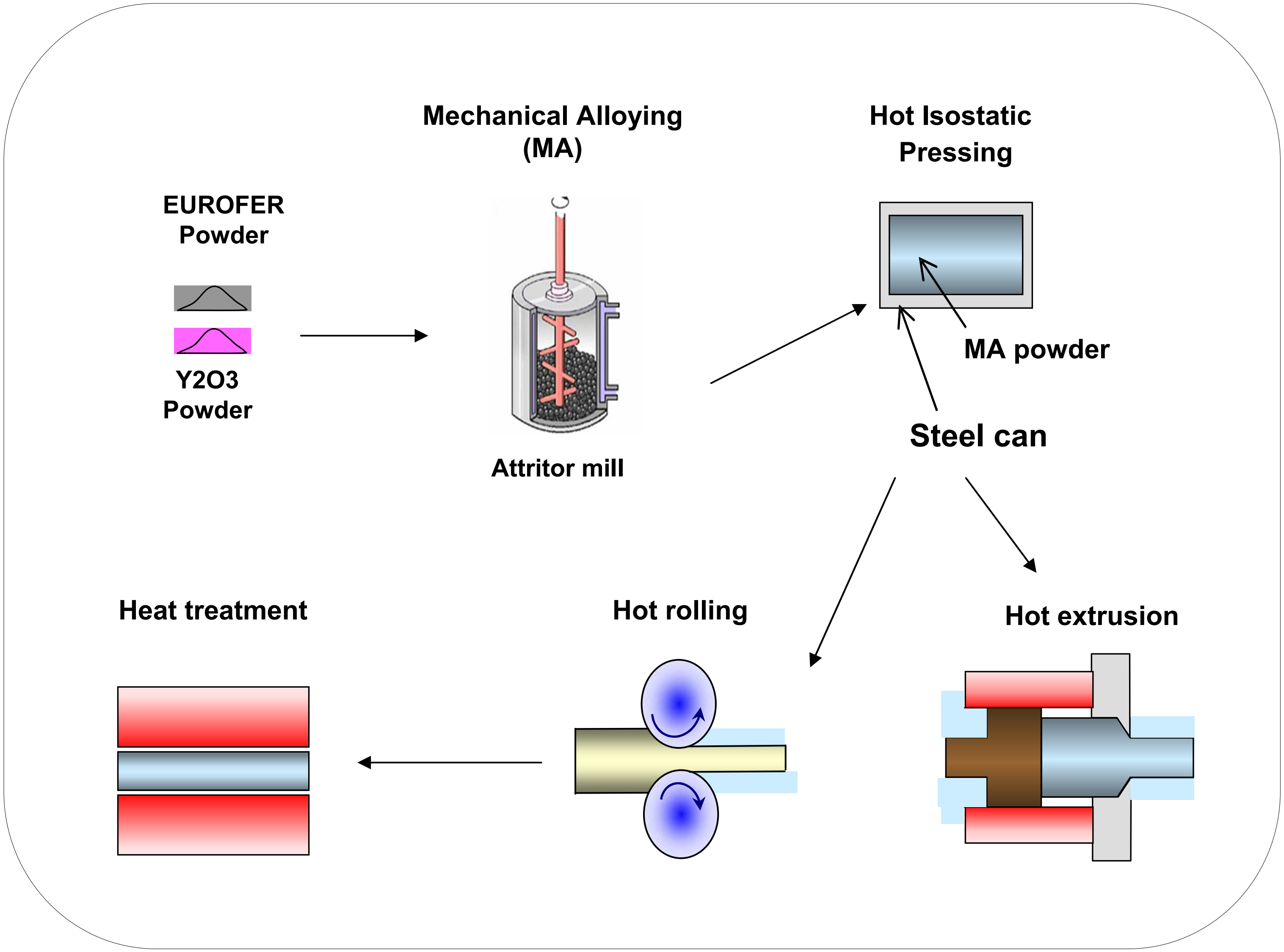
- Carbon addition
  - increase of strength, but negative effect on ductility
- Reducing the grain size
  - Thermomechanical treatment; mechanical milling of steel powder
- Precipitate hardening
  - carbide, nitride forming
  - maraging steels: Ni (25%), Al, Ti, Nb, Mo, Co addition
- Thermomechanical treatment
  - deforming the austenite (γ) phase before/during/after phase transition

Evolution of ferritic/martensitic steels

controlling the microstructure

- Cr-Mo ferritic steel introduced in 1920
- Goal for the power-generation industry in the '60s: 565ºC
  Addition of Mo, Nb, V to Cr-Mo steels (Sandvik HT9)
- Fast breeder nuclear reactor program in the '70s:
  - Irradiation program for 9Cr-1Mo, 2.25Cr-1Mo (up to 200 dpa)
- Fusion reactor program in the '80s:
  - first choice was Sandvik HT9
  - low activation steels concept, replacing Mo, Nb with W, Ta, V
    Eurofer, F82H, Optifer, ORNL 9Cr-2WVTa, Manet
- 5-9% Cr content favoured: low swelling, good thoughness
- New ideas: increase of W, adding B

Mechanical alloying and sintering



Oxide Dispersion Strengthened steels

- Oxide particles: Y_2O_3 or Ti_2O_3 + excess oxygen in the matrix
- Mixing particles with steel powder in

  high energy ball mill / attritor
- Higher operational temperature (T window above 700ºC)
- Poor impact (dynamic) properties
- Limited volume
- 9%Cr: radiation resistant martensitic matrix,
- 12%Cr – better corrosion resistant, fully ferrite

Ongoing work on ODS steel development

- Several laboratories are working on small scale batches
- Examples:

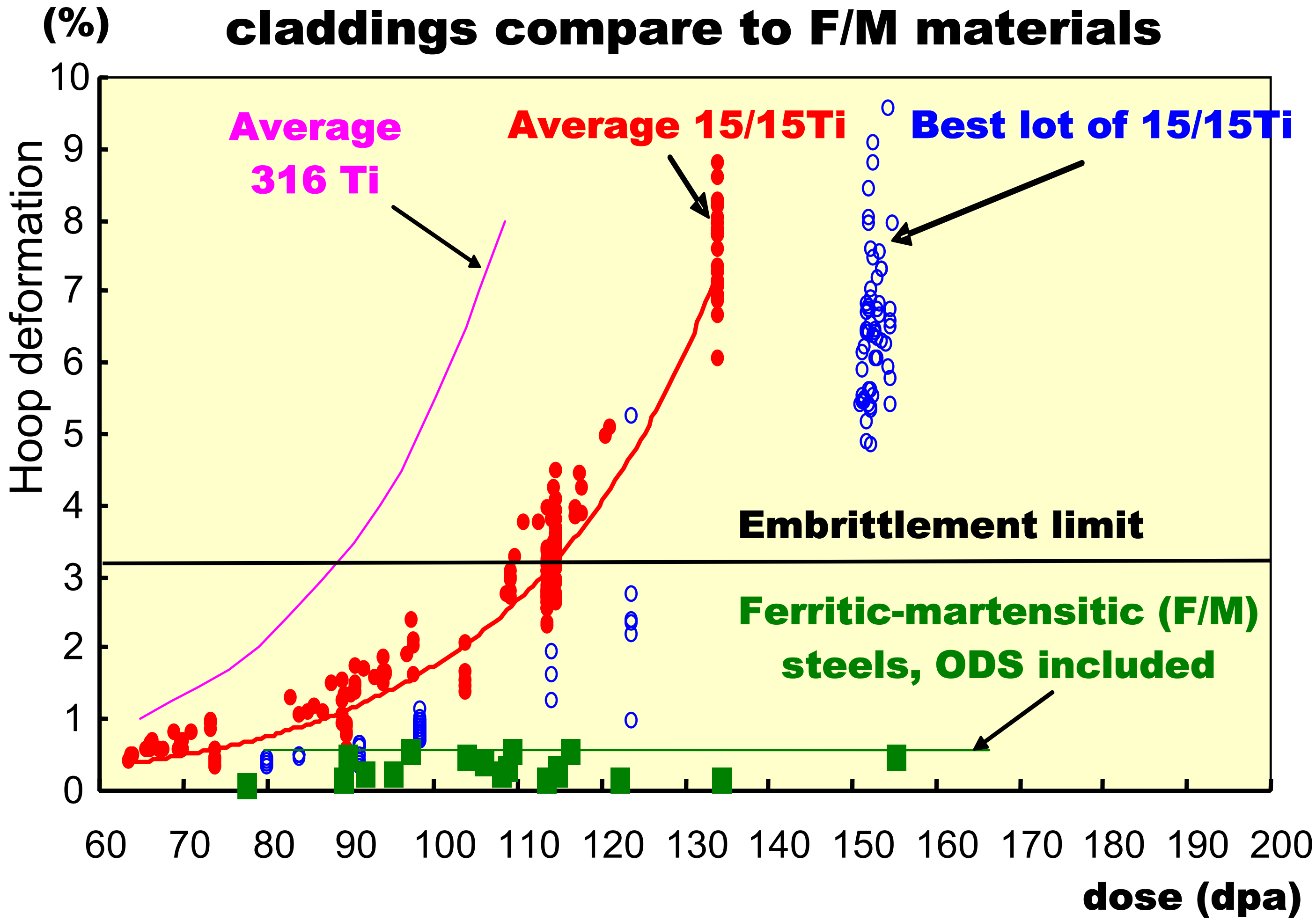
  ODS Eurofer – Fe-9Cr, MA-957 – INCO Metals, MA-956 – Special Metals Corp., Fe-12Cr-0.25Y_2O_3,, Fe-12Cr-2.5W-0.4Ti-0.25Y_2O_3, PM2000 – Fe-19Cr, Optifer – 9Cr - 1W, Optimax

- Small number of fast spectrum reactors (with high energy neutron) exists for irradiation tests.
- Fabrication volume is limited
- Neutron diffraction, SANS studies for characterising microstructure – issue: homogeneity

Ongoing work on ODS steel development

- EU FP7 GETMAT project started in 2008
  - Improve the PIE qualification of 9-12% Cr F/M steels
  - Develop and characterise ODS Fe-Cr alloys. Alternative fabrication route will also be investigated
  - Investigate corrosion and irradiation resistance
    - SCWR, Gas cooled, Lead cooled reactors
  - Develop models describing radiation damage effects in Fe-Cr alloys

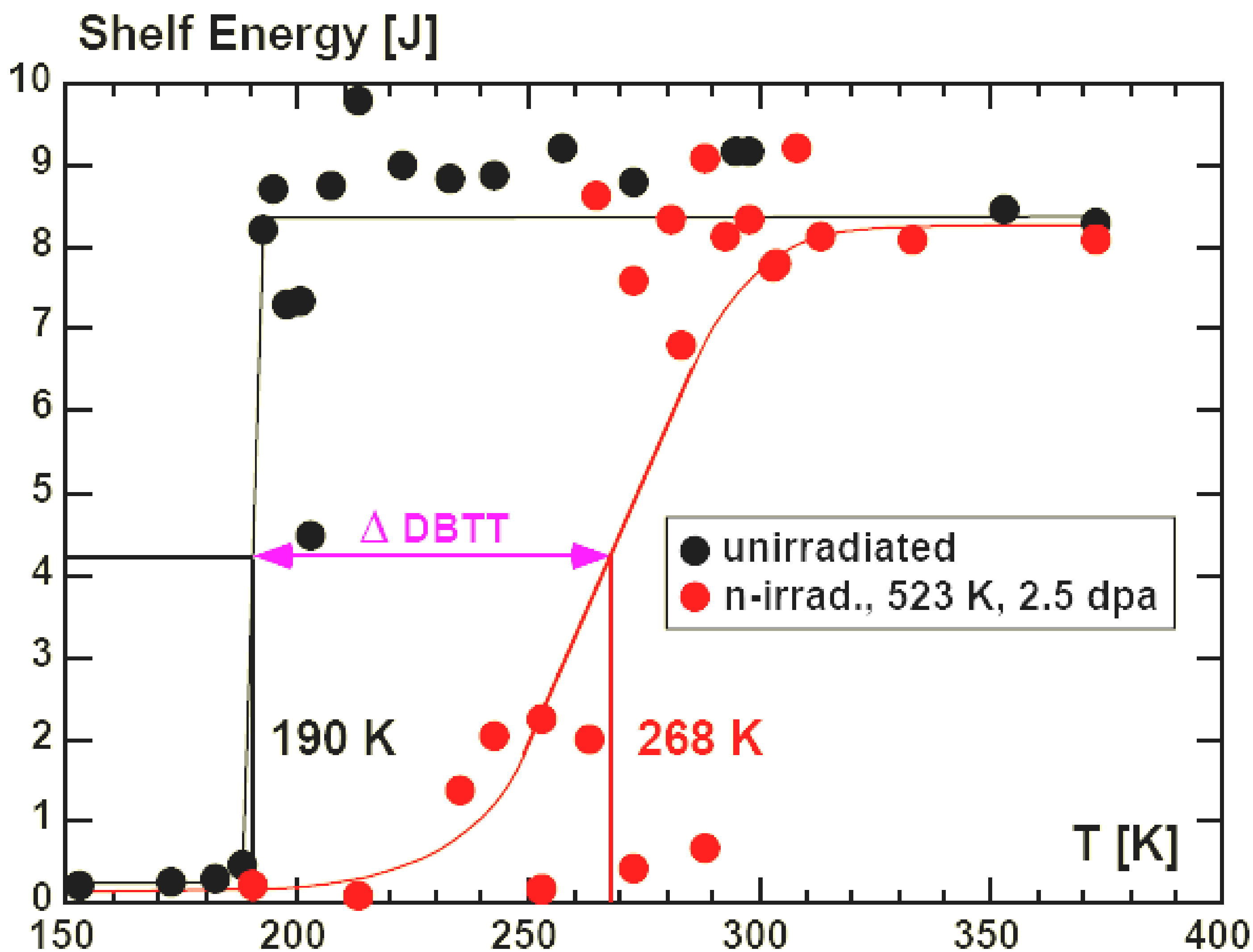
Swelling of austenitic Phénix claddings compare to F/M materials



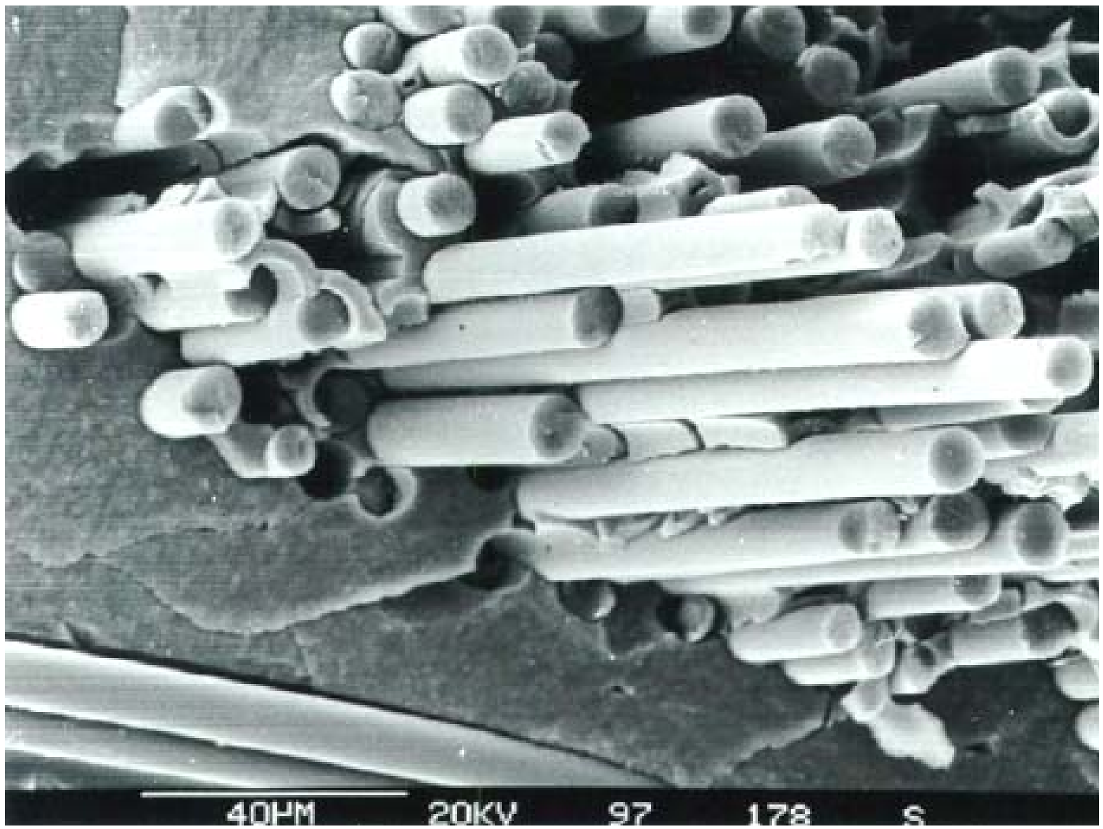
P.Yvon, F.Carré, J.Nucl.Mat. 285 (2009)

Impact properties of Optimax A (9%Cr-1%W)

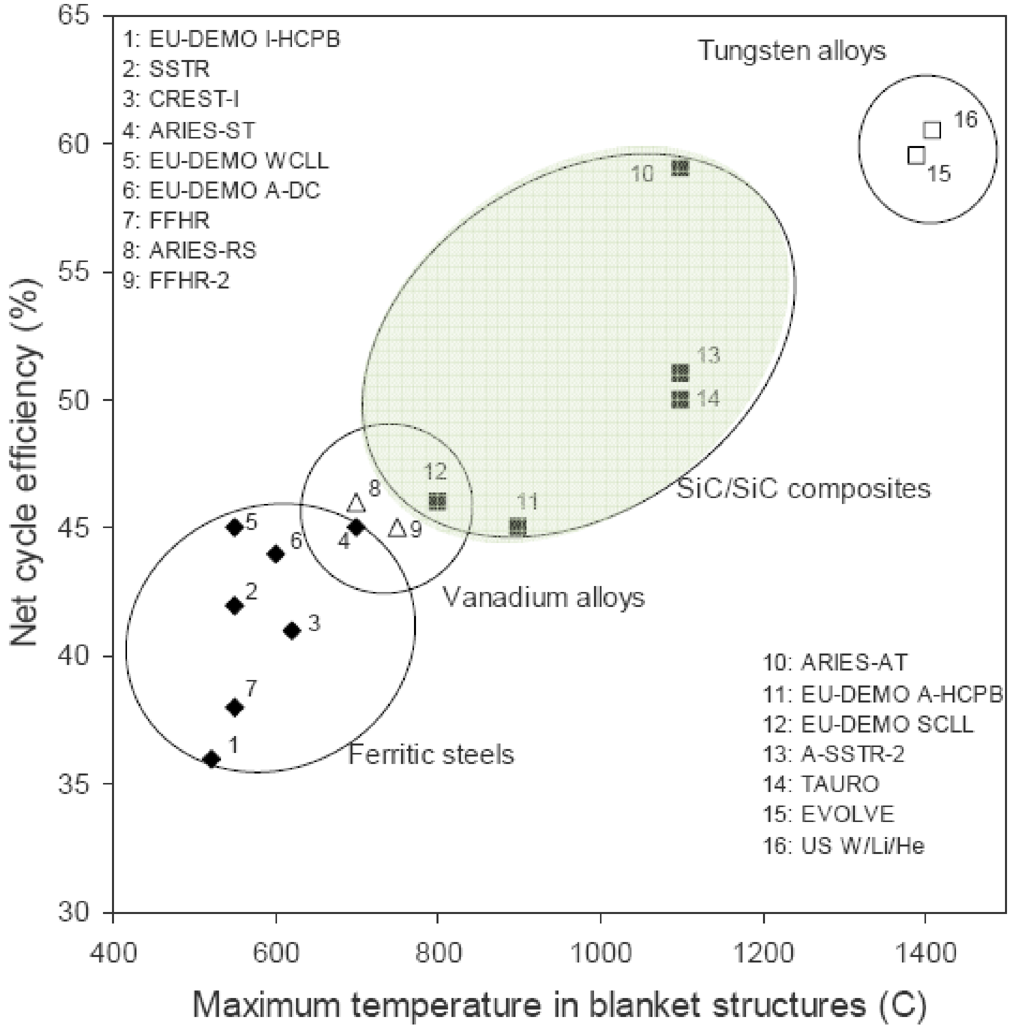
irradiated at 250ºC, 2.5 dpa



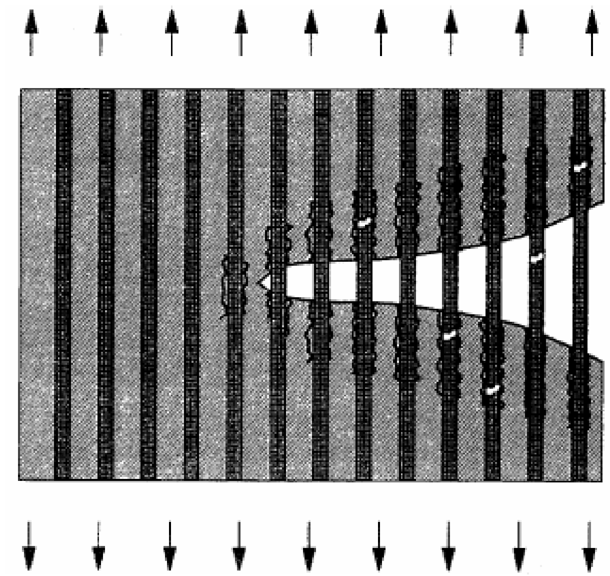
Ceramic composites



Ceramic composites for nuclear application



Katoh et al., ASTM-ERM22(2004)



Crack bridging mechanism in tough ceramics

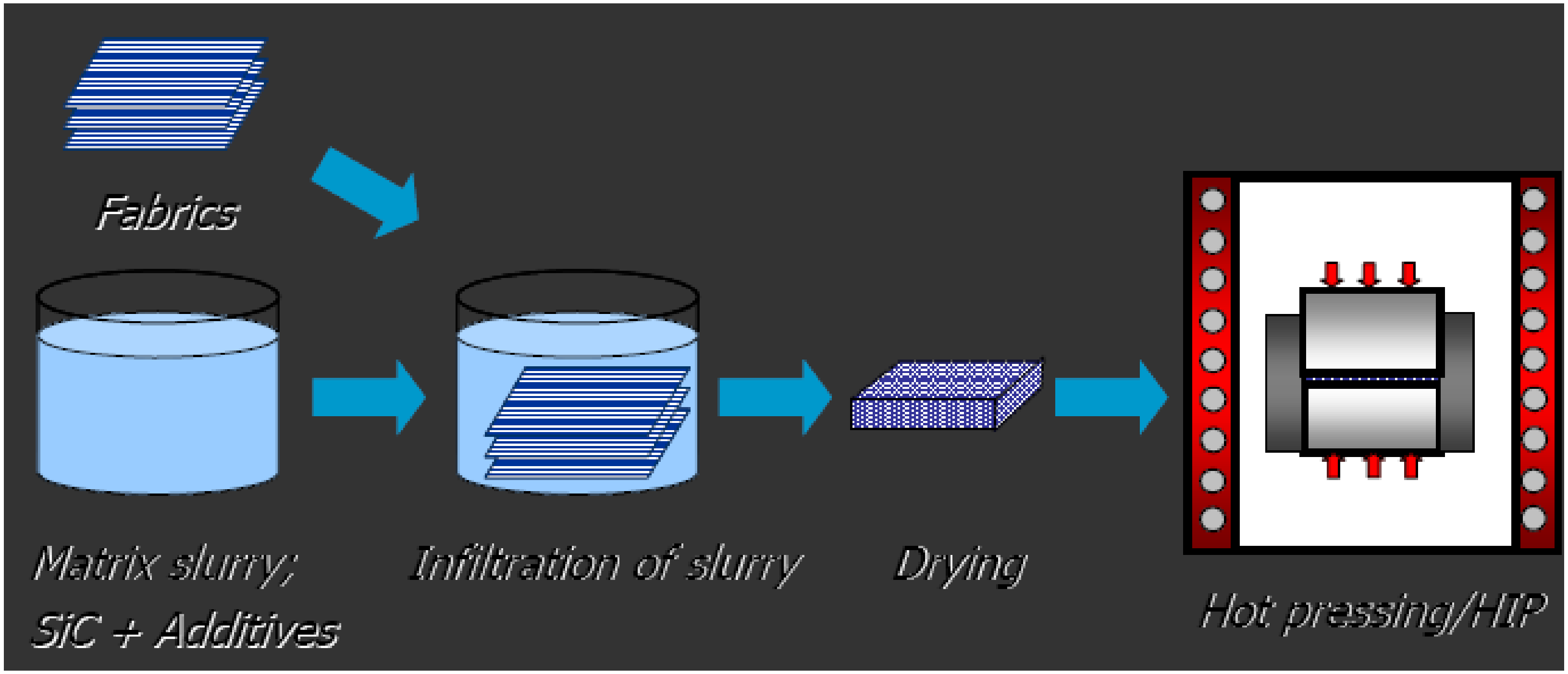
M. Kuntz, University of Bremen

Ceramic Matrix Composites compared with conventional technical ceramics

- Very high crack resistance and fracture toughness comparable to metals
- High elongation capability up to 1%
- High dynamical loadability of over 10^6 cycles
- Extreme thermal shock resistance
- Machining without risks
- Probability of failure not depending on component size

Advanced matrix densification method: NITE-SiC/SiC (Nano-Infiltration Transient Eutectic Phase Process)

- High density, excellent hermeticity, chemical stability
- Good radiation resistance anticipated

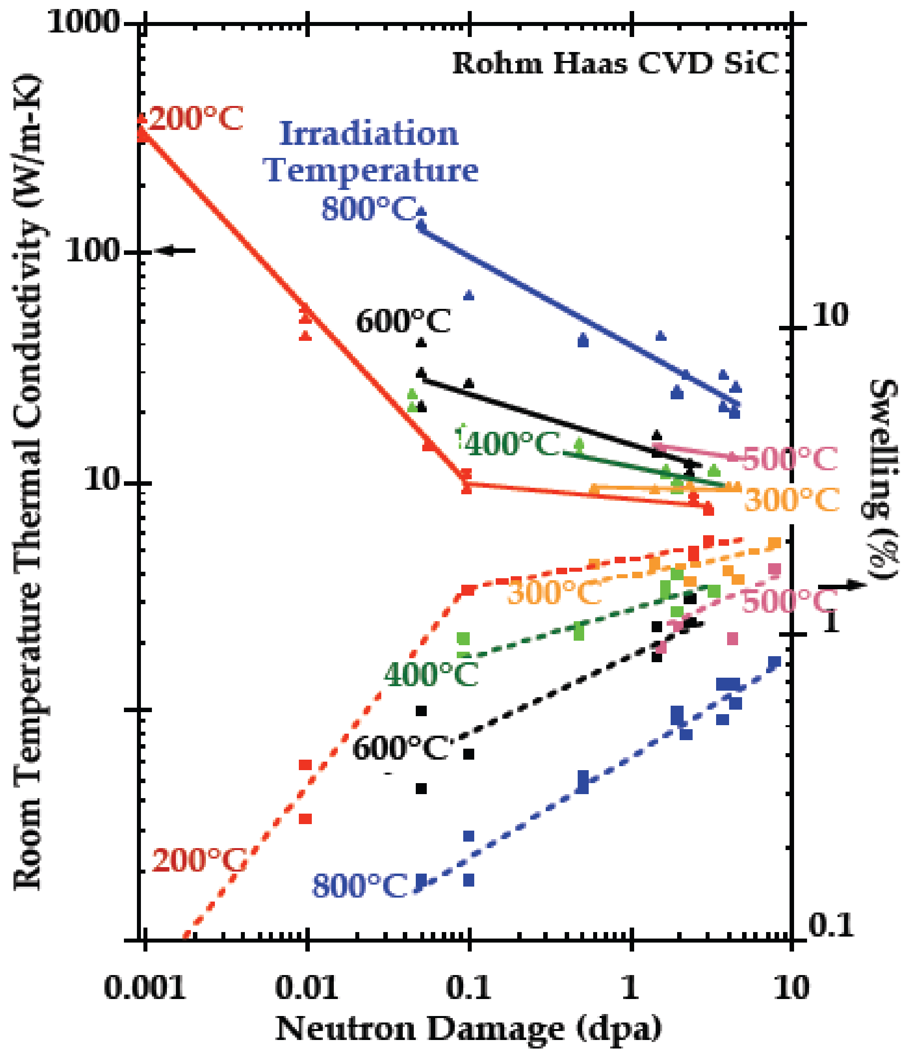


Properties of SiC/SiC composite

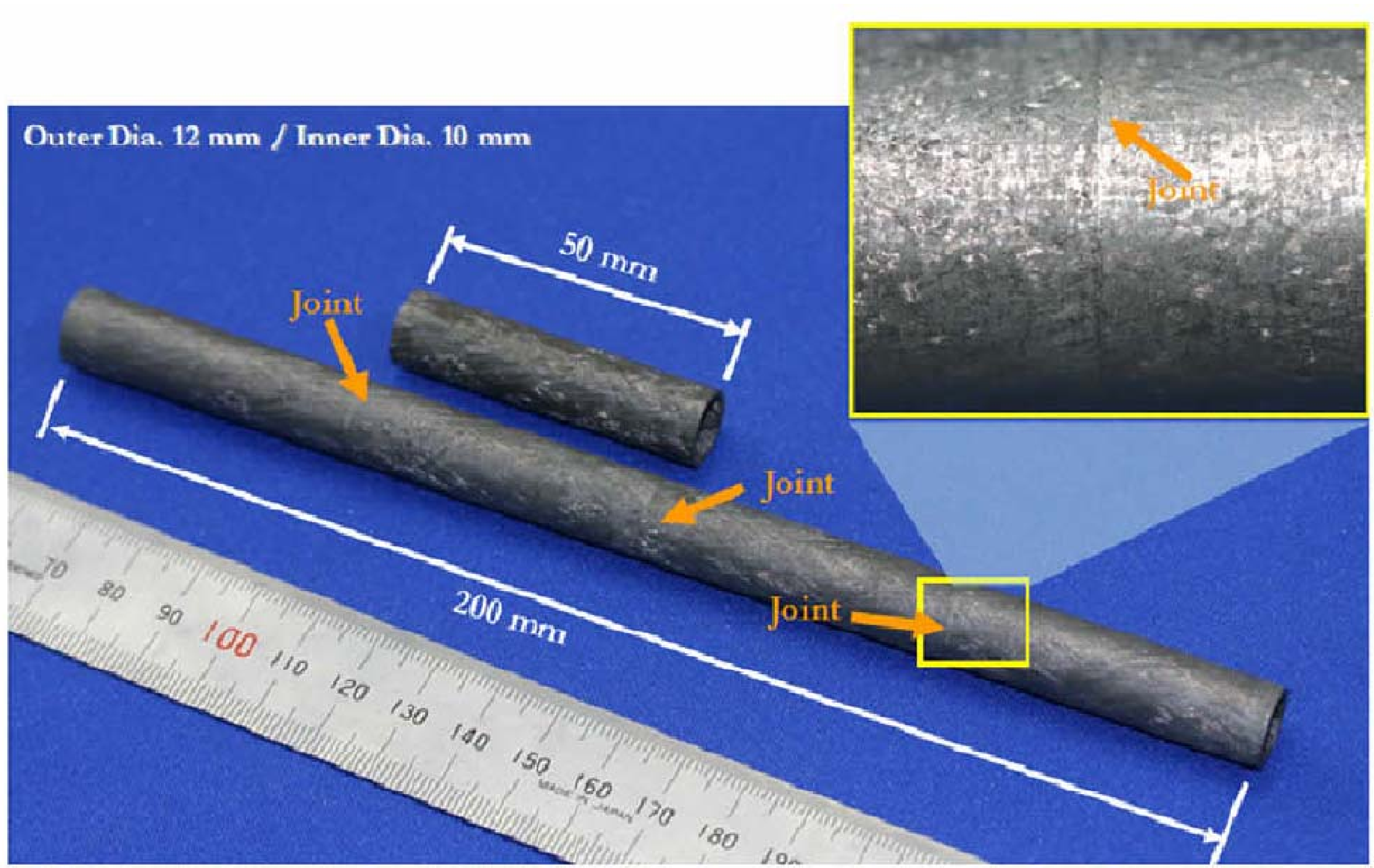
- Under irradiation, thermophysical properties for T< 1000ºC saturate by a few dpa

- In the 1st and 2nd generation of SiC/SiC composites exhibited significant degradation in mechanical properties due to non-SiC impurities

- Thermal conductivity reduction under irradiation is due to vacancies. It cannot be improved.



NITE joined SiC/SiC tube



Hinoki, Kohyama, Ann.Chim.Sci.Mater.,30(2005)

SiC/SiC advantages and drawbacks

+Very low activation

+High operating temperatures

+High strength at elevated temperatures

+Little reduction in strength up to 1000ºC

+Moderate swelling in the range 150 - 900 ºC for bulk SiC

– Low surface heat capacity (0.84kW/K.m at RT)

– Strong irradiation-induced reduction in thermal conductivity, and fracture toughness

– Irradiation-induced crystalline to amorphous phase transition at T<150 ºC

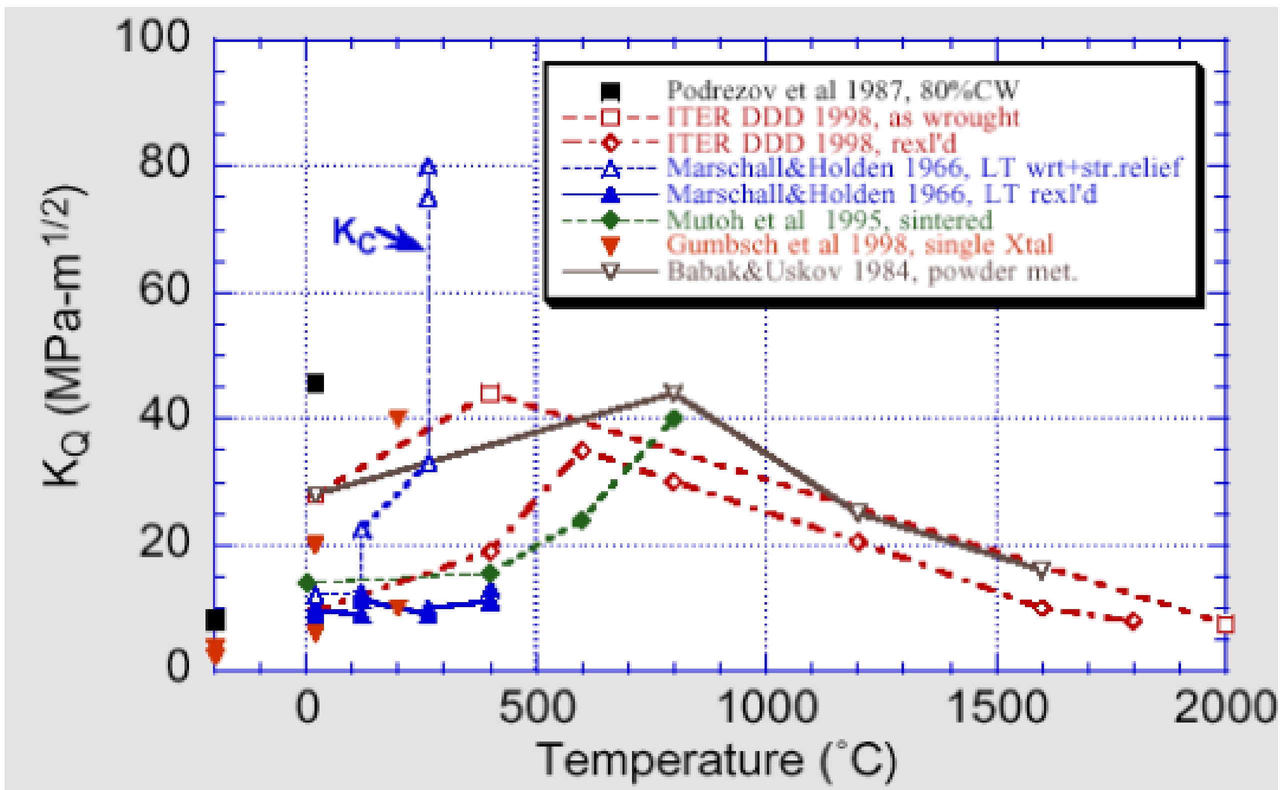
– High He and H production rates under irradiation; swelling of 11vol% at T<150 ºC for bulk SiC

– Temperature window of use: 600-1000 ºC

Refractory metals and alloys

- Group V (Nb, Ta, V) and Group VI(Cr, Mo, W) alloys: bcc, exhibit low temperature brittle fracture
- Group V are easier to fabricate

Zinkle, Kohyama, 19th IEEE/NPSS SOFE, 2002



Advantages and drawbacks

+High melting point (W: Tm>3400 ºC), high strength at high temperatures

+Ta: good surface heat capability (>11 kW/mK)

+Cr: good corrosion and oxidation resistance

+W: low erosion material

- Main problems:

–very low fracture toughness at all temperatures

–strong irradiation-induced embrittlement below 700 ºC

–Refractory metals and alloys are most suitable for special applications (plasma facing materials, coatings)

Perspectives for refractory alloys

- Development of advanced alloys by mechanical alloying

W-0.3Ti-0.05C has good low temperature ductility, small grain size (about 2 μm)

- Development of nanocrystalline materials

Improving ductility and radiation damage resistance

- Development of coatings

W coatings for protecting the structural material against first wall conditions (plasma spraying)

Summary

Advanced ferritic steels, RAFM steels are the most promising materials for the next generation nuclear reactors

It is expected that nanocomposited ferritic ODS steels expand the operating temperature up to 800 ºC

There are significant advances in the development of radiation resistant SiC/SiC ceramic composites, in terms of mechanical properties, joining and coating technology

Research on new materials should be supported with irradiation capacity. Only a few reactor exist worldwide, which are capable to generate high dpa in the materials.

Thank you !