The Way to Fusion Energy

Materials Challenges for ITER

– Current Status and Future Activities

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Outline

ITER

- Status of project
- Materials activity strategy

Materials selection for different components

- Vacuum vessel
- In-vessel components
    - Stainless steel 316L(N)
    - CuCrZr alloy
    - Alloy 718
    - Ti-6Al-4V
    - NiAl bronze
    - Armour materials (Be, W, CFC)

Test Blanket Modules Activities

Summary

Status of ITER

ITER is international fusion energy research project.

ITER goals:

- ✓ Show scientific and technological feasibility of fusion energy for peaceful purposes
- ✓ Integrate and test all essential fusion power reactor technologies and components
- ✓ Demonstrate safety and environmental acceptability of fusion

ITER activities were started in 1992, Final Design Report was issued in 2001.

Extensive negotiations about construction agreement, selection of site, sharing between Parties, etc. are being carried out during 2001-2005.

Finally, in June 2005, the ITER construction site was selected – Cadarache, France.

ITER Design Parameters (FDR 2001)

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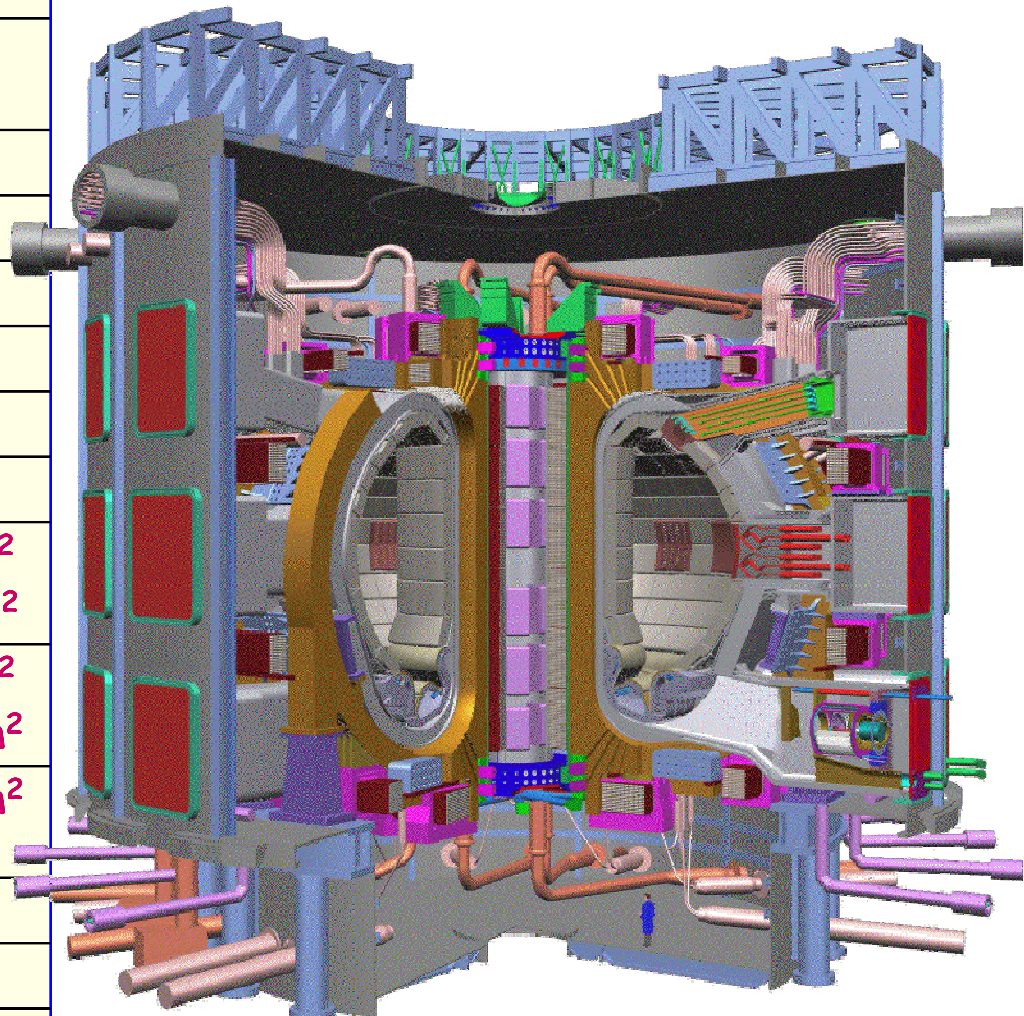
Total Fusion Power	500 (700) MW
Q=Fusion Power/Heating power	10
Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Toroidal field, 6.2 m	5.3 T
Plasma current	15 (17.4) MA
Plasma Volume	837 m^3
Plasma Surface	678 m^2
Neutron flux	Av. 0.57 MW/m^2 Max. 0.8 MW/m^2
Neutron fluence	Av. 0.3$MW*a/m^2$ Max 0.5$MW*a/m^2$
Heat flux, First Wall	0.2 - 0.5 MW/m^2
Heat flux, Divertor	10 (20) MW/m^2
Number of pulses	~ 30.000
Pulse length	~ 400 s



ITER is the first tokamak, with significant neutron fluence.

Selection of Materials

Selection of materials for the ITER components was a challenging task, due to unique operational conditions, e.g.:

- Magnet – operation at 4K, high stresses;
- In-vessel components – combined effect of n-irradiation, heat flux, hydrogen environment, mechanical loads, complicated design with different type of joints;

Experience from current tokamaks has been taken into account, (plasma facing, diagnostics materials, etc.).

Knowledge from fission neutron irradiation programs was used.

However, in many cases, the choice was not simple, because for a number of materials the existing data base was not sufficient.

Selection of Materials – General strategy

The material choice for ITER has been orientated toward industrially available materials while taking account of physical and mechanical properties, maintainability, reliability, corrosion performance and safety requirements at the ITER operational conditions.

The ITER materials categories:

- **Standard materials with established manufacturing technologies, (e.g. steel 304, steel 316L(N), alloy 718, W).**
- **Standard materials, which require some modifications, such as more stringent limits on the alloying elements, etc. (e.g. steel EK1, JJ1, CuCrZr, etc.).**
- **Recently developed materials (e.g. CFC).**

Materials were selected based on the evaluation of the impact of manufacturing technologies on materials properties and assessment of their performance at the ITER operational conditions.

These selection and justification were supported by the results of the dedicated world-wide R&D program.

Materials documentation – FDR 2001 (2004)

ITER Materials Properties Handbook (MPH-Magnet, Cryo, VV&IC):

- A collection of design-relevant data on physical and mechanical properties of a large variety of the ITER relevant materials.

ITER Materials Assessment Report (MAR):

- A description of the rationales for the selection of the specific materials grades for VV and In-vessel components and assessment of the materials performance.

Appendix A of the ITER Addendum to the RCC-MR:

- Design data for materials for the Vacuum Vessel.

Appendix A of the ITER Structural Design Criteria (SDC-IC):

- Design data for in-vessel components (including neutron irradiation).

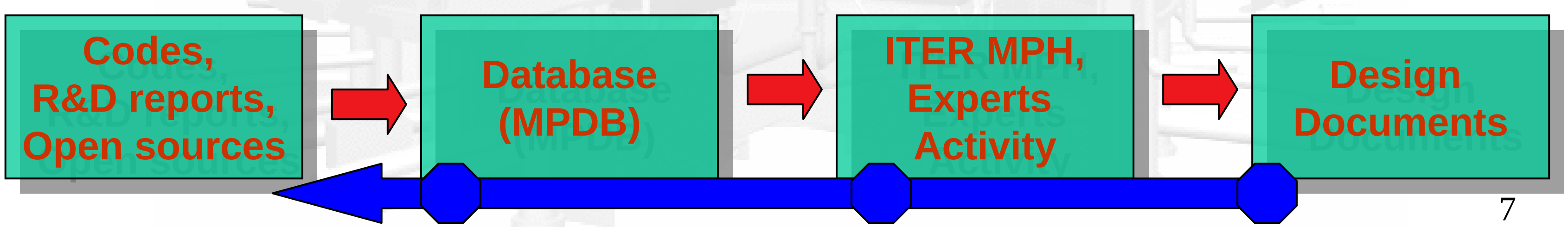
Safety Report:

- Collection of safety relevant properties.

ITER Materials Properties Database (MPDB):

- Collection of raw experimental data - base for further recommendations

These documents justify the selection and materials performance.



Materials Activity in current stage

Multidisciplinary task:

- **Preparing of the procurement specifications for materials for various components (in accordance with construction schedule);**
  - Discussion with Industries for implementing the ITER requirements
  - Discussion of the possible deviations
  - Schedule for materials procurements

- **Consolidation of the materials properties database and modifications of the ITER Materials Documents;**
  - Assessment of the new data from R&D program
  - Preparing of recommendations based on Design Codes requirements
  - Completion of MPH and App. A for VV Code, In-vessel SDC and Magnet SDC

- **Carrying out the R&D in some still critical areas:**
  - Further optimisation and simplification of design and manufacturing route
  - Generating of new data needed for the completion of the design evaluation

Selection of materials for ITER components

No.	WBS Element
1.	TOKAMAK BASIC MACHINE
1.1	TOROIDAL FIELD (TF) COILS SYSTEM
1.2	POLOIDAL FIELD (PF) COILS SYSTEM
1.3	CENTRAL SOLENOID (CS) SYSTEM
1.5	VACUUM VESSEL
1.6	BLANKET SYSTEM
1.7	DIVERTOR
2.	TOKAMAK ANCILLARIES AND CRYOSTAT
2.3	REMOTE HANDLING (RH) EQUIPMENT
2.4	CRYOSTAT
2.6	COOLING WATER SYSTEM
2.7	THERMAL SHIELDS
3.	TOKAMAK FLUIDS
4.	POWER SUPPLIES - COMMAND CONTROL
5.	PORT INTERFACING SYSTEMS
5.1	ION CYCL. HEATING (IC H&CD) SYSTEM
5.2	ELECTRON CYCL. HEATING (EC H&CD) SYSTEM
5.3	NEUTRAL BEAM HEATING (NB H&CD) SYSTEM
5.4	LOWER HYBRID HEATING (LH H&CD) SYSTEM
5.5	DIAGNOSTICS
5.6	TEST BLANKETS

Magnet – T operation- 4-77 K

Specification	Components
EK1 or JJ1 forged sections	TF coil case (inner leg basic elements) including stub elements, Pre-compression

Vacuum vessel and In-vessel materials:

- structural
- plasma facing

1.5	VACUUM VESSEL
1.6	BLANKET SYSTEM
1.7	DIVERTOR
5.1	ION CYCL. HEATING (IC H&CD) SYSTEM
5.2	ELECTRON CYCL. HEATING (EC H&CD) SYSTEM
5.3	NEUTRAL BEAM HEATING (NB H&CD) SYSTEM
5.4	LOWER HYBRID HEATING (LH H&CD) SYSTEM
5.5	DIAGNOSTICS

Glass epoxy G10	insulation
Ag coating	Coating, 5 μm (emissivity)

region)	F doped silica (core)/F doped (clad)/Al jacket (JA F-doped)
(IR region)	Pure silica, F doped (core)/F doped (clad)/Al jacket
Mirrors/Reflectors	First mirrors: Metal (Cu, W, Mo, SS, Al), LIDAR Single coated (Rh/V), Dielectric mirrors:(HfO_2/SiO_2, TiO_2/SiO_2), LSMs: (Mo/Si, W/B_4C and W/C), X- ray crystals: (Ge, Si, SiO_2, Graphite)
Magnetic coils	MI cables
Bolometers	Mica substrate, Au meander

Selection of materials – Vacuum Vessel

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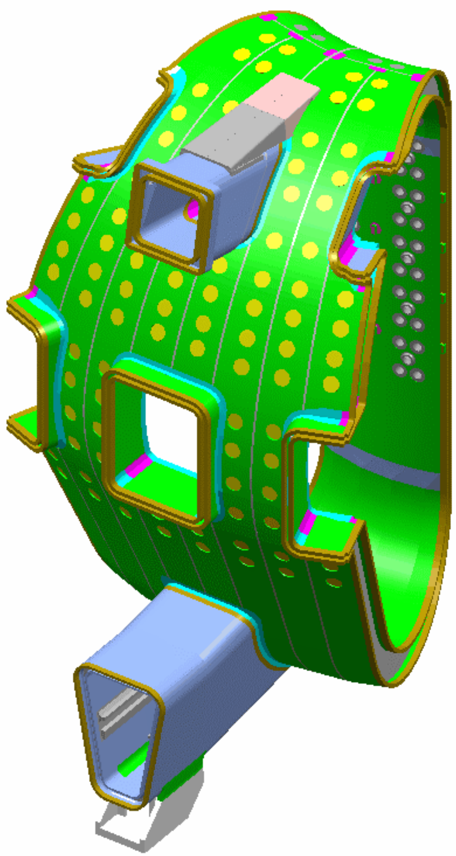
- **Safety Important Component => licensing in France**
- **Code – RCC-MR + ITER addendum**
- Main structural material – 316L(N)-IG is the Code qualified and main specifications are available
- Other structural materials: steel 304, steel grade 660, Alloy 718 are also in the Code
- Only functional materials (borated steels, etc.) are not in the Code.



Materials for Vacuum Vessel:

Austenitic steel 316L(N)-IG	plates, forgings, rods
Borated steels 304B7 and 304B4	shielding plates
Ferritic steel 430	plates
Steel 660	fasteners, forgings
Steel 304	plates, beams
Alloy 718	bolts
Weld filler materials	electrodes, wire
XM-19	bolts for shielding
Steel 316	bolts (B8M)
Pure Cu	clad on VV

Materials for Vacuum Vessel support:

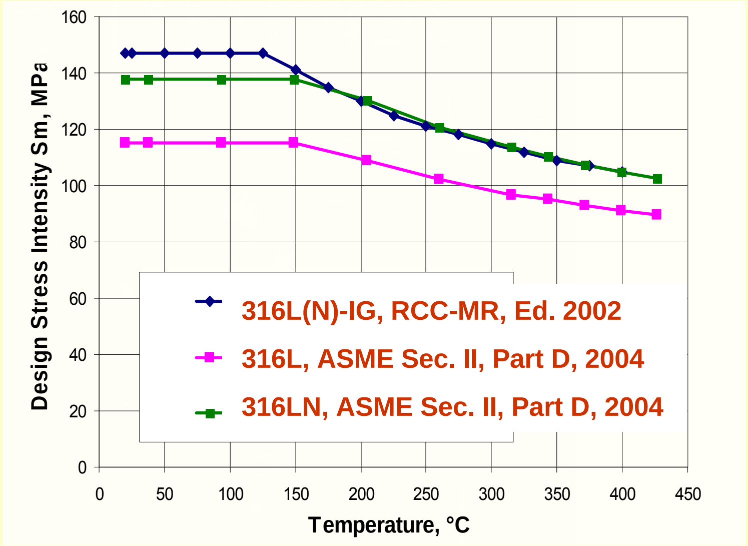
Steel 304	plates, forgings, rod
Alloy 718	bolts
Steel 660	forgings, bolts
NiAl bronze	pins
PTFE	for sliding elements
Neoprene rubber	

Selection of materials – Vacuum Vessel

Chemical composition of steels

Element	316L ASME A240		Z2 CND 17-12 controlled nitrogen RCC-MR 2002		316L(N)-IG ITER grade	
	min	max	min	max	min	max
C		0.03		0.030		0.03
Mn		2.00	1.60	2.00	1.60	2.00
Si		0.045		0.50		0.50
P		0.030		0.035		0.025
S		0.75		0.025		0.01
Cr	16.00	18.00	17.00	18.00	17.00	18.00
Ni	10.00	14.00	12.00	12.50	12.00	12.50
Mo	2.00	3.00	2.30	2.70	2.30	2.70
Nb+Ta+Ti						0.15*
Cu				1.00		0.30
B				0.0020		0.002 (0.001)**
Co				0.25		0.05
N		0.1	0.060	0.080	0.060	0.080
Sm, RT	115		147		147	

Nb < 0.1, Ta < 0.01



Materials for VV – ongoing activity:

Complete App. A to ITER Addendum to RCC-MR

- Introduce required additional properties (e.g. fracture toughness) for structural materials
- Introduce properties of functional materials in the ITER Addendum

Non-metallic materials – justification of the properties for licensing

- Windows, etc.

Properties of welds

- In case of use welds, which are not in Code, – provide the needed justification.

Preparation of the Procurement Specifications

- Composition, minimum properties, NDE&QA

Selection of materials – In-vessel components

General considerations:

- *Design of structural elements – in accordance with the ITER Structural Design Criteria for IC (SDC-IC)*
- *Design of some elements (Be/Cu, CFC/Cu, Window/Cu etc.) – by experiment*

ITER SDC-IC:

- *Needs reliable and traceable materials data (including neutron irradiation effect)*
- *Properties of joints (welds, SS/Cu, etc.) have also to be assessed*

ITER MPH includes the justification of recommendations.

Properties needed for design analyses:

- *Physical (incl. neutron irradiation) - average (+deviation)*
- *Tensile properties for design (incl. neutron irradiation) - minimum and average*
- *Design fatigue curves (incl. neutron irradiation) - minimum ($\Delta\varepsilon/2$; Nf/20)*
- *Fracture toughness (incl. neutron irradiation) - minimum and average*

Specifications for materials supply:

- Chemical composition,

- Minimum properties;

- NDE&QA

Selection of materials – In-vessel components

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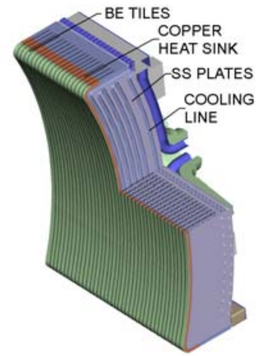
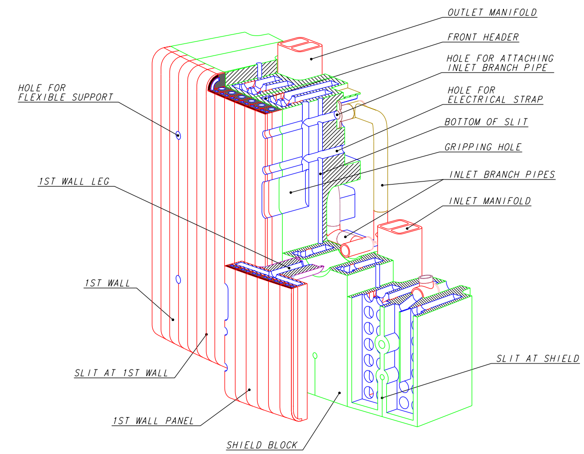
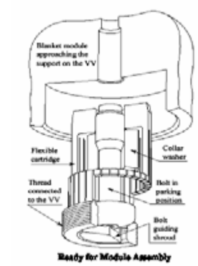
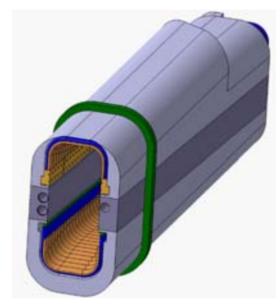
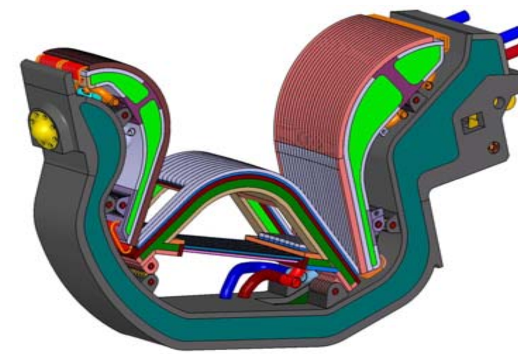
Material	Material Grade	Components
• **Armour**		
Beryllium	S-65C VHP or equivalent	• Armour for first wall and limiter
Tungsten	Pure W	• Armour for divertor
CFC	SEP NB 31 or equivalent	• Armour for divertor
• **Structural**		
Austenitic steels	316L(N)-IG	• Blanket shield modules • Thin walled pipes • Cooling manifolds • Divertor body
	304L, 316L	• Cooling pipes
	XM-19	• Divertor support
PH steel	Steel grade 660	• Divertor support
Cu alloys	CuCrZr	• PFCs, heating systems, electrical strips, etc.
	NiAl bronze	• Divertor attachment
	CuNiBe	• Support system
	DS Cu	• heating systems,
• **Functional**		
Austenitic steel	316	• Fastening components
PH steel	Steel grade 660	• Fastening components
Ni alloys	Alloy 718	• Bolts • Divertor connections
Ti alloy	Ti-6Al-4V	• Blanket attachment
Ceramic	Al_2O_3 or $MgAl_2O_4$	• Electrical insulators
Special materials		• Pure Cu • Pure Ni • Low C iron • Brazes • Weld fillers

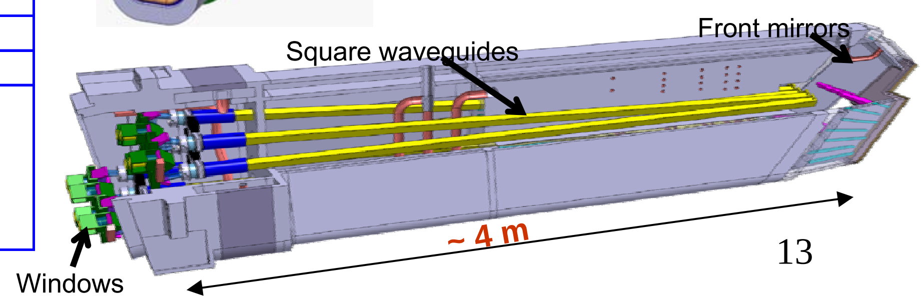












V.Barabash et al., ITER Materials, ICFRM-12, December 4 - 9, 2005, Santa Barbara, USA

Stainless steel 316L(N)-IG

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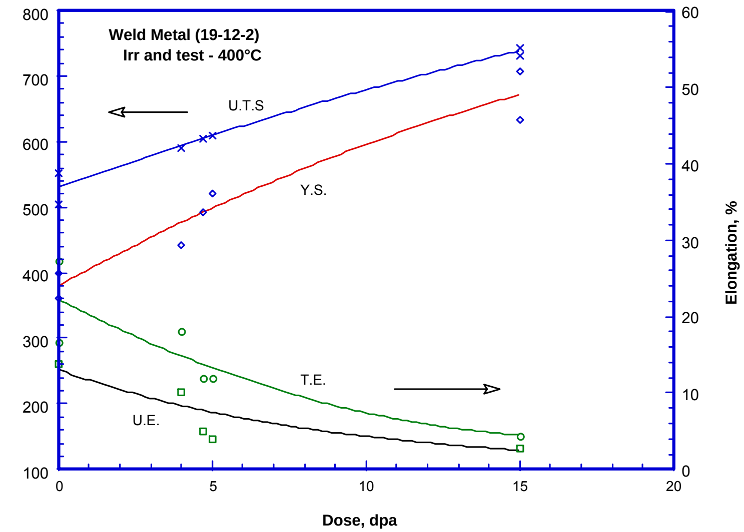
Welding and joining

Different types of steels (diffe

- Un-irradiated data for welds are Code qualified;
- Irradiated data are being reviewed, the behavior is similar to base metal; the same safety margin can be used;
- The properties of joints after HIP (solid and powder) joining technique are adequate.

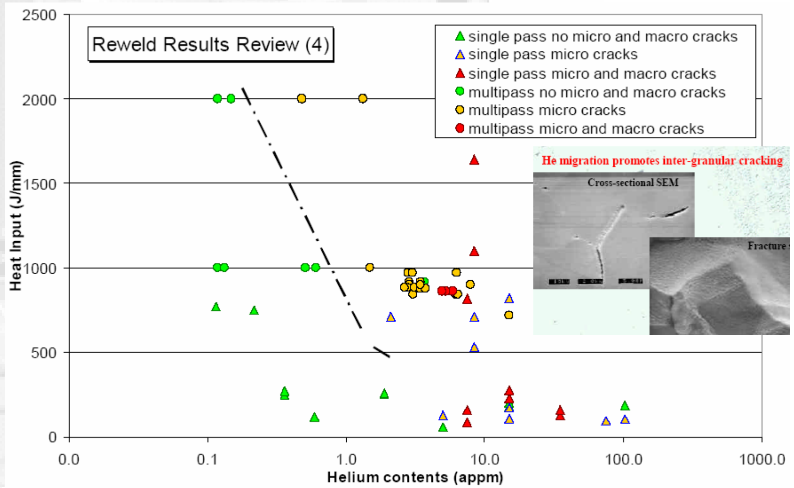
A.A. Tavassoli, this Conf.



Rewelding

ITER recommendation for the reweldability limits, provided by the allowable levels for He production in weld:

– < 1 appm for thick plate welding,
– < 3 appm for thin plate or pipe welding.



K. Asano, J. van der Laan, MAR, 2001

Stainless steel 316L(N)-IG

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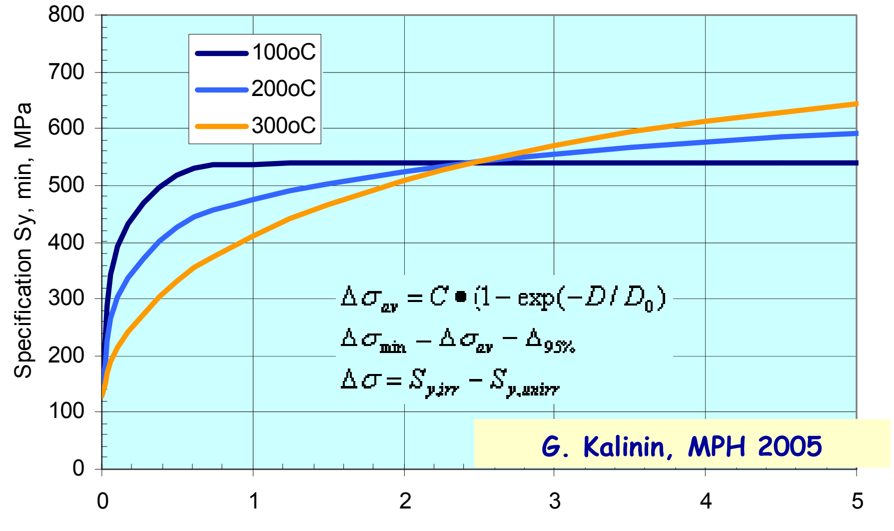
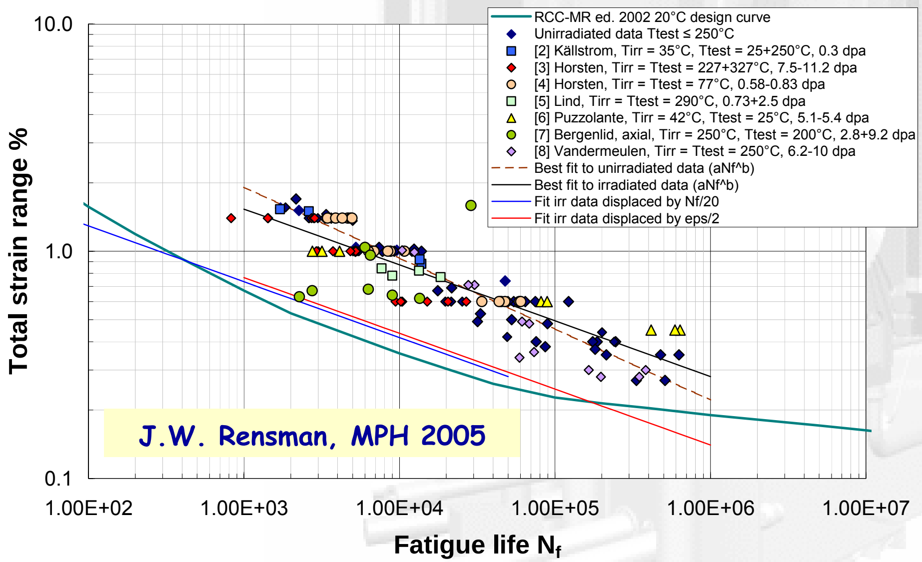
Neutron effect:

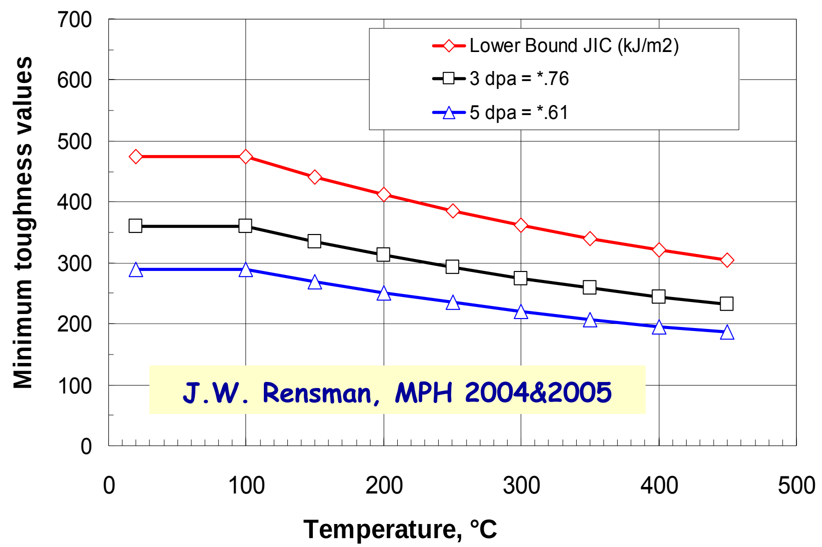
Tensile properties:
-Strengthening and loss of ductility (loss of strain hardening)

Fatigue:
- no effect on fatigue

Fracture toughness:
- reduction, but material still ductile







CuCrZr alloy

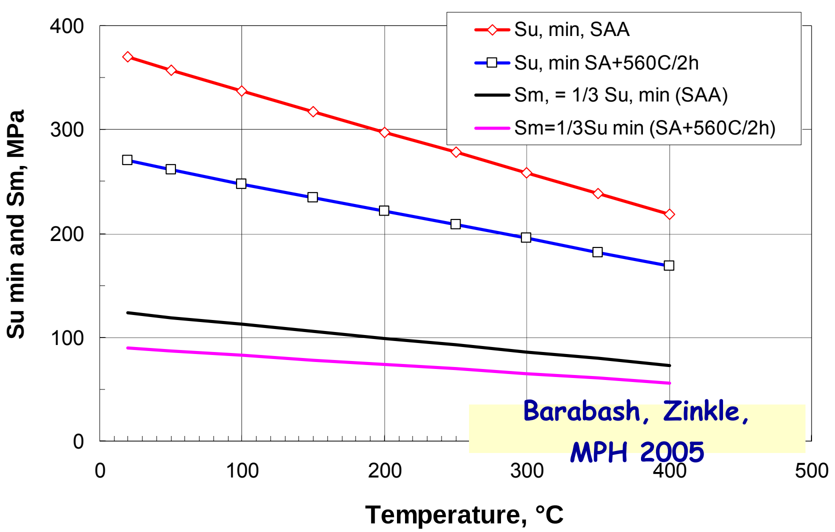
Chemical composition

Alloy Designation	Cu	Cr	Zr	O	Other elements
CuCrZr, RF	base	0.4-1.0	0.03-0.08		0.1 max
CuCrZr, C18150	base	0.5-1.5	0.05-0.25		
CEN/TS 13388	base	0.3-1.2	0.03-0.3		0.2
CuCrZr ITER Grade	base	*0.60-0.90*	*0.07-0.15*	*0.002 max*	*0.01 max* *0.05 -Cd*

Reasons for modification of the chemical composition:
- smaller scatter of properties,
- less coarser Cr particles – better toughness,
- better radiation resistance is expected,
- welding improved.

Effect of treatment on properties.

Manufacturing treatments:
(SA – 980-1000°C + water quench, Ageing – 450-500°C
- SAA (different cooling rate, etc.)
- SA + cold work + A
- SAA + cold work
- cast CuCrZr + SAA



CuCrZr alloy

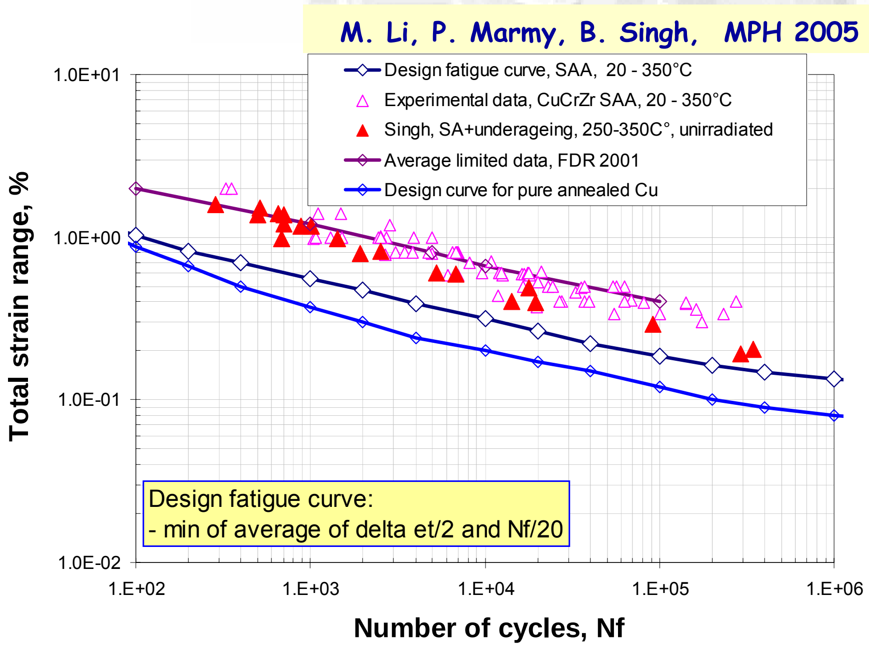
Fatigue:

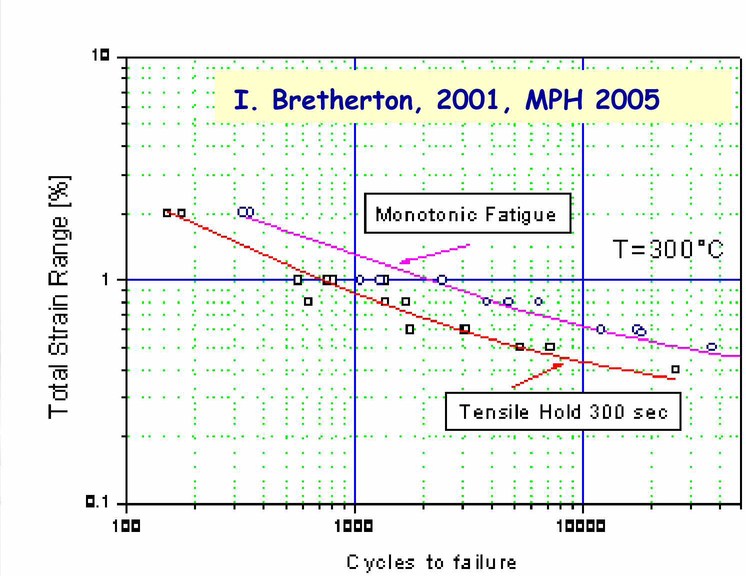
- Seems that fatigue performance is similar for CuCrZr with different treatment

Creep – fatigue interaction:

- very complicated performance:
  - => Generally there is reduction of lifetime with hold time;
  - => Higher Sy – higher fatigue lifetime

(see presentation of B. Singh, this Conference)





CuCrZr alloy

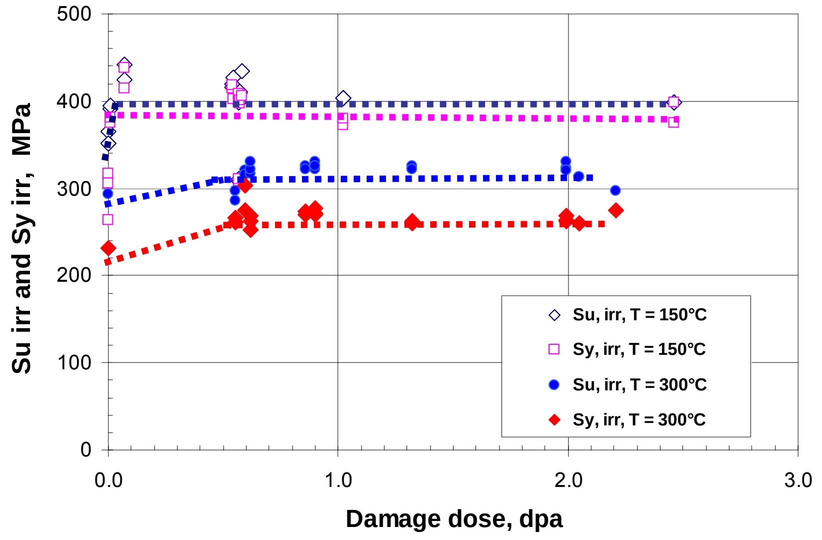
Neutron effect:

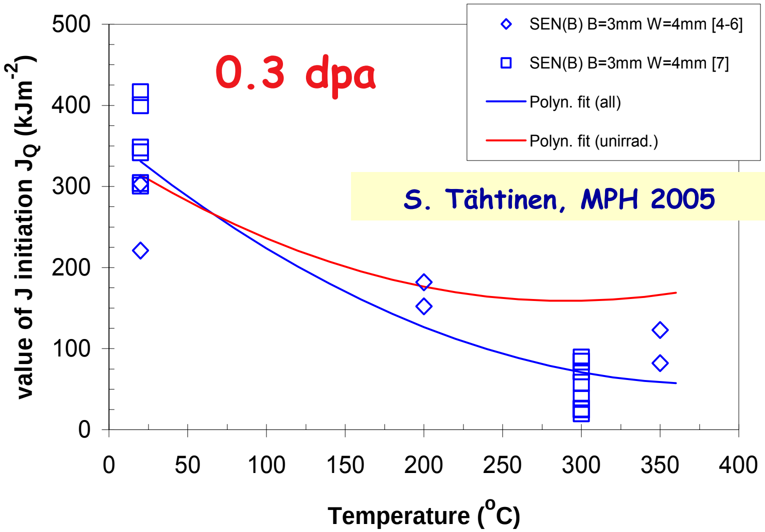
Tensile properties:
- loss of ductility (loss of strain hardening): saturation at ~ 0.1-0.5 dpa at T ~ 100-300°C.
- Some improvements of ductility is observed after baking treatment (see Fabritsiev, this Conference)

Fracture toughness and fatigue:
- effect is small, but data are only up to 0.3 dpa

There is no correlation between loss of ductility at tensile tests and fracture toughness.

V.Barabash & S.Zinkle, MPH 2005





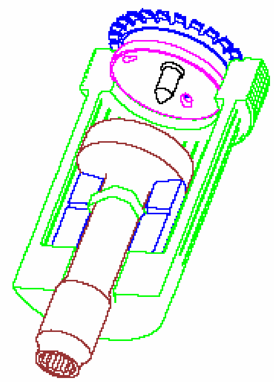
Summary for CuCrZr:
- Final characterization after selected heat treatment (s);
- There are some missing data: irradiation creep, fracture toughness and fatigues at high doses;
- Importance of creep-fatigue interaction shall be understood.

Alloy 718

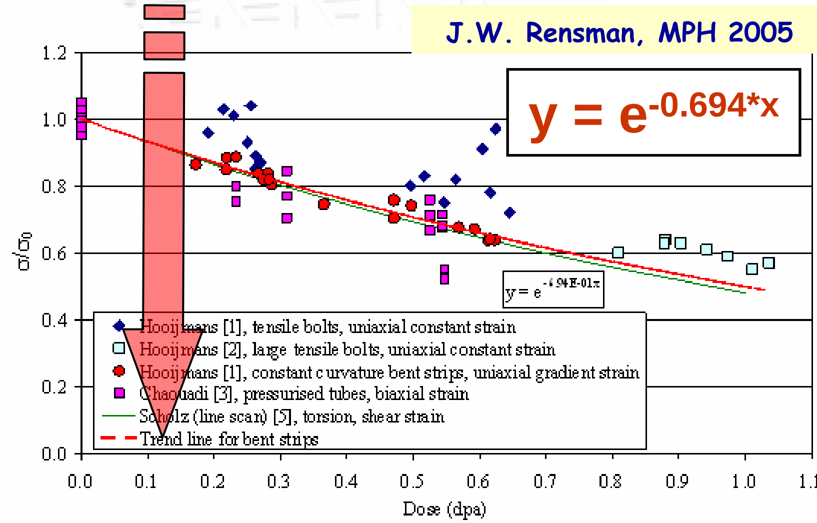
Key issues:

Stress relaxation -bolts:

- ITER goal ~ 0.1 dpa

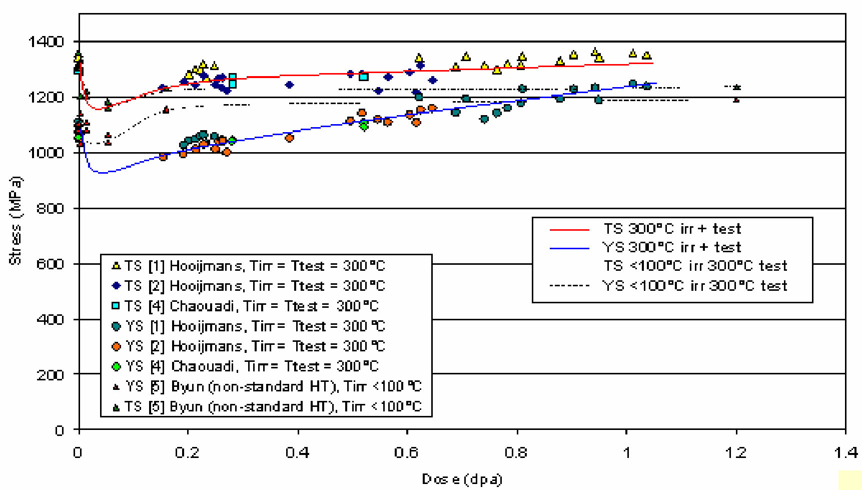


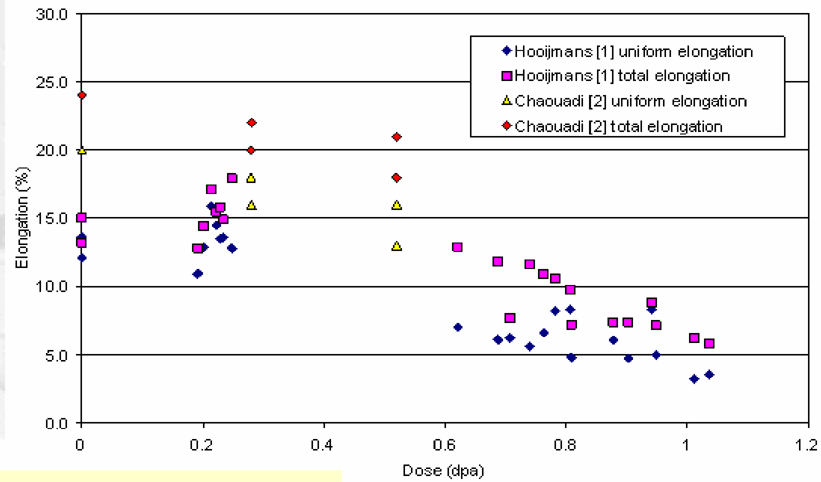
J.W. Rensman, MPH 2005



Loss of strength at low damage dose:

- effect is ~ 15%.





J.W. Rensman, MPH 2005
T.S. Byun, ORNL

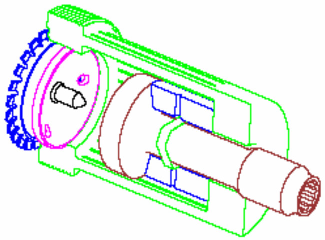
Ti-6Al-4V alloy

Reasons: low elastic modulus and high strength provide high flexibility.

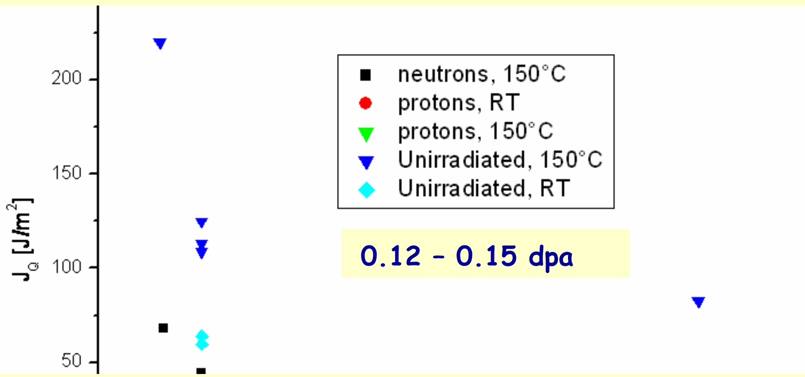
Key issues:

Neutron irradiation embrittlement:
- ITER goal ~ 0.1 dpa

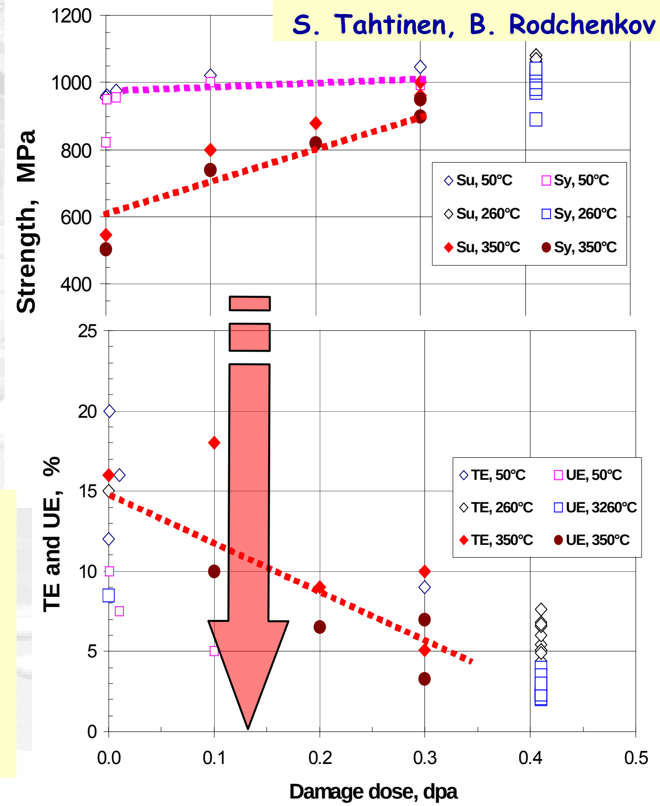
Hydrogen environment:
- it is well known that H affects properties.



Hydrogen levels up to 150 wppm have moderate effect on toughness, at a test temperature of 150°C. P. Marmy, 2004



MPH 2005:
S. Tahtinen, B. Rodchenkov



However, remaining issues:

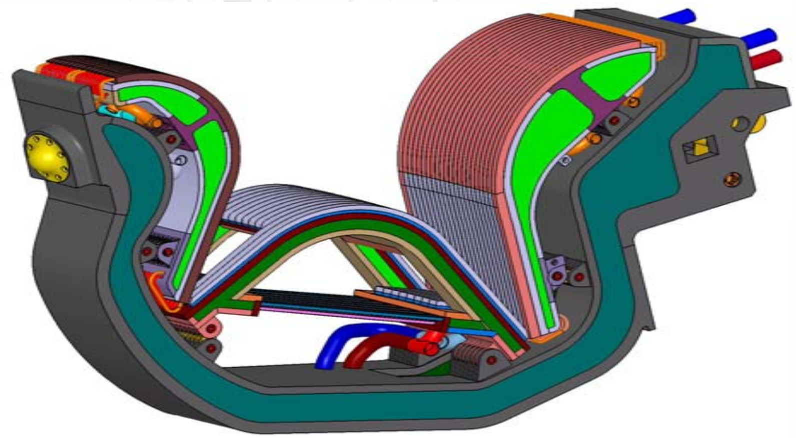
- Role of ionizing radiation on possible enhanced hydrogen uptake (MIT launcher, May 2005)
- Fracture toughness and fatigue of irradiated Ti alloy.

NiAl bronze

NiAl bronze (CuAl10Ni5Fe4):

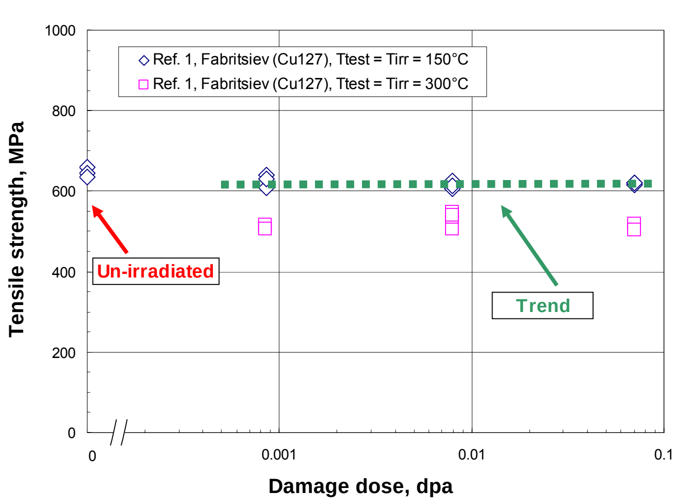
ASTM B150, C63200
DIN EN 12163/1216

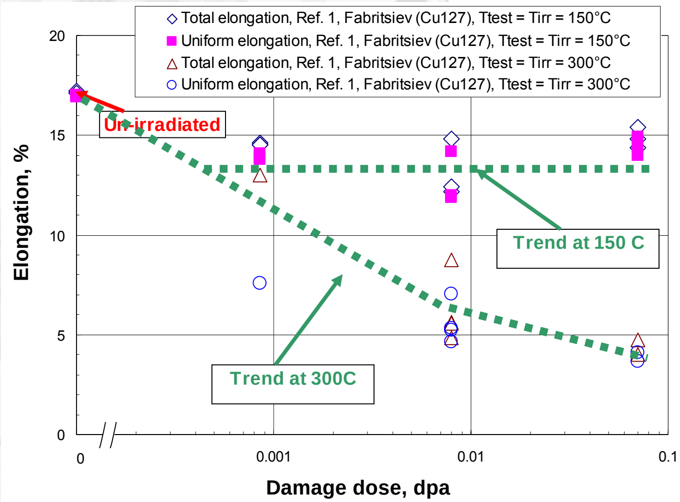
High strength, low friction and spark resistance are the key properties.



Neutron effect:

First data are presented at this Conference.





V. Barabash, S. Fabritisiev, this Conference

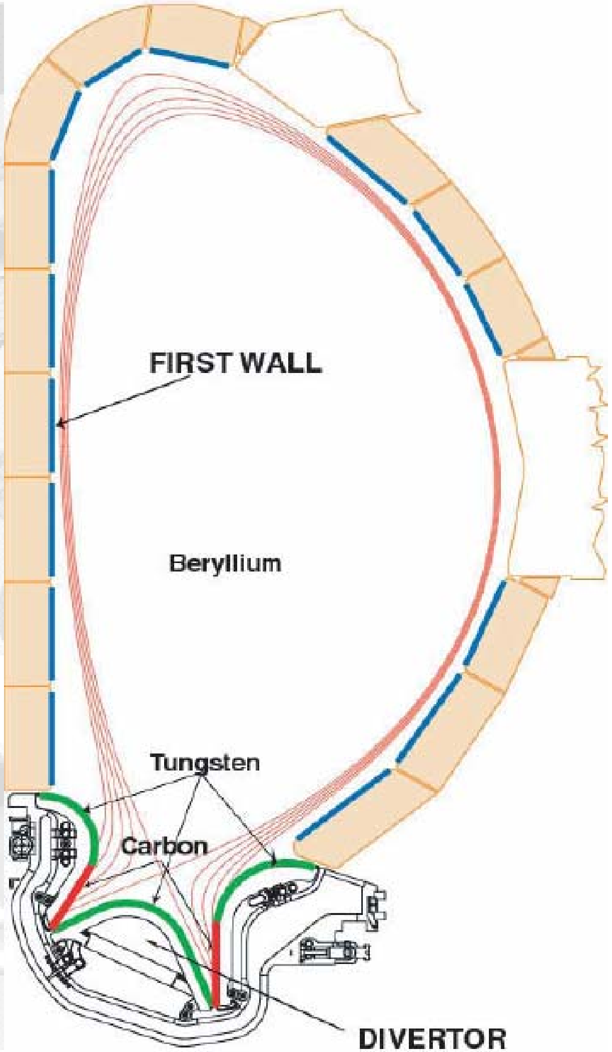
Selection of armour materials

Compromise: Plasma Performance ←→ Materials Lifetime ←→ T retention

~ 680m^2 Be first wall
→ low Z compatibility with wide operating range and low T retention

~ 50 m^2 CFC Divertor Target
- → **No melting under transients (ELMs and Disruptions)**
- → **Low Z compatibility with wide range of plasma regimes ($T_{e,div}$ ~ 1 – 100 eV)**
- → **Large T retention (co-deposition)**

~ 100m^2 Tungsten Baffle/Dome
→ Low Erosion, long Lifetime and low T retention



For PSI issues see:
G. Federici, "Plasma Wall Interactions in ITER", to appear in Physica Scripta.
G. Federici, et al., "Plasma material interactions in current tokama and their implications for next step fusion reactors". Nucl. Fusion 41 (2001)1967.

Carbon Fibre Composites

SEP NB31, CX-2002U, or equivalent

Key issues:

Properties variation at mass production (ITER needs ~ 10 tons):

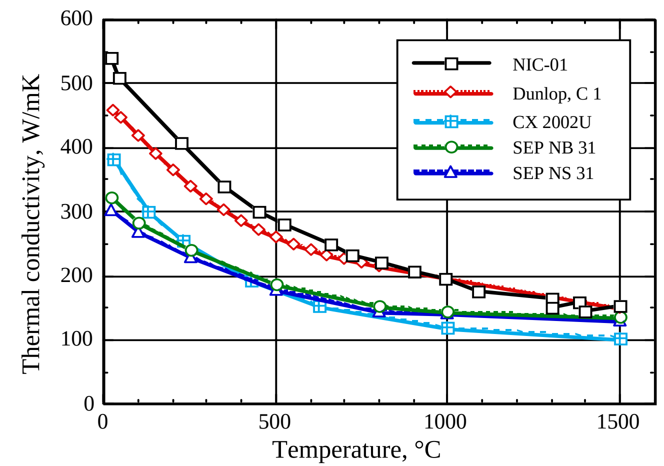
- variation of thermal conductivity (SD_{RT} < 10 W/mK);
- stable mechanical properties

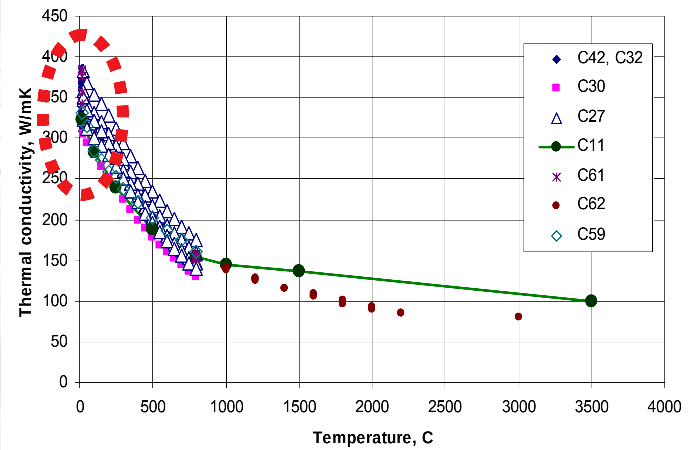
Neutron effect:

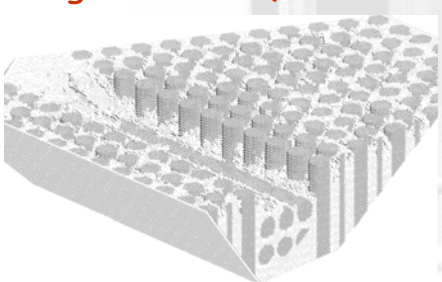
- it is well known neutron irradiation affect thermal conductivity, nevertheless the thermal performance is adequate (V.Barabash, ICFRM-11).

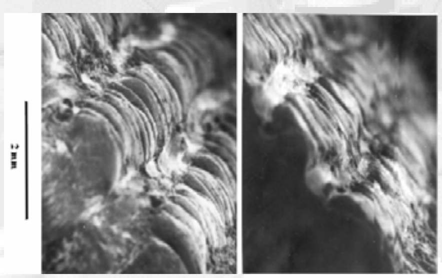
Thermal erosion at transient loads:

- is being assessed (EFDA+ITER+TRINITI, RF)









Improving of manufacturing technology is ongoing.

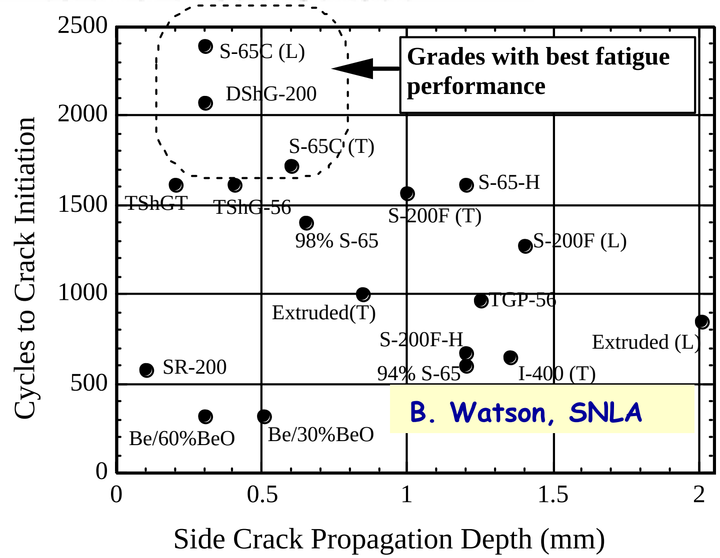
Beryllium

S-65C, Brush Wellman USA, or equivalent grade(s)

Key issues:

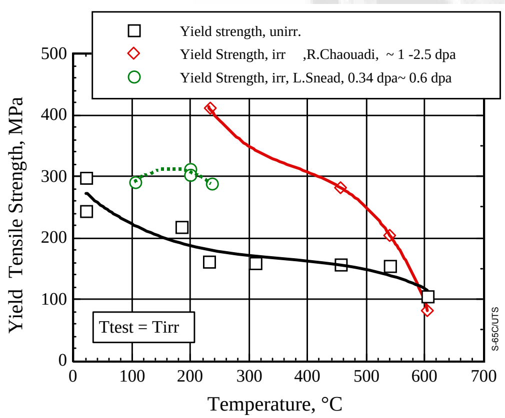
Thermal fatigue/thermal shock resistance

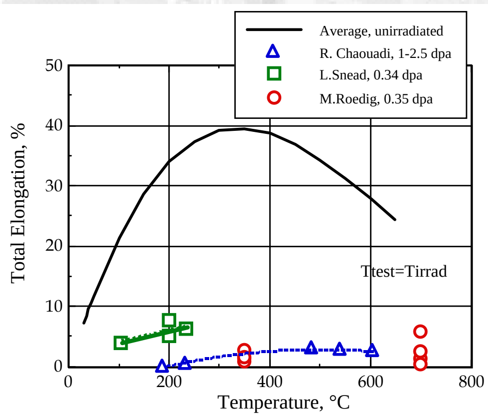
- S-65C VHP has the better performance, but others may be also acceptable

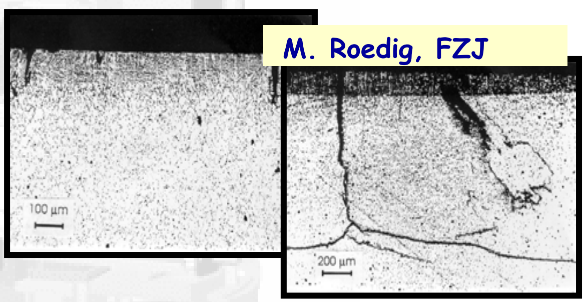


Neutron effect:

- The behavior of all Be grades with BeO < 1% seems very similar.
- However, the performance of irradiated Be in the irradiated components seems good, based on the results of in-pile tests and test of FW mock-ups after irradiation (see J. Linke, A. Gervash).







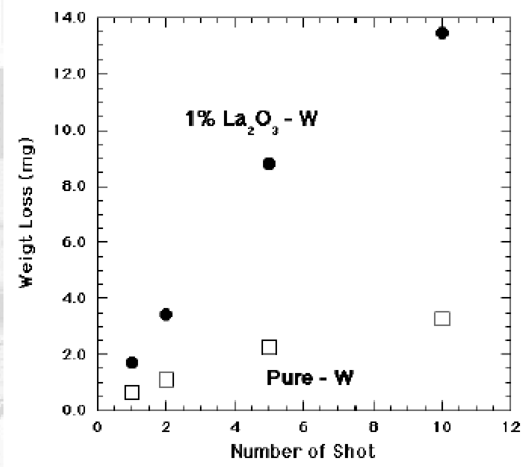
Metallography of S-65C and TR-30 after disruption heat load

V.Barabash et al., ITER Materials, ICFRM-12, December 4 - 9, 2005, Santa Barbara, USA

Tungsten

Pure sintered W is selected
Data base for pure W is sufficient.

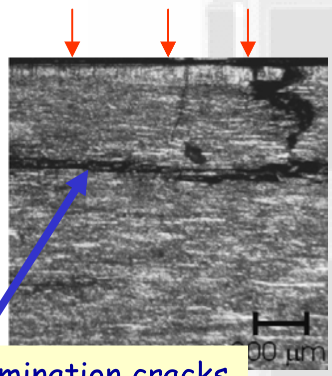
Taniguchi, JAERI, 2000

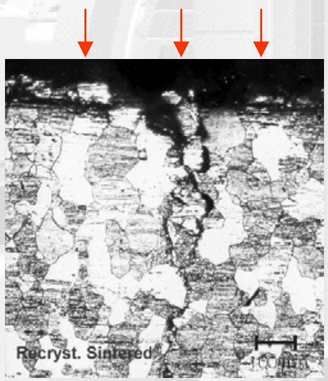


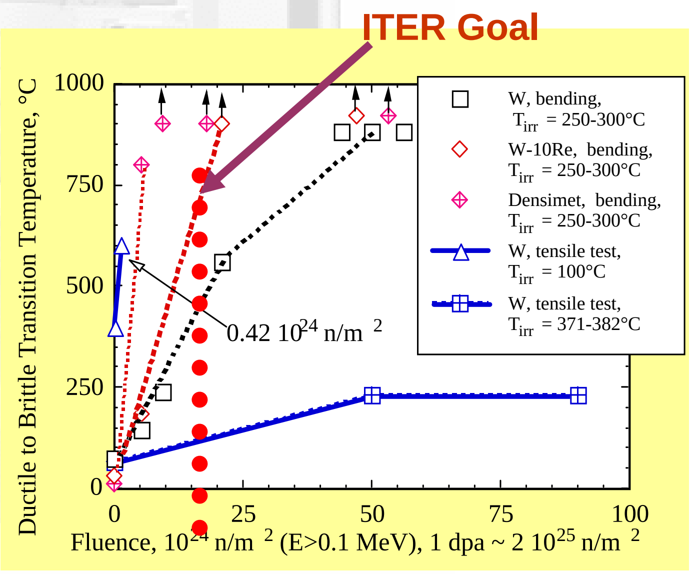
Key issues:

Thermal fatigue/thermal shock resistance

- Performance of W significantly depends on orientation of grains and production history (plate, rod, recrystallization, etc.)







Neutron effect:

- Due to low irradiation temperature (~ 150-500°C, all W grades will be brittle at low dose irradiation
- However, the performance of 'brittle' W in the irradiated components seems good (see M. Roedig, FZJ).

Remaining R&D issues

ITER is ready to be build, however, there is still a list of materials issues to be solved.

- Site adaptation: for safety important components a complete information have to be presented for the licensing needs in France;
- In some areas R&D is on-going with goal to simplify design, reduce cost, increase reliability – materials data for supporting of these designs are needed, e.g.:
  - US propose cast steel for blanket modules – need neutron irr. data;
  - RF and China – cheaper Be grades – need to qualify them;
  - Different technologies used for FW – need qualify CuCrZr properties;
  - Etc.
- Need to have all missing data, which could impact the performance of materials in ITER
- Finally we need to provide the recommended data for Ultimate assessment and acceptance of the design.

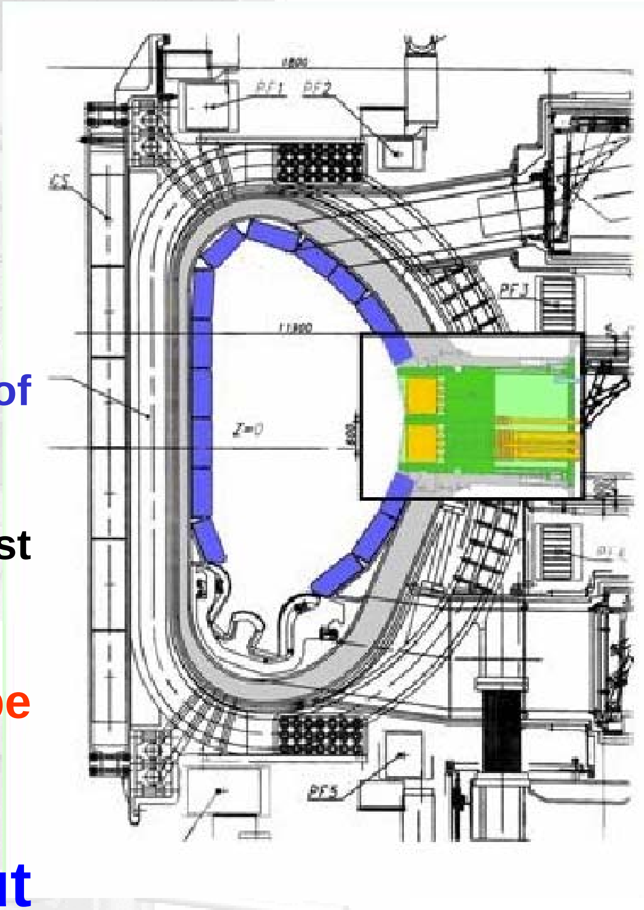
These issues have to be resolved before the starting of the procurements.

Test Blanket Module Program in ITER:

ITER is considered as a most suitable test-bed for the breeding blanket of next step.

3 equatorial ports are allocated for TBM.
Size of port ~1310 x 1760 mm.

Each port could include 2 types of TBM



The first TBMs must be installed in ITER since the start of the operation:

- **Finalisation of the design and supporting R&D must be completed soon.**
- **All modules before installation in ITER must be qualified for licensing in France:**

=> sufficient information about materials should be provided.

Summary

- The design and technical preparation for the construction of ITER are ready for implementation and inter-government negotiations are nearing to completion.

- The design of the ITER components is supported by the proper and justified materials selection. This is a results of extensive and successful world-wide ITER materials and technological R&D program.

- During construction phase the materials activity will be focused on:
  - Resolving of the urgent remaining issues before starting the procurement of materials,
  - Materials procurement and evaluation of the acceptance of the materials in the final components,
  - Further consolidation of the data, which are needed for the licensing and for justification of the safe and reliable performance of materials during the ITER operation.