Structural Metallic Materials

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NRG, Petten

9th Course
TECHNOLOGY OF FUSION TOKAMAK REACTORS
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OVERVIEW

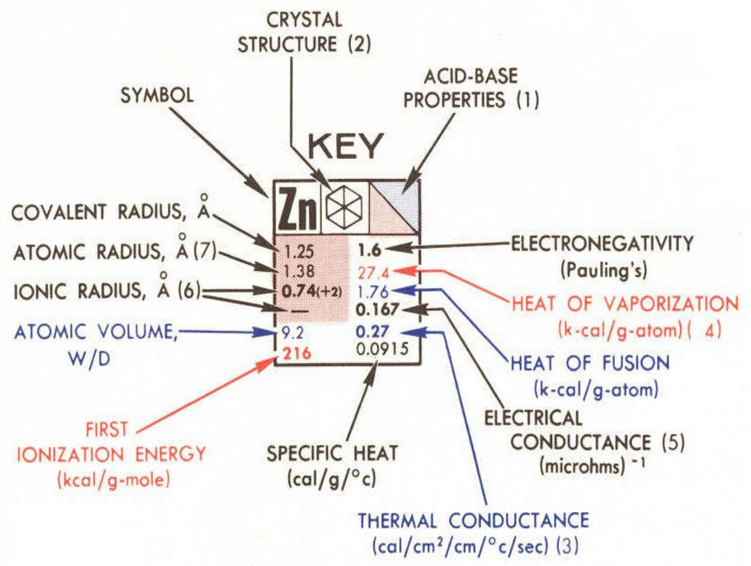
- Metals
- Alloys
- Thermal mechanical treatment
- Selection criteria for fusion power plant alloys
- Neutron radiation damage
- Mechanical loading
- Manufacturing options
- Alloy development paths
- Conclusion

METALS

- Ductile, for forming and shaping.
- Joining by diffusion and fusion welding.
- Tough, no brittle rock-like fracture.
- Strong,allowing slender structures.
- Properties controlled by:
  - Composition
  - Heat treatment
  - Mechanical treatment
- Compatibility control by composition or coating

Physico-chemical properties of fusion metals

IIIB	IVB	VB	VIB	VIIB	
Sc 1.44, 1.62, 0.81(+3), —, 15.0, 151 / 1.3, 81, 3.8, 0.015, 0.015, 0.13	**Ti** 1.32, 1.47, 0.90(+2), 0.68(+4), 10.6, 158 / 1.5, 106.5, 3.7, 0.024, —, 0.126	**V** 1.22, 1.34, 0.74(+3), 0.59(+5), 8.35, 156 / 1.6, 106, 4.2, 0.04, —, 0.120	**Cr** 1.18, 1.30, 0.69(+3), 0.52(+6), 7.23, 156 / 1.6, 72.97, 3.3, 0.078, 0.16, 0.11	**Mn** 1.17, 1.35, 0.80(+2), 0.46(+7), 7.39, 171 / 1.5, 53.7, 3.50, 0.054, —, 0.115	**Fe** 1.17, 1.26, 0.76(+2), 0.64(+3), 7.1, 182 / 1.8, 84.6, 3.67, 0.10, 0.18, 0.11
Y 1.62, 1.78, 0.93(+3), —, 19.8, 152 / 1.3, 93, 2.7, 0.019, 0.035, 0.071	**Zr** 1.45, 1.60, 0.80(+4), —, 14.1, 160 / 1.4, 120, 4.0, 0.024, —, 0.066	**Nb** 1.34, 1.46, 0.70(+5), —, 10.8, 156 / 1.6, —, 6.4, 0.080, 0.125, 0.065	**Mo** 1.30, 1.39, 0.68(+4), 0.62(+6), 9.4, 166 / 1.8 •, 128, 6.6, 0.19, 0.35, 0.061	**Tc** 1.27, 1.36, —, —, —, 167 / 1.9, 120, 5.5, —, —, —	**Ru** 1.25, 1.34, 0.69(+3), 0.67(+4), 8.3, 173 / 2.2, 148, 6.1, 0.10, —, 0.057
La★ 1.69, 1.87, 1.15(+3), —, 22.5, 129 / 1.1, 96, 1.5, 0.017, 0.033, 0.045	**Hf** 1.44, 1.67, 0.81(+4), —, 13.6, 127 / 1.3, 155, 5.2, 0.031, 0.22, 0.035	**Ta** 1.34, 1.49, 0.73(+5), —, 10.9, 138 / 1.5, 180, 6.8, 0.081, 0.13, 0.036	**W** 1.30, 1.41, 0.64(+4), 0.68(+6), 9.53, 184 / 1.7, 185, 8.05, 0.181, 0.40, 0.032	**Re** 1.28, 1.37, —, —, 8.85, 182 / 1.9, 152, 7.9, 0.051, 0.17, 0.033	**Os** 1.26, 1.35, 0.69(+4), —, 8.43, 201 / 2.2, 162, 6.4, 0.11, —, 0.031

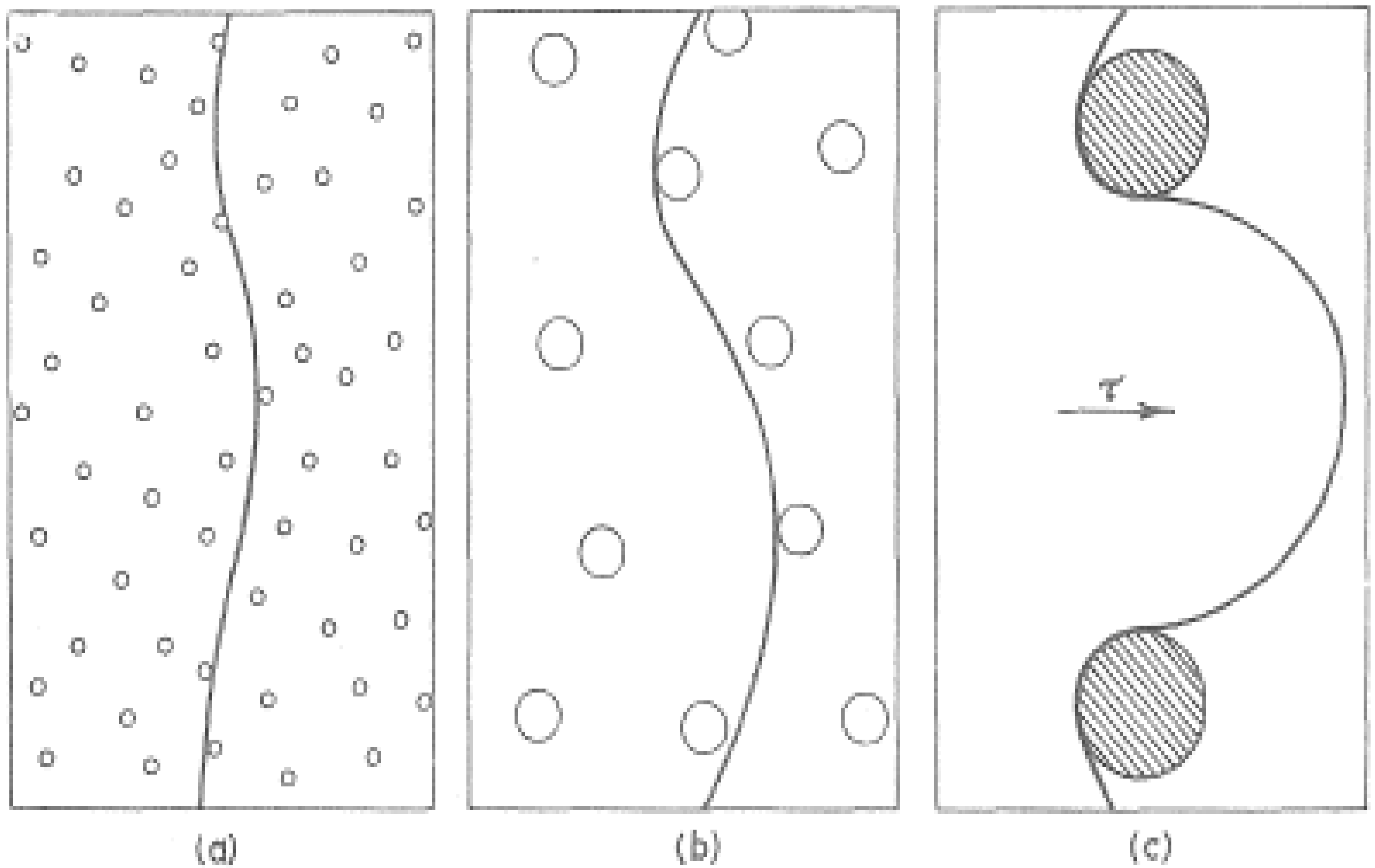


Cubic, face centered; cubic, body centered; diamond; cubic;
hexagonal; rhombohedral; tetragonal; orthorhombic; monoclinic.

Deformation by dislocation movement

- Low energy process by:
  - Edge dislocation: carpet wave.
  - Screw dislocation: stairway shape.
  - Mixed mode.
- Strength & ductility control with obstacles for dislocation movement:
  - interstitials and substitutionals
  - precipitates & phase borders
  - grain boundaries

Obstacles effects on deformation by dislocation movement



Main properties of refractory metals

	V	Nb	Ta	Cr	Mo	W
Melt Temp. , °C	1890	2468	2996	1875	2610	3410
Recrystall. , °C	900	1150	1350	900	1200	1500
Conductivity	0.09	0.15	0.16	0.16	0.28	0.30
Strength	High	V.high	V.high	High	V.high	V.high
Toughness	Fair	Fair	Fair	Poor	Doubt	Poor
Forming	Good	Good	Good	Poor	Depends	Poor
Welding	Depends	Good	Good	Poor	Depends	V. Poor
Compatibility	Limited	Limited	Limited	Fair	Good	Good
Activation	Excellent	Poor	Good	Good	Poor	Fair

ALLOYS

- Simple mixtures with:
  - interstitial atoms: carbon & nitrogen in iron.
  - substitutional atoms: chromium in iron.
- Precipitation hardening with basic metal: Fe_3C carbide.
  Temperature increases coarsen precipitation: weakening
- Dispersion of extraneous particles:
  - Oxide particles in steel: Y_2O_3 more thermally stable.
- Mixtures with fibres:
  - Aligned: direction dependent properties
  - Random: isotropic properties

Character of solubility of Elements in Iron

Solubility of the elements in the crystal lattices of iron.

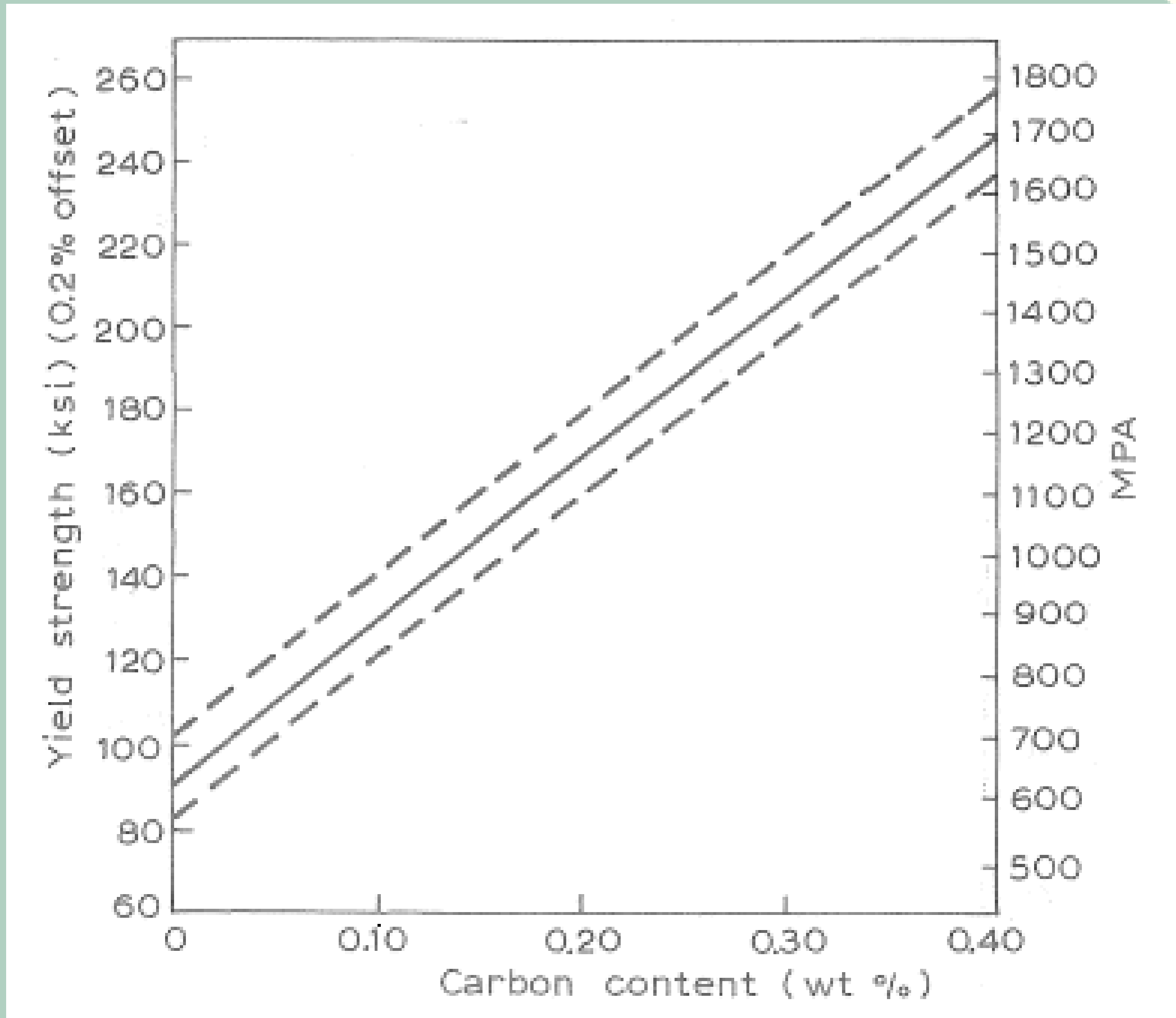
H 1																	He 3
Li 3	Be 2											B 1	C 1	N 1	O 1	F 3	Ne 3
Na 3	Mg 3											Al 2	Si 2	P 2	S 3	Cl 3	Ar 3
K 3	Ca 3	Sc 3?	Ti 2	V 2^b	Cr 2^b	Mn 2^b	Fe	Co 2^b	Ni 2^b	Cu 2	Zn 2	Ga 2	Ge 2	As 2	Se 3	Br 3	Kr 3
Rb 3	Sr 3	Y 3?	Zr 2	Nb 2	Mo 2	Tc 2	Ru 2	Rh 2^b	Pd 2^b	Ag 3	Cd 3	In 3	Sn 2	Sb 2	Te 3	I 3	Xe 3
Cs 3	Ba 3	La 3?	Hf 2?	Ta 2	W 2	Re 2	Os 2	Ir 2^b	Pt 2^b	Au 2	Hg 3	Tl 3	Pb 3	Bi 3	Po 3?	At 3	Rn 3
Fr 3	Ra 3	Ac 3?	Th 3?	Pa 3?	U 3	Np 3?	Pu 3?	Am 3?	Cm 3?	Bk 3?	Cf 3?						

1. interstitial elements
2. substitutional elements
3. practically no solubility

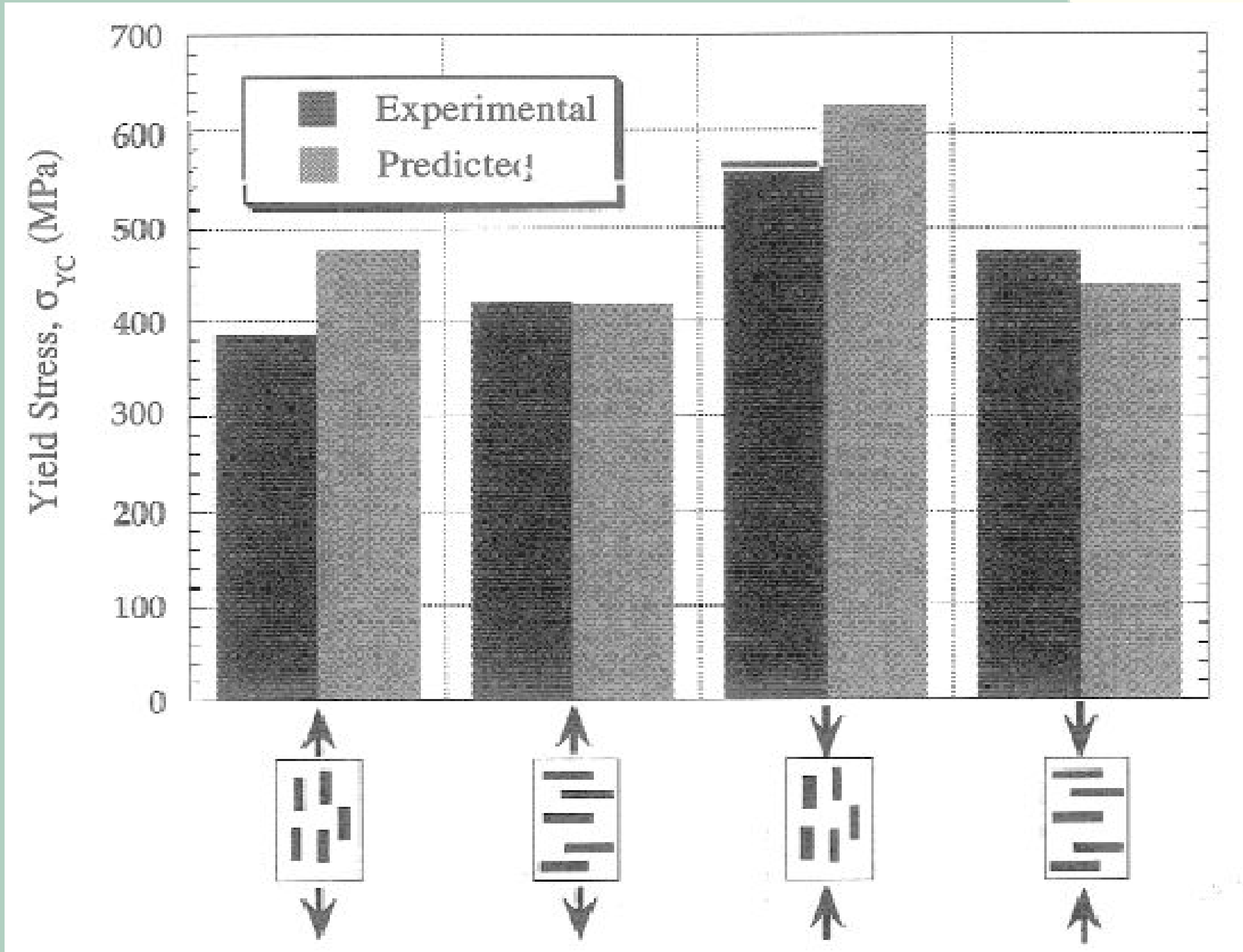
P may be interstitial in the fcc structure.

[b] complete solubility at certain temperatures.

Carbon effects on strength of Iron



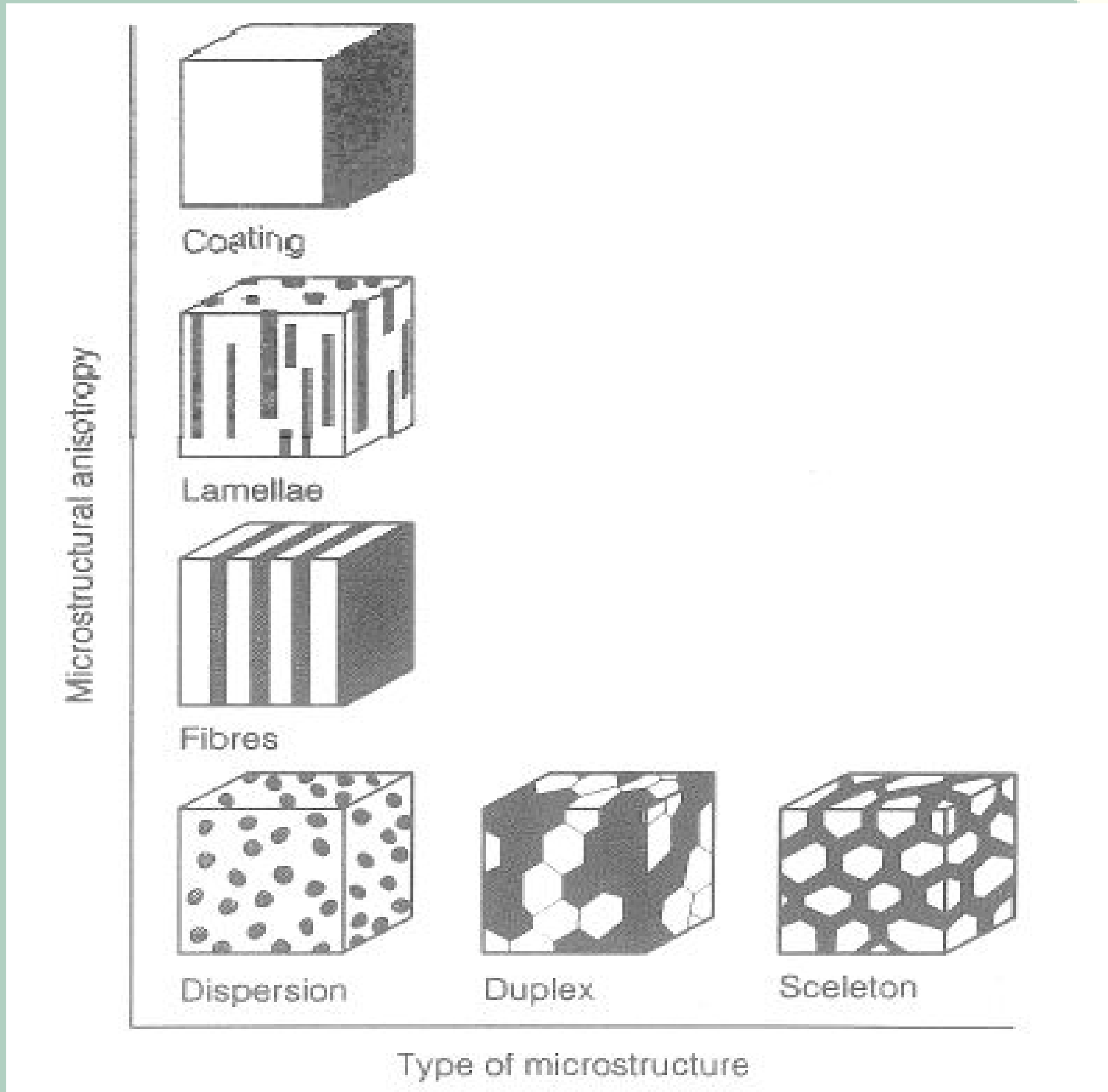
Experimental and predicted fibre direction effect on strength



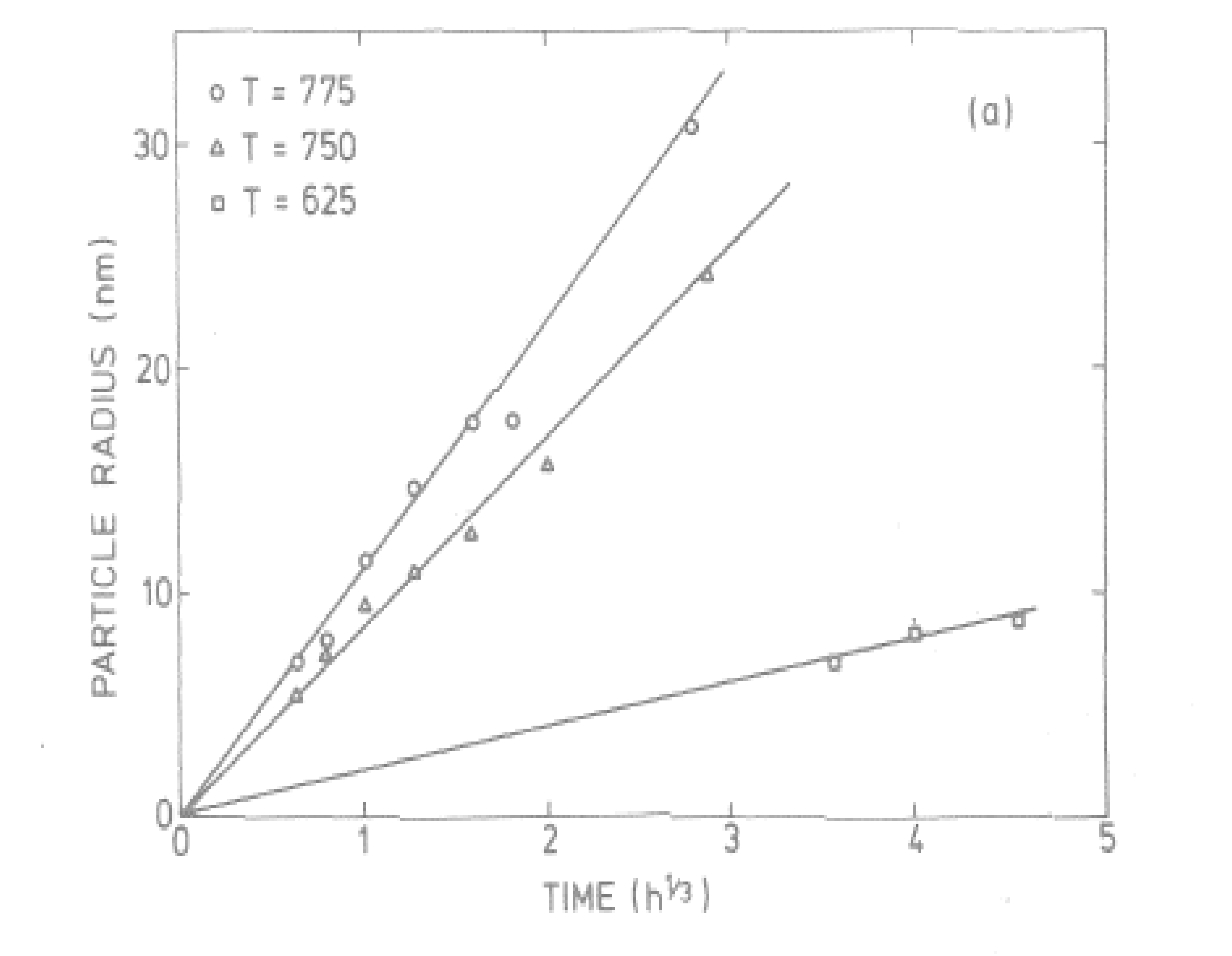
THERMAL MECHANICAL TREATMENT

- * Thermal treatments:
  - - Solid state reactions: precipitation control
  - - Phase transitions
    - - Equilibrium microstructures
    - - In freezing of meta-stable microstructures
- * Mechanical treatments:
    - - Breaking up of precipitates
    - - Refine grain size
    - - Create cold work or dislocation sub-structures

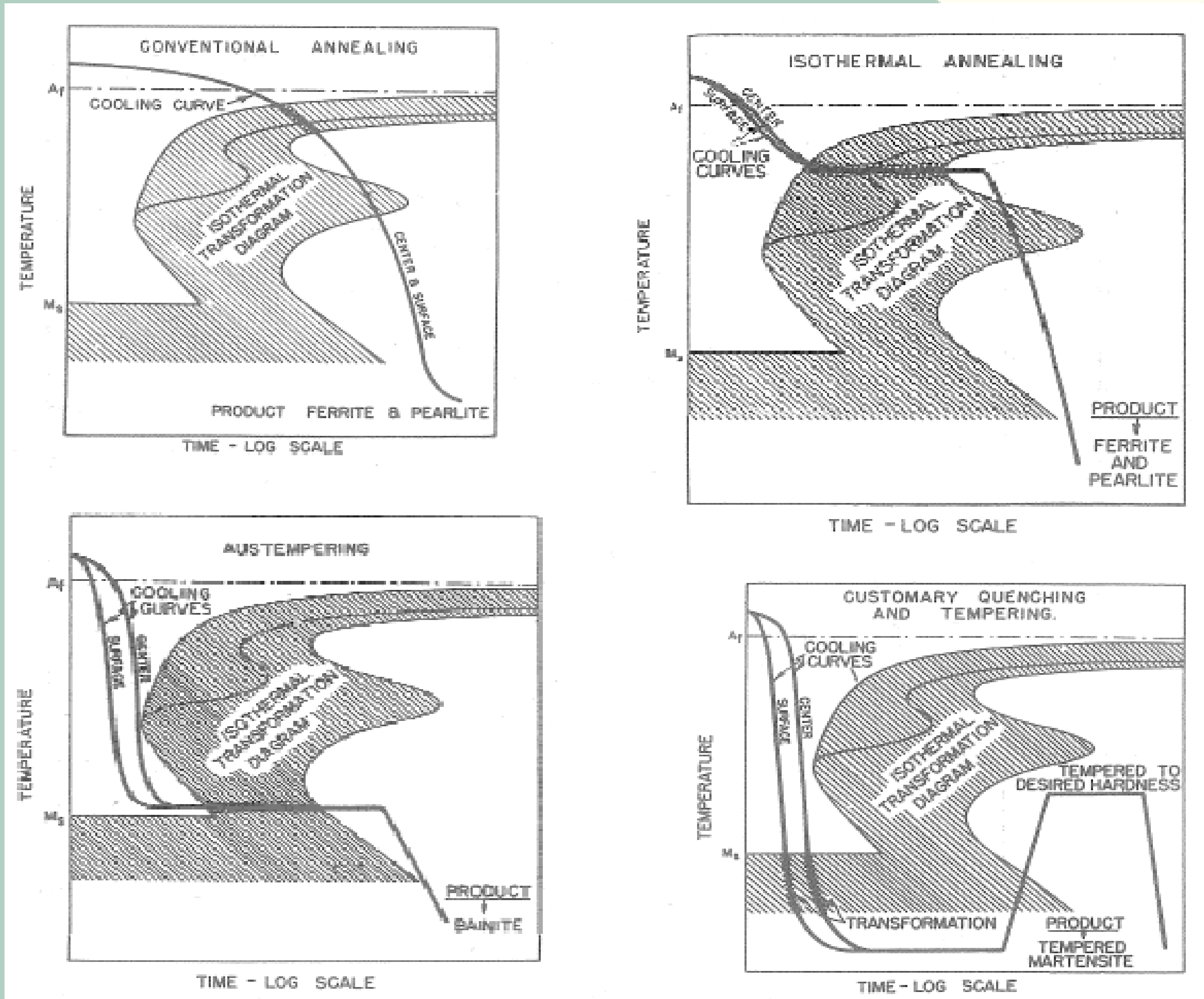
Microstructure Classification



Particle growth in dependence of temperature



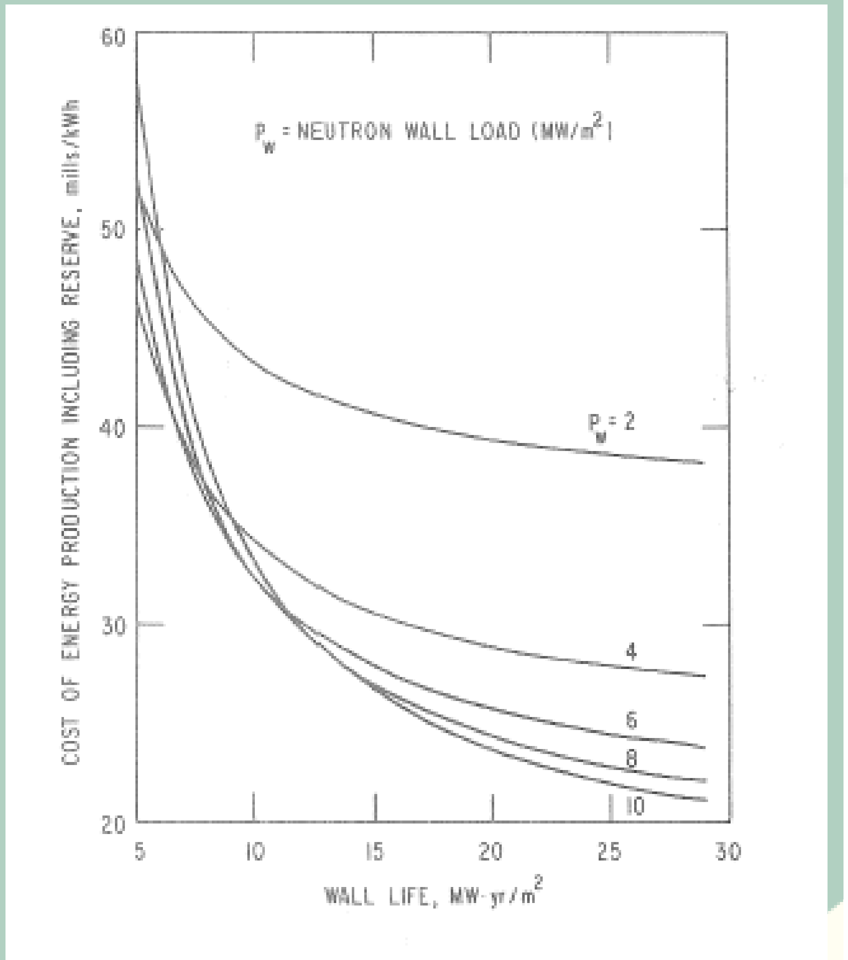
Thermal treatment effects on steel

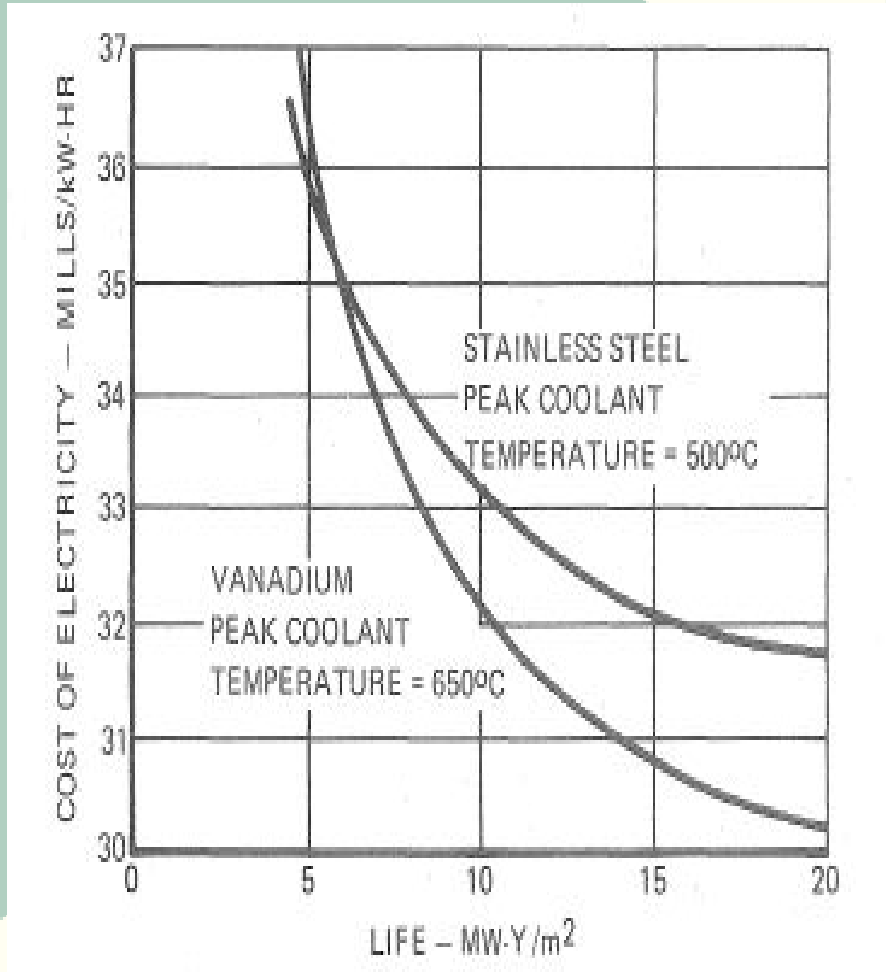


SELECTION CRITERIA FOR FUSION POWER PLANT ALLOYS

- Neutron radiation:
  - Dimensional stability: swelling < 0.1%.dpa-1
  - Displacement damage: 30 dpa.y-1 of 14 MeV neutrons
  - Transmutation products: Helium & Hydrogen
- Activation of alloying elements and impurities
- Compatibility with coolants.
- Static and dynamic mechanical properties.
- Thermal properties: stress parameter.
- Materials availability and production.
- Manufacturing: forming and joining.
- Cost.

Effects of neutron wall load and operating temperature on cost of power generation





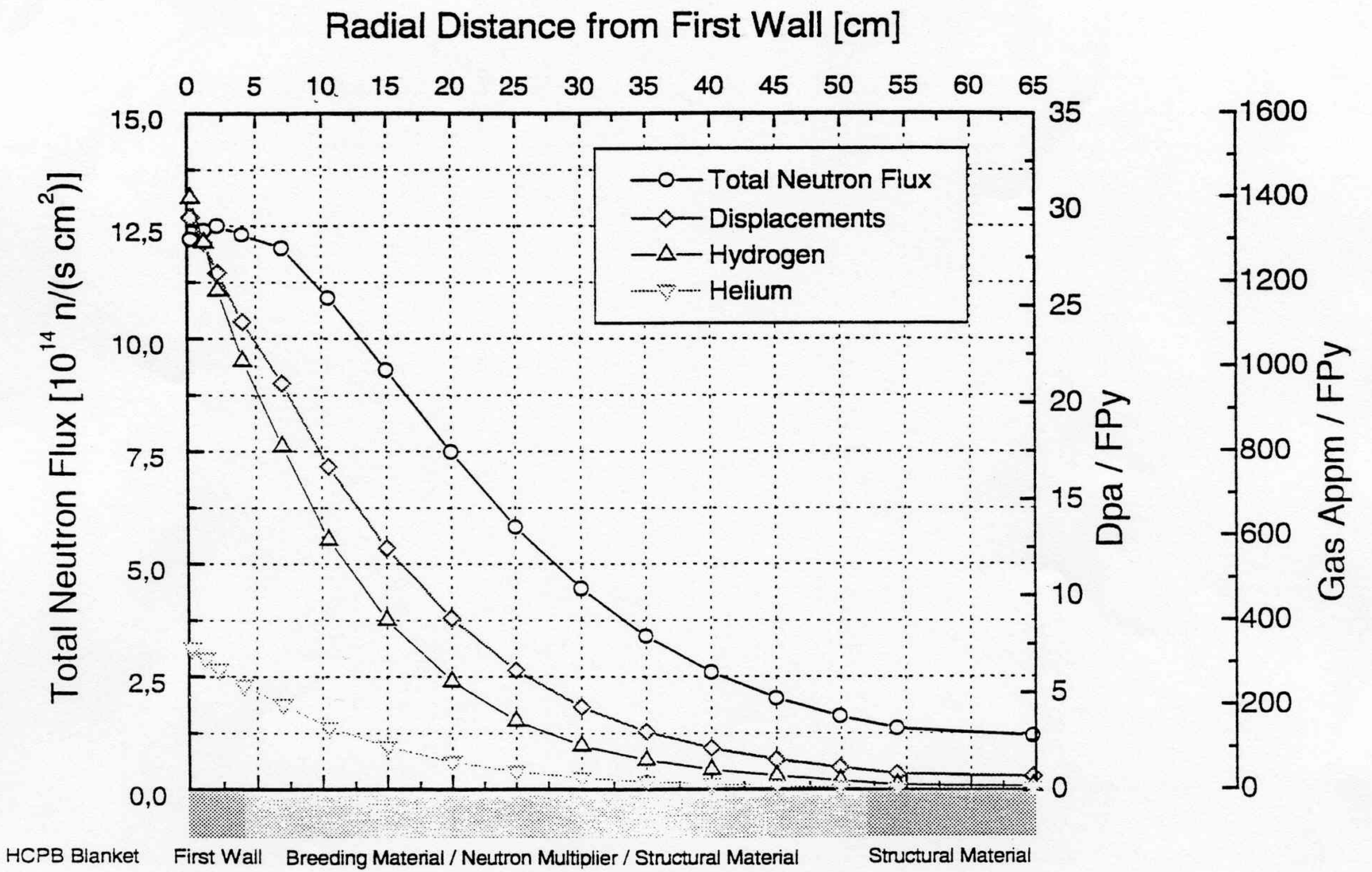
Primary power plant requirements

- **Low investment costs**:
  - High efficiency needing high operating temperatures.
  - Compact plant: smaller buildings and components.
- **Low operating costs**:
  - High reliability of components and materials.
  - Short refuelling & maintenance outages.
- **Economic decommissioning**:
  - Simple shaped structures and components.
  - Re-cycling of materials
  - Compact waste of low activity level.

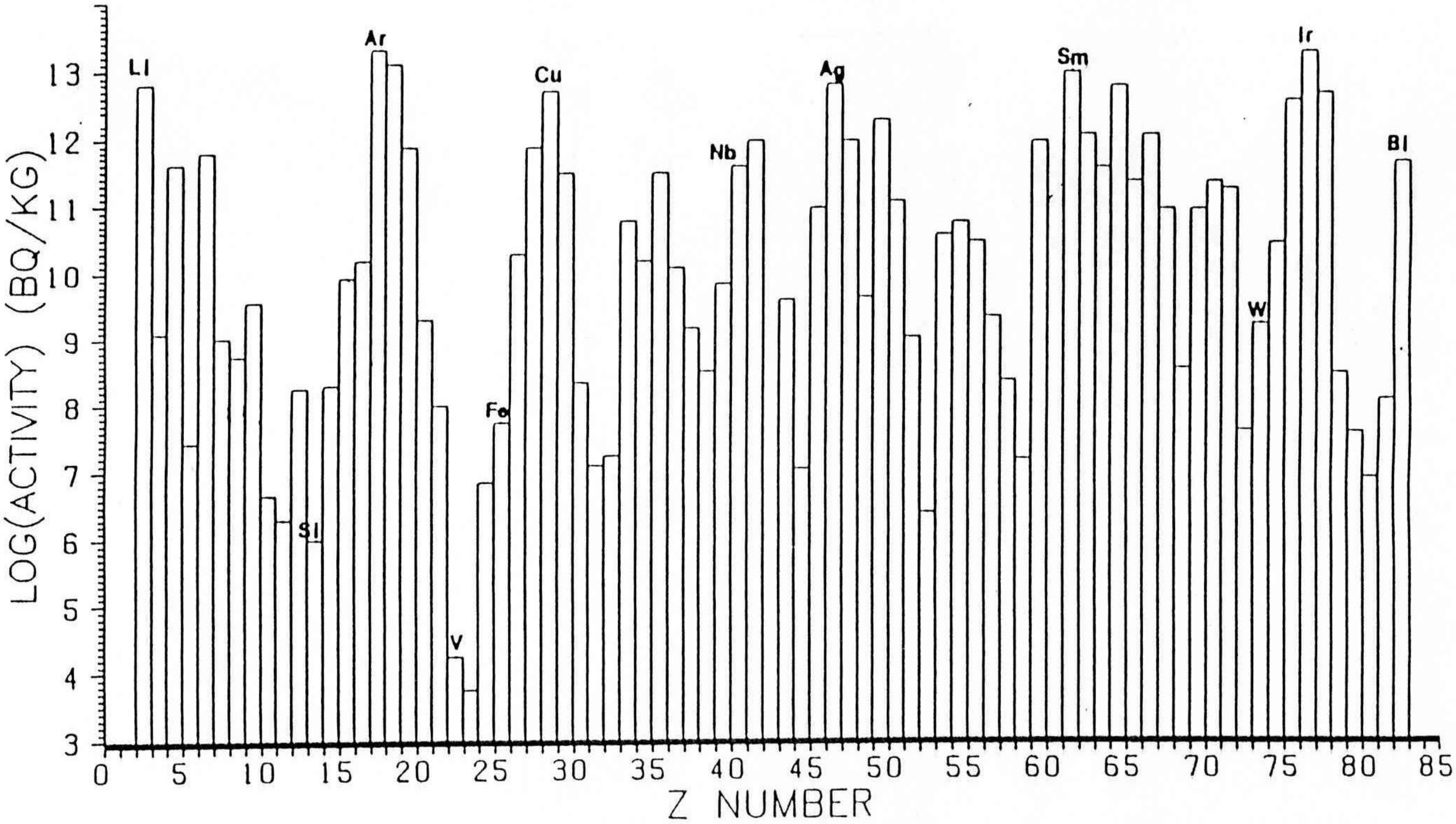
Materials choice consequences

- Sufficient mechanical properties window with high upper operating temperature.
- Mechanically reliable joints with negligible defects
- Components with inspectable shapes and joints.
- Long term compatibility at high operating temperature.
- Re-cycling of materials with trusted composition.
- Low activation properties of the alloy constituents.
- Strict control down to ppb level for some impurities.

NEUTRON RADIATION DAMAGE

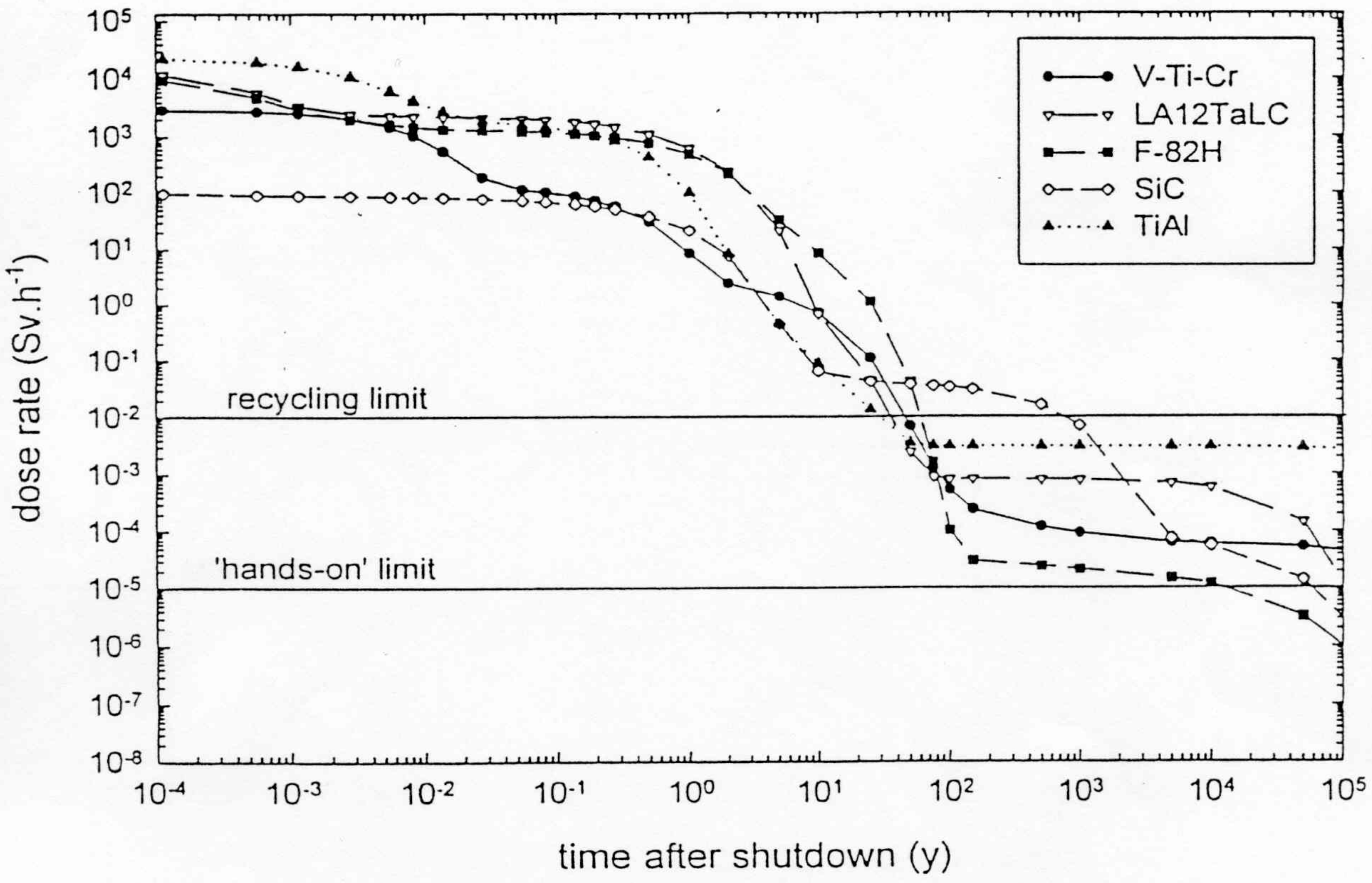


Activitity of the elements after 100 years

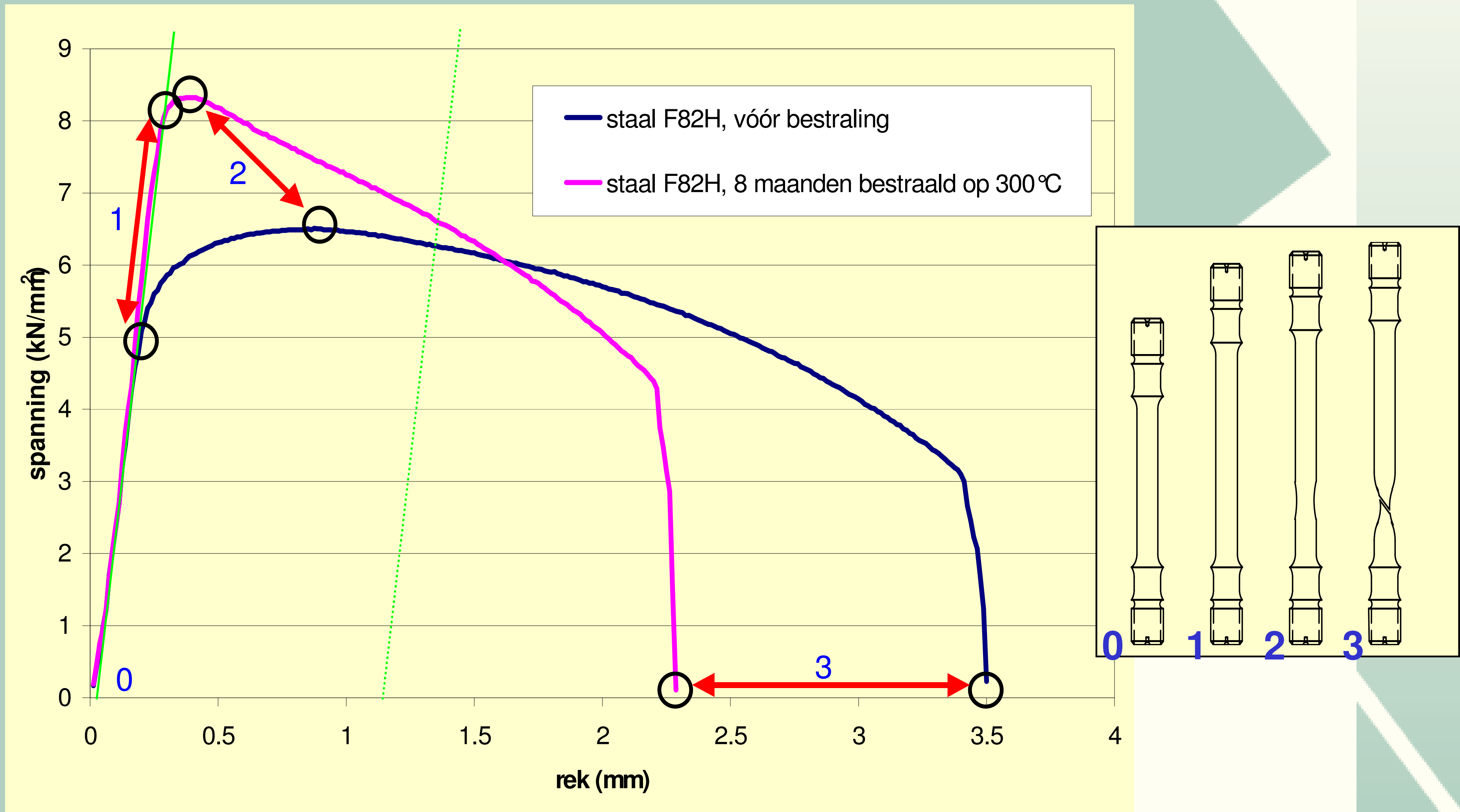


Activities of Pure Elements after 100 years

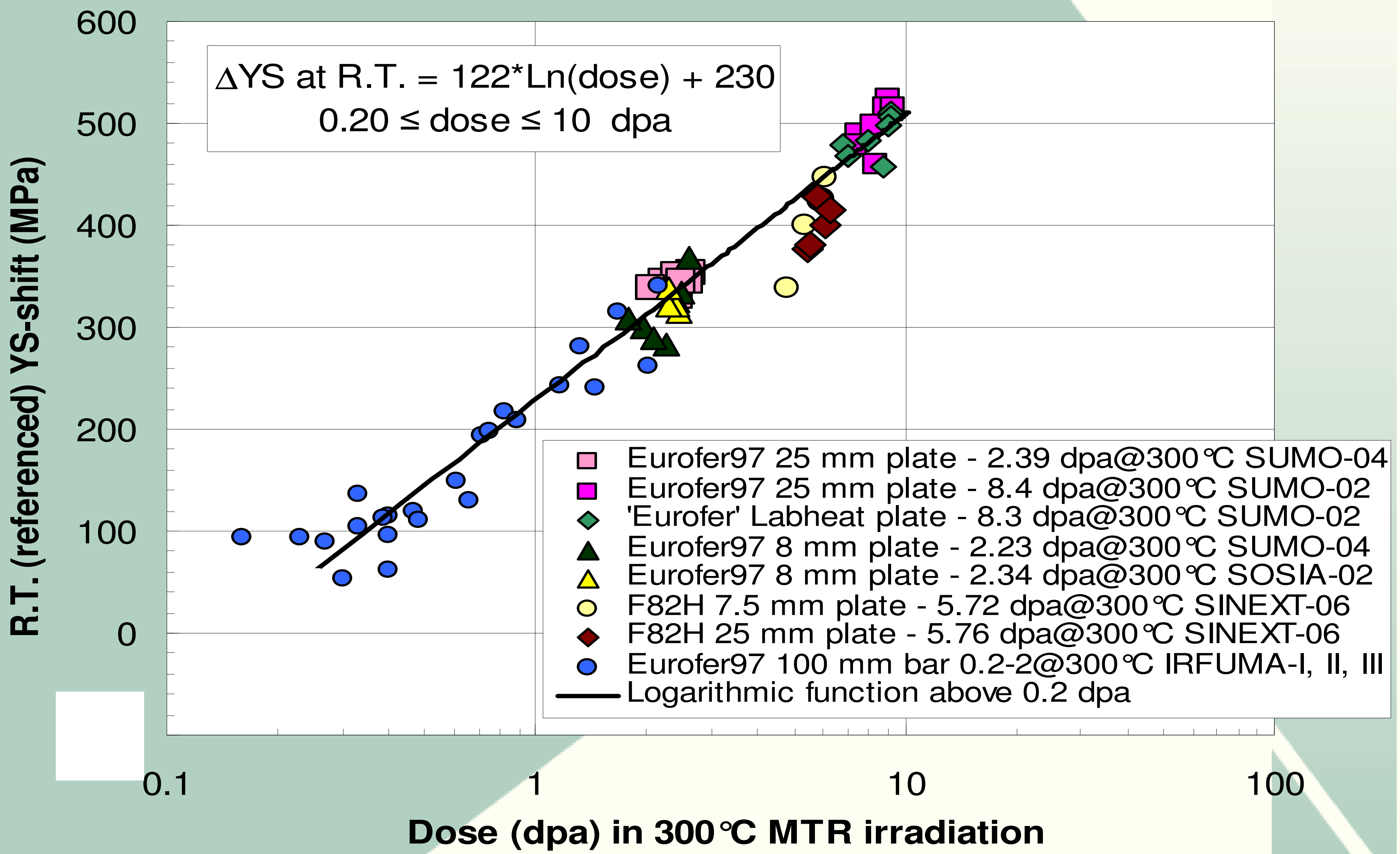
Alloy activation reduction in time



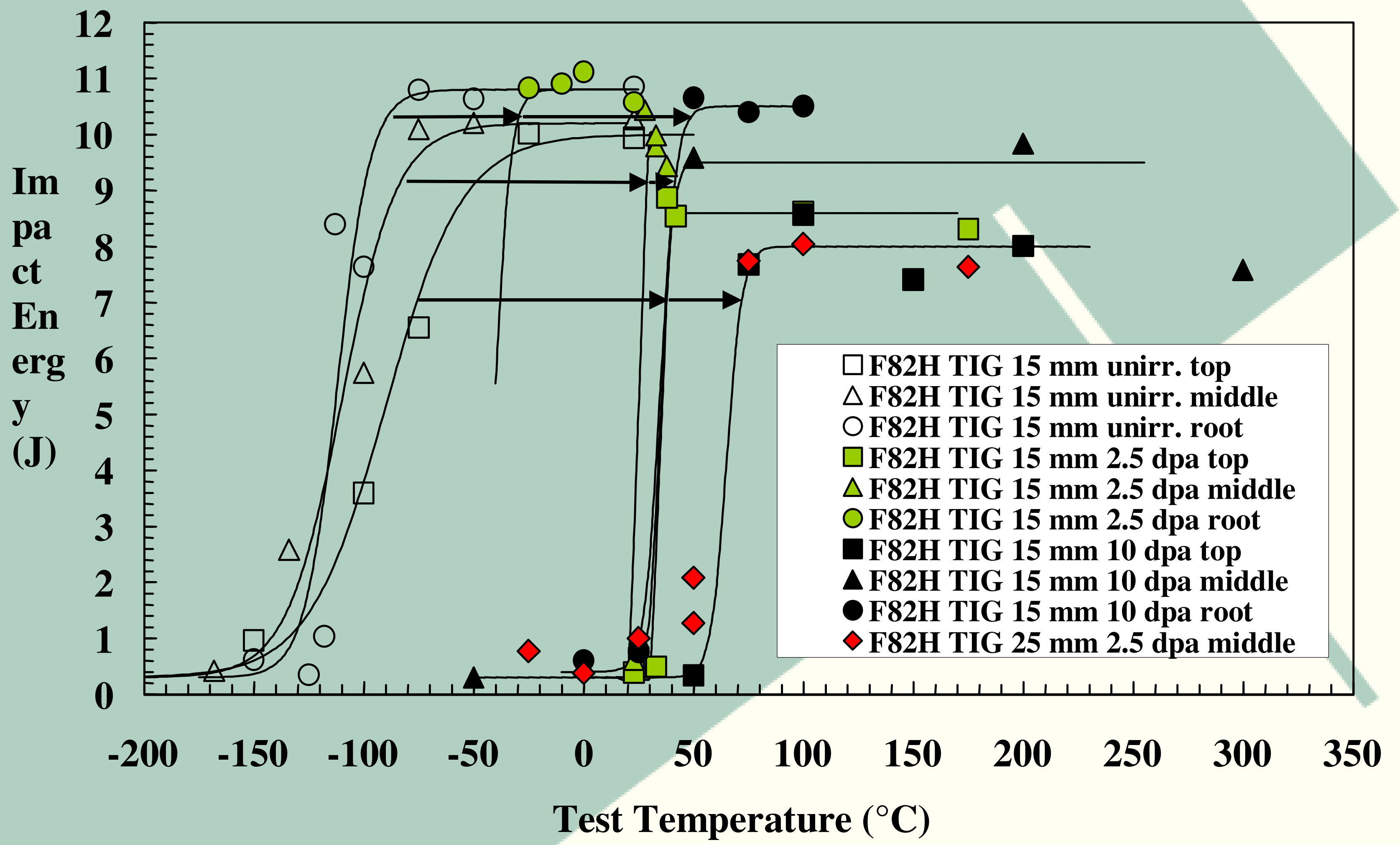
Tensile curves of 9% Cr reduced activation steel



Irradiation Hardening



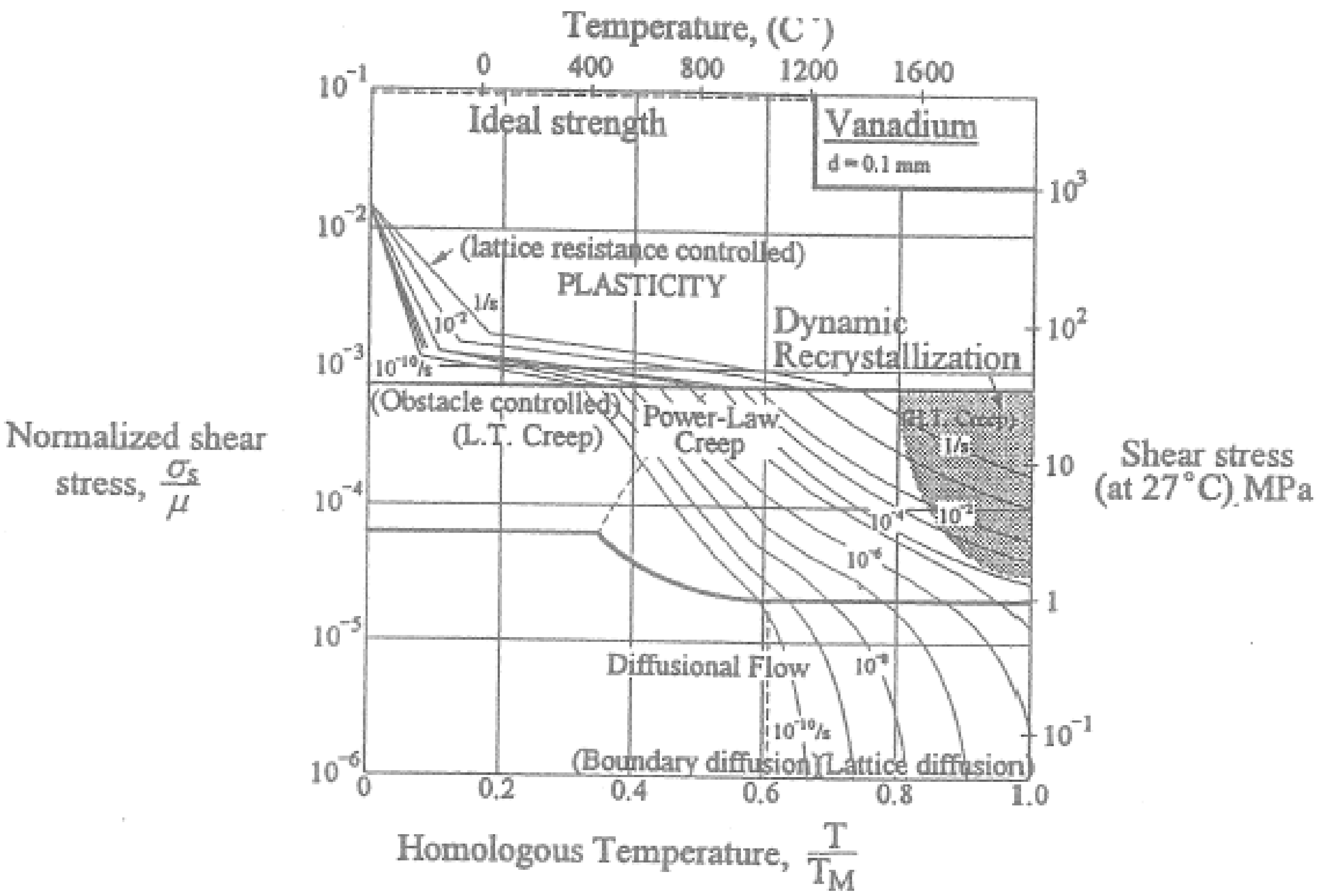
Irradiation effects on toughness



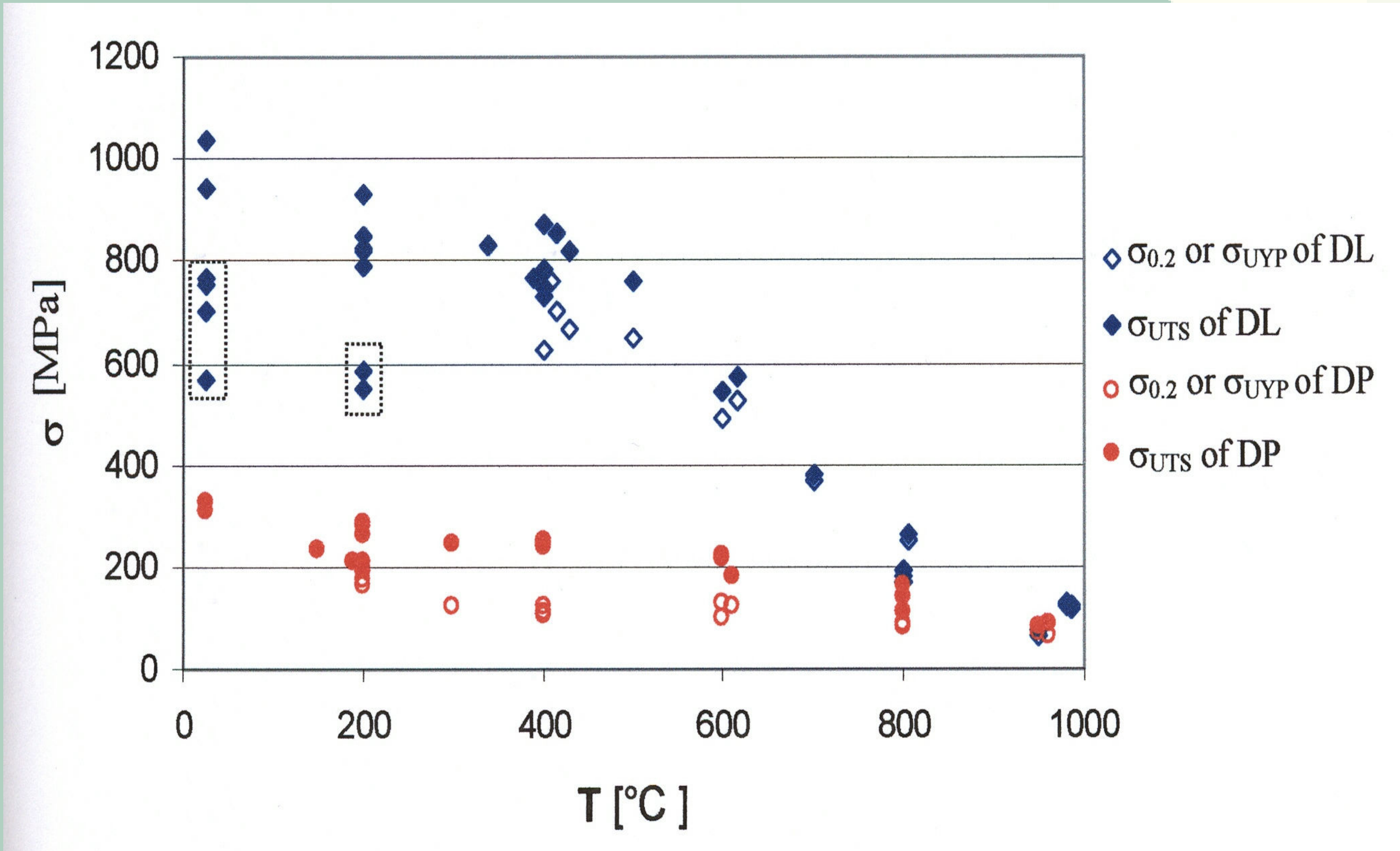
MECHANICAL LOADING

- **Static**
  - Tensile strength and ductility, rate > 10E^{-6} s^{-1}
  - Creep strength and ductility
  - Relaxation
  - Fracture toughness
- **Dynamic**
  - Thermal & mechanical low cycle fatigue, $N<10^5$
  - Thermal & mechanical high cycle fatigue, $N>10^5$
  - Crack propagation
  - Impact toughness

Deformation map of Vanadium



Tensile strength of pure Chromium and a Chromium alloy



Thermal stress resistance

Alloy	Thermal stress resistance $[W.m^{-1} * 10^{-3}]$
Annealed type 316	1.3
RAFM 9% CrW steel	8.5
Titanium 6% Al 4% V	10.2
Vanadium 20% Ti	12.3
Niobium 1% Zr	19.8

Thermal stress resistance: $2 * \sigma_Y * K * (1-\nu)/(\alpha * E)$

and:

σ_Y = yield stress

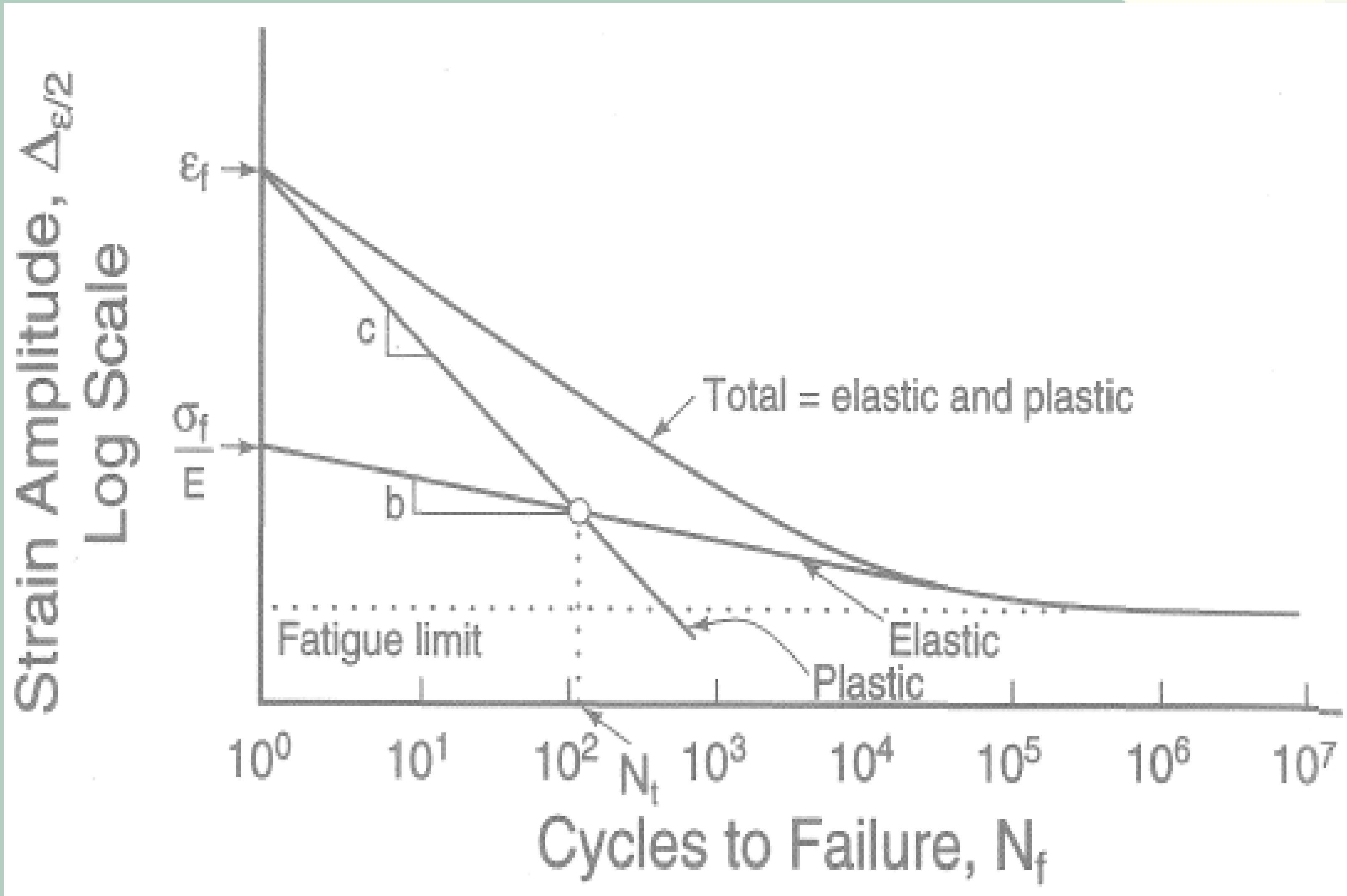
K = Thermal conductivity

ν = Poisson's ratio

α = Thermal expansion coefficient

E = Elastic modulus

Low and high cycle fatigue endurance

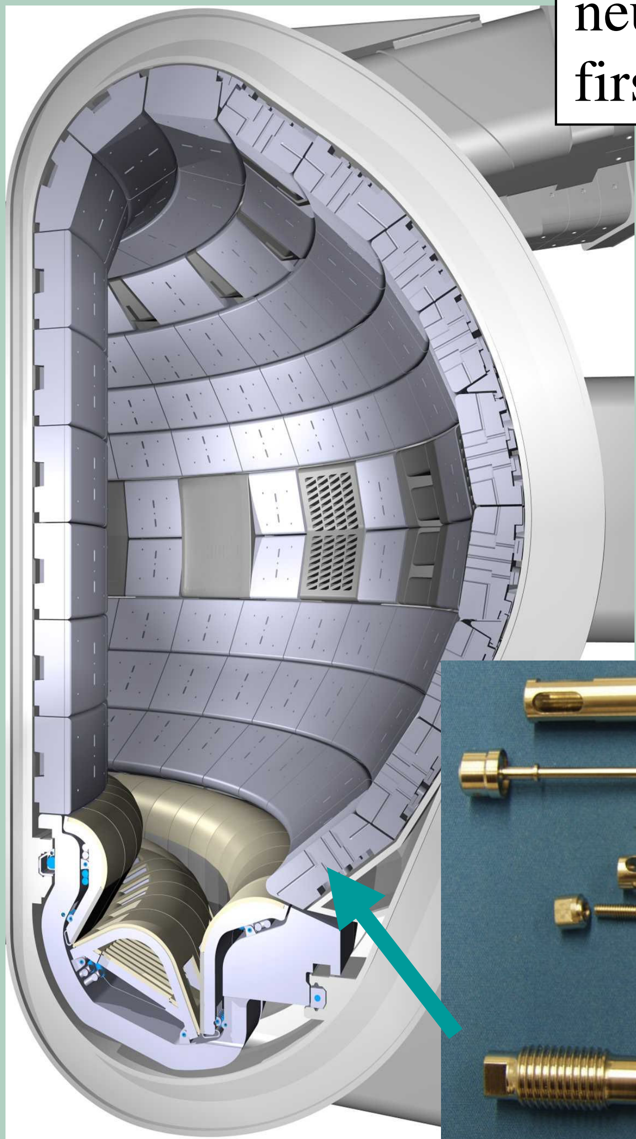


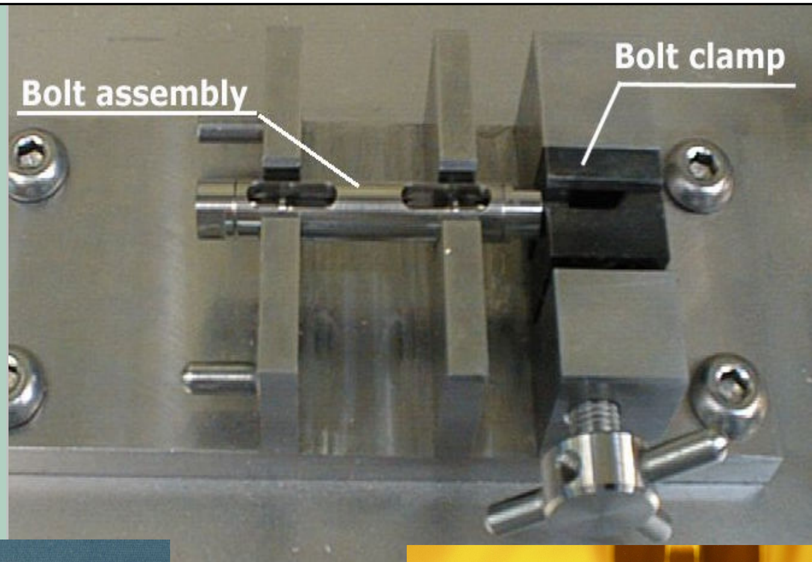
MANUFACTURING OPTIONS

* Half products
  - Forging and rolling curved/flat plates
  - Drawing round & square tubes.
* Shaping
  - Free form Powder HIP
  - Extrusion of all kinds of profiles.
* Welding
  - Tungsten & metal inert gas fusion
  - Electron/Laser beam
  - Diffusion welding: solid HIP of structures

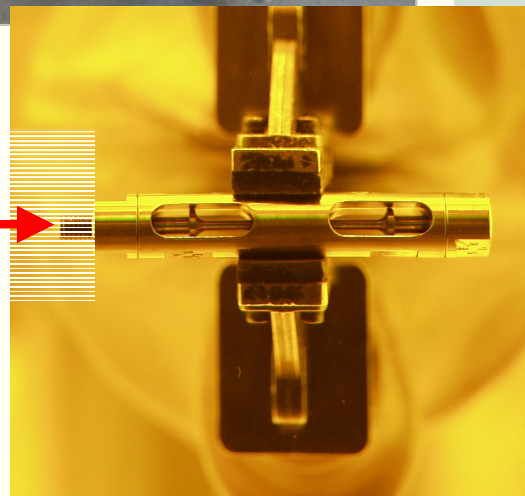
Bolting structures in ITER

Stress relaxation in high strength alloys by neutron radiation for design verification of ITER first wall & shield module attachment



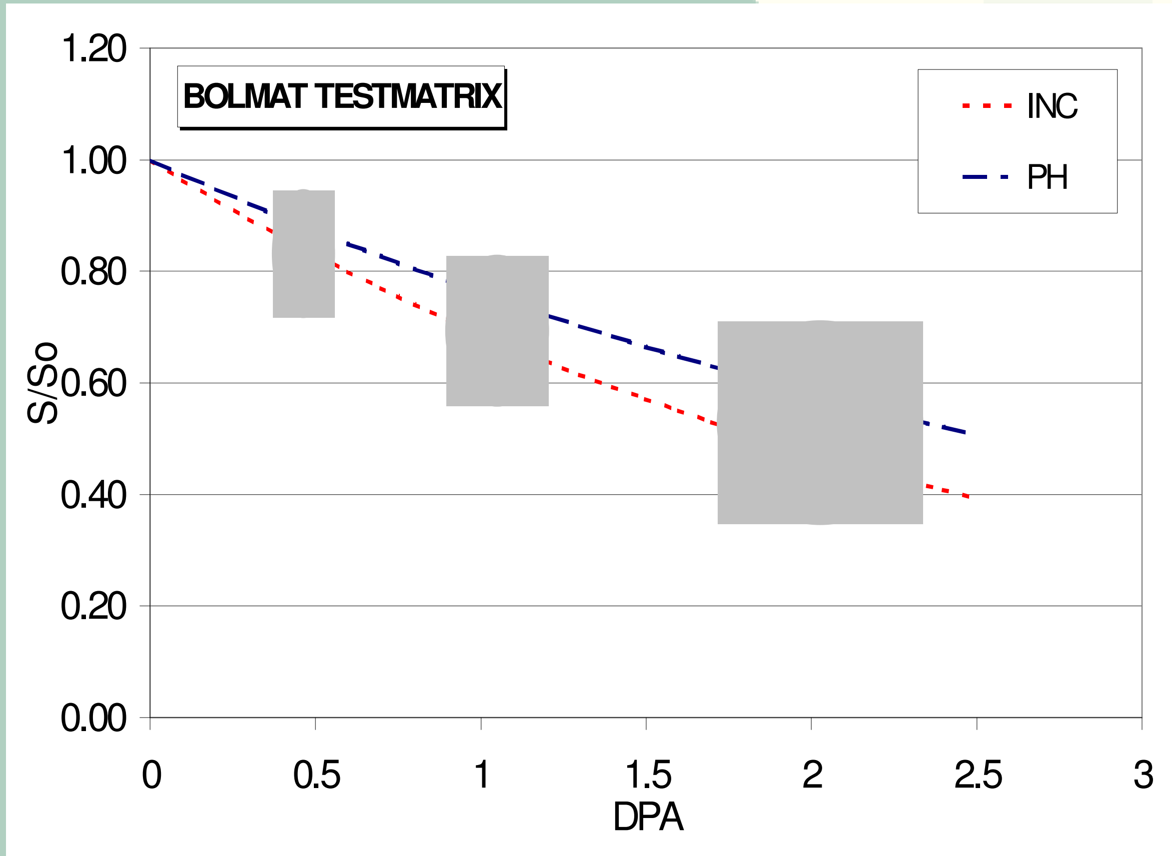


Miniature stressed bolt



Test results bolting structures for ITER

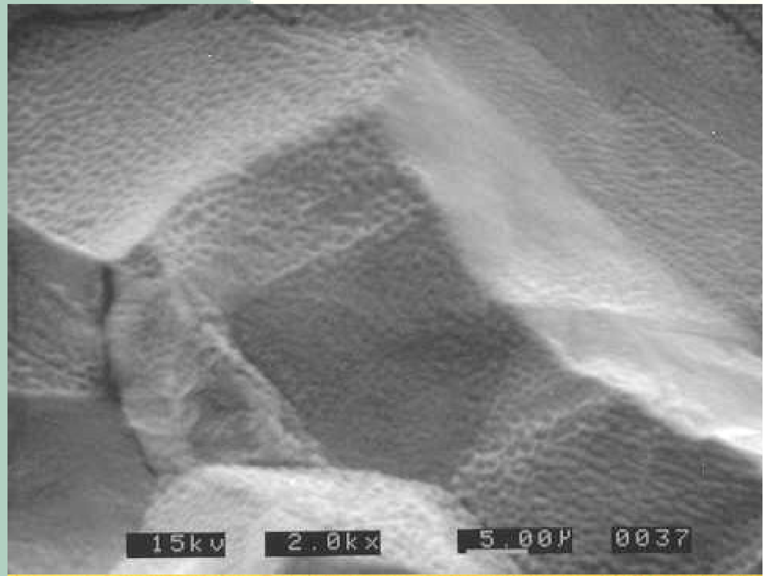
* Radiation of pre-stressed bolts & strips in the HFR, Petten, using STROBO rig.
* Temperature: 300±15° C
* Accuracy better than 3 µm
* Neutron dose variation: 0.5, 1 en 2 dpa

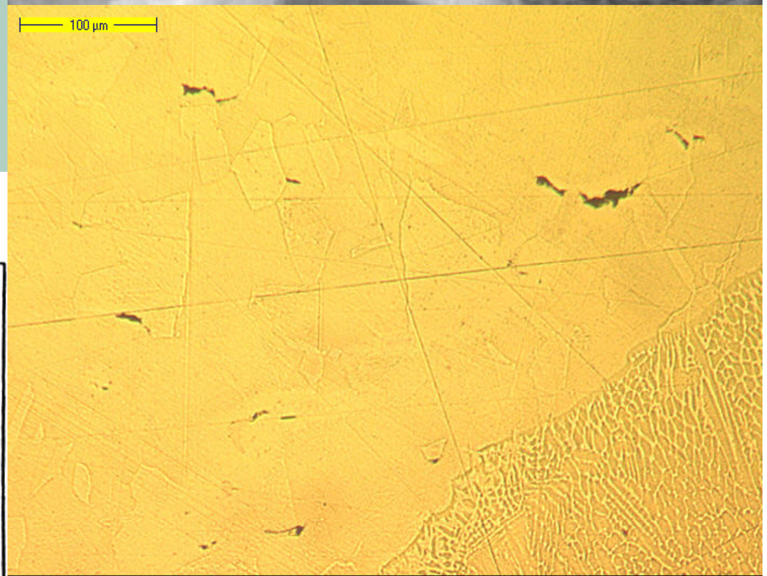


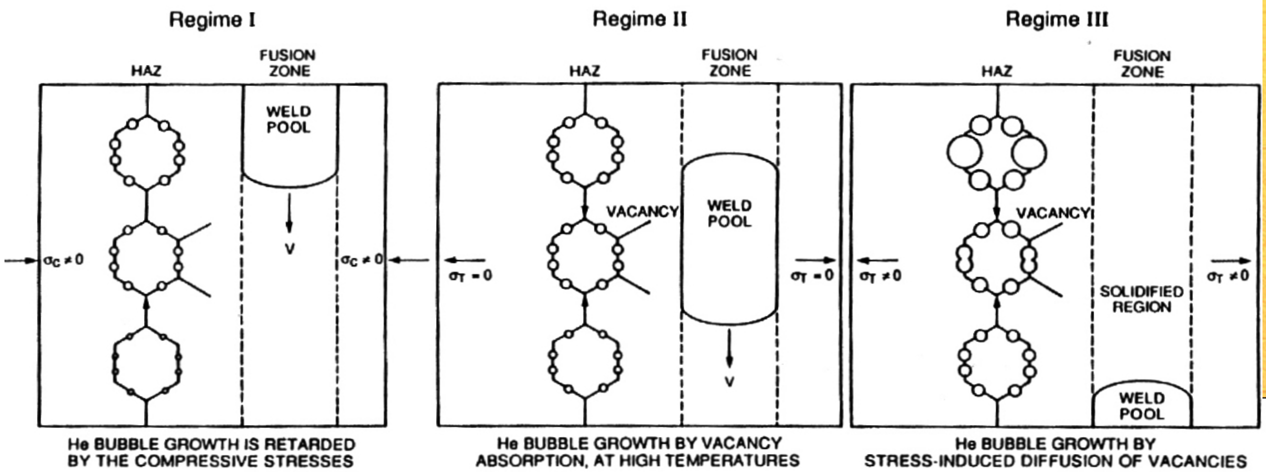
Welding tests for ITER Vacuum Vessel

Welding of irradiated Type 316L(N):

* Neutron radiated steel contains **Helium** from neutron reactions with ^{10}B en Ni
* Irradiated Type 316L(N) suffers helium embrittlement
* Welding difficult caused by lack of ductility from He-bubbles







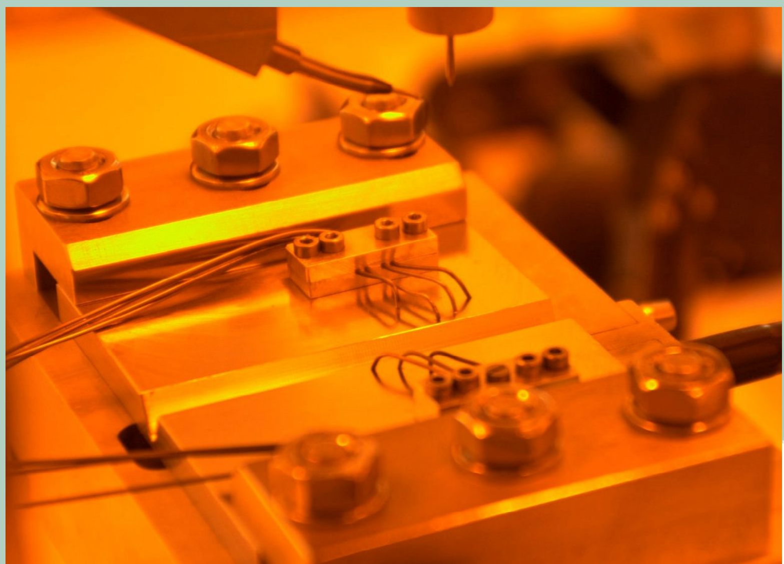
Welding tests for ITER Vacuum Vessel

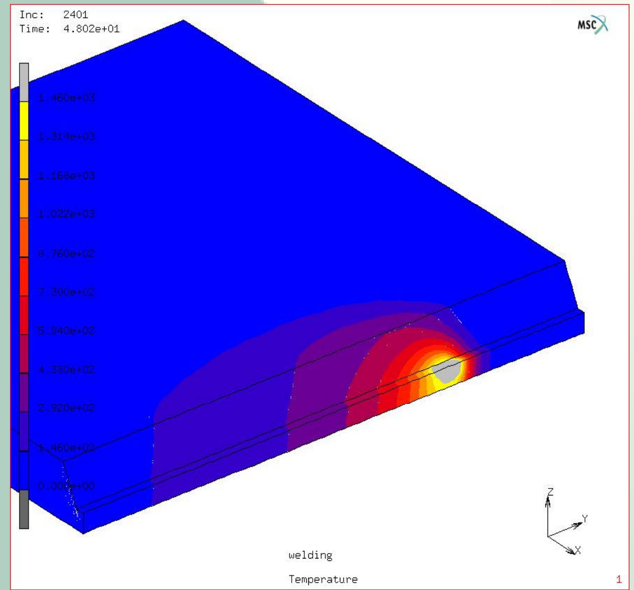
Development of 3D plasticity model for:

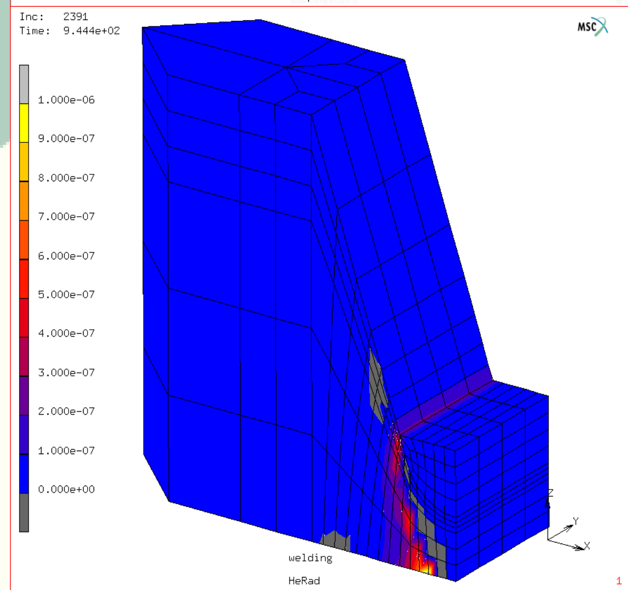
1: Critical locations.

2: Optimal weldparameters.

3: Determination of sample size for re-welding demonstration with Type 316 steel irradiated in the HFR, Petten







ALLOY DEVELOPMENTS PATHS

* Improvement of the weaker alloys through
  - Use of high strength fibre re-inforcement
  - Refinement of dispersions for strength
* Apply multi-axial deformation processes for the introduction of nano-microstructures to improve toughness of the high temperature -high strength refractory alloys.
* Shorten re-cycling period with reduction in impurity content of scrap and equipment.

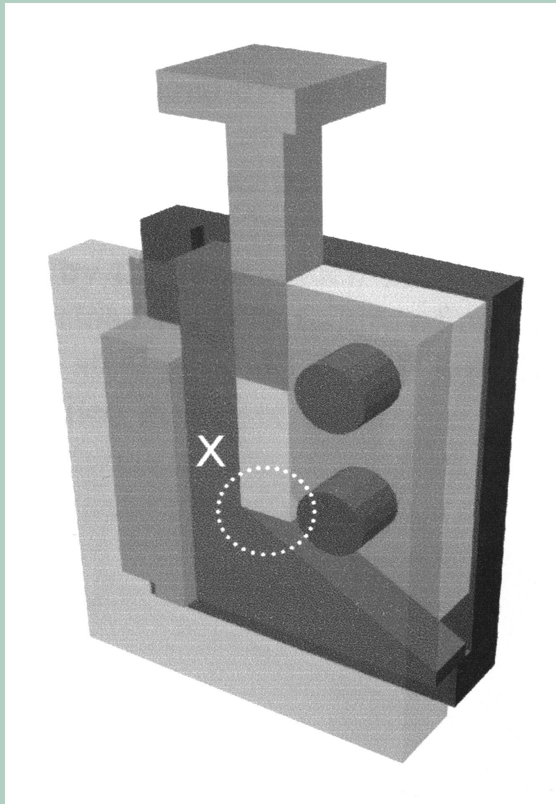
Operating temperature boundaries in °C

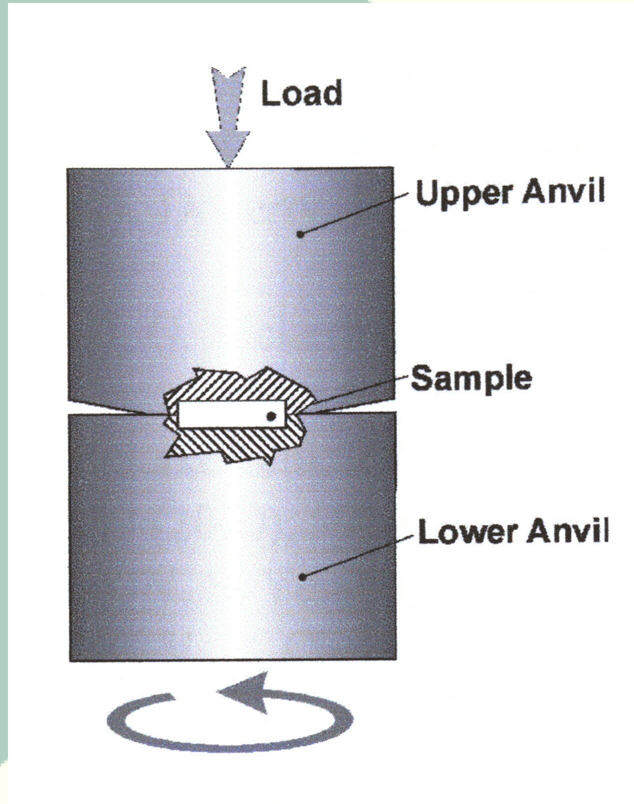
Material	Lower	Upper
Tungsten	900	1200
Tantalum	775	1200
Molybdenum	850	1200
Niobium	750	1150
Chromium	500	800
Vanadium 4Cr4Ti	400	700
9%Cr ODS steel	275	700
9%Cr steel	275	550
Type 316 ss	RT	600

Fusion relevant alloys evaluation

* **Refractory alloys**	**Doubts**
- Vanadium 4 Cr4Ti.	Li coolant only, interstitials
- Tungsten Rhenium alloys.	Composition unstable, brittle
- Chromium, particle hardened.	Manufacturing, brittle
- TZM Molybdenum	Activation
- Niobium.	Activation, availability
* **Steels:**	
- Austenitic Type 316, (20 % CW)	Swelling, helium brittleness
- Austenitic Manganese steels	Radiation brittle, compatibility
- 9 % Chromium steels	Radiation brittleness
* **Titanium alloys**	Hydrogen compatibility
* **Aluminium alloys**	Low operating temperature

Severe Plastic Deformation for nano-structured materials





Equal Channel Angular extrusion **High Pression Torsion**

- Sub micrometer & nanometer grains
- High ductility materials

Fusion Materials Theory Development Fields

Time [s]	Length[m]	Theory	Main Effects	Verification Test
10^{-15}-10^{-8}	10^{-12}-10^{-8}	Molecular Dynamics	One place Lattice defects	TEM
10^{-8}-10^{+3}	10^{-8}-10^{-3}	Kynetic Monte Carlo	Accumulation Voids, bubbles precipitation	TEM, SANS, positron annihilation.
10^{-3}-10^{+3}	10^{-6}-10^{-4}	Dislocation Defect Dynamics	Growth & deterioration of microstructure	SEM, TEM, Mechanical tests
10^{-3}-10^{+9}	10^{-6}-10^{-1}	Rate equations	Physico-Chemis Properties	Mechanical tests, Corrosion.
1-10^{+9}	10^{-6}-10	Constitutive equations	Physico-Chemis Properties	Component operation

Development path Costs

Stage	Description	Mass [kg]	Cost [Meuro]	Duration [year]
1	Scientific test	0.1	0.1	<0.3
2	Materials engineering test	1-10	1.0	0.3-2.0
3	One small component test in-pile	50-200	10	2-4
4	Certified properties determination	$>10^4$	50	4-8
5	Prototype testing	$>10^3$	100	2-4
6	Optimalisation of composition, fabrication and manufacturing practices	$>10^5$	200	2-6
7	Accepted codes, standards & practices	$>10^5$	500	10-15

CONCLUSION

* Humans built metals expertise for 8 millennia. Metals offer fusion a myriad of property combinations to exploit.
* At present ferrous alloys have the most advanced status for application in fusion power plant structures.
* The expected upper limit of steel operating temperature, about 700 ^{o}C, drives the development of refractory alloys.
* Vanadium alloys have potential up to 700 ^{o}C in lithium.
* Tungsten and chromium based alloys have the potential for operating temperatures of 800 and 1200 ^{o}C.
* Toughness and manufacturing practices have to be improved, before refractory application in fusion devices will be technically feasible.