Assessment of Plastic Flow and Fracture Properties with Small Specimen Test Techniques for IFMIF-Designed Specimens

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Specificity of neutron fusion irradiation (1)

For the fusion neutron spectrum, different nuclear reactions with the nuclei of the surrounding materials are possible:

neutron < 1 MeV: (n, n) elastic and inelastic scattering
(n, γ) capture

Primary knock-on atom energy up to about 40 keV.

****

neutron > 1 MeV: Transmutation reactions come into play
(n, p), (n, d) (n, t) (n, He)… H, and He production

Primary knock-on atom energy up to several hundreds keV.

Specificity of neutron fusion irradiation (2)

Expected dose at the end of life of a reactor.

Fusion reactor first wall: 100 to 200 dpa (displacement per atom) with a helium production of about 10 appm He/dpa and 40 appm H/dpa.

Fission reactor vessel: 0.1 dpa without He.

The International Fusion Materials Irradiation Facility (IFMIF)

An irradiation facility that reproduces as close as possible the fusion neutron environment is necessary to *qualify and develop* structural, functional, breeding, magnet… materials.

IFMIF requirements …

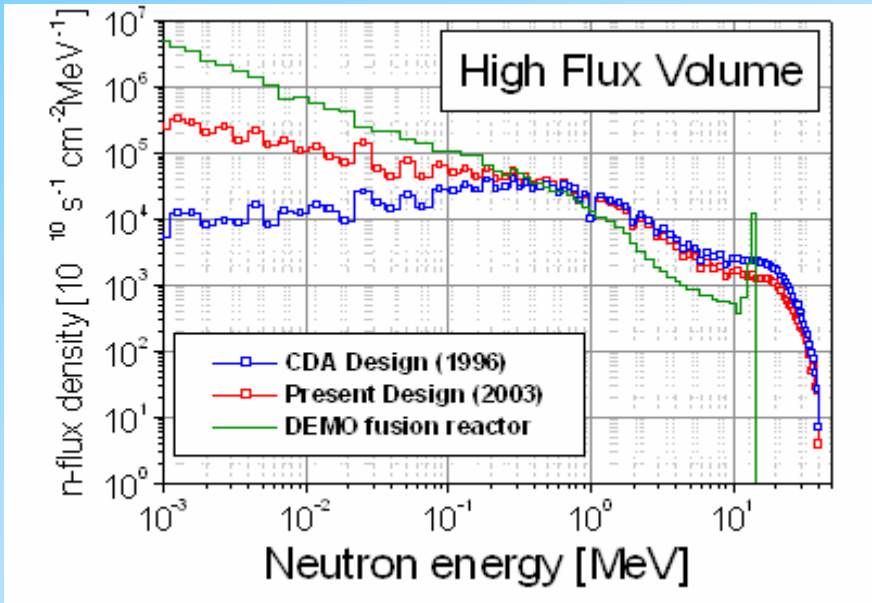
… to be fulfilled in terms of the neutron spectrum are mediated by:

1. He and H production rates as well as other transmutation reaction rates.

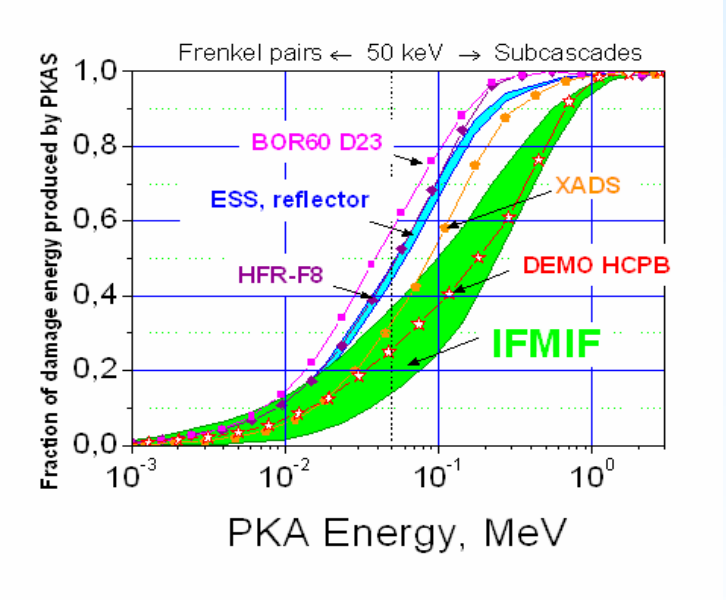
2. The damage production function W(T), which characterized the primary recoil energy spectrum, has to mimic that of a fusion reactor.

Comparison of the neutron spectrum and the damage production function -W(T) - between IFMIF and DEMO in its current design

A. Möslang *et al.* Comprehensive Design Report (2004)



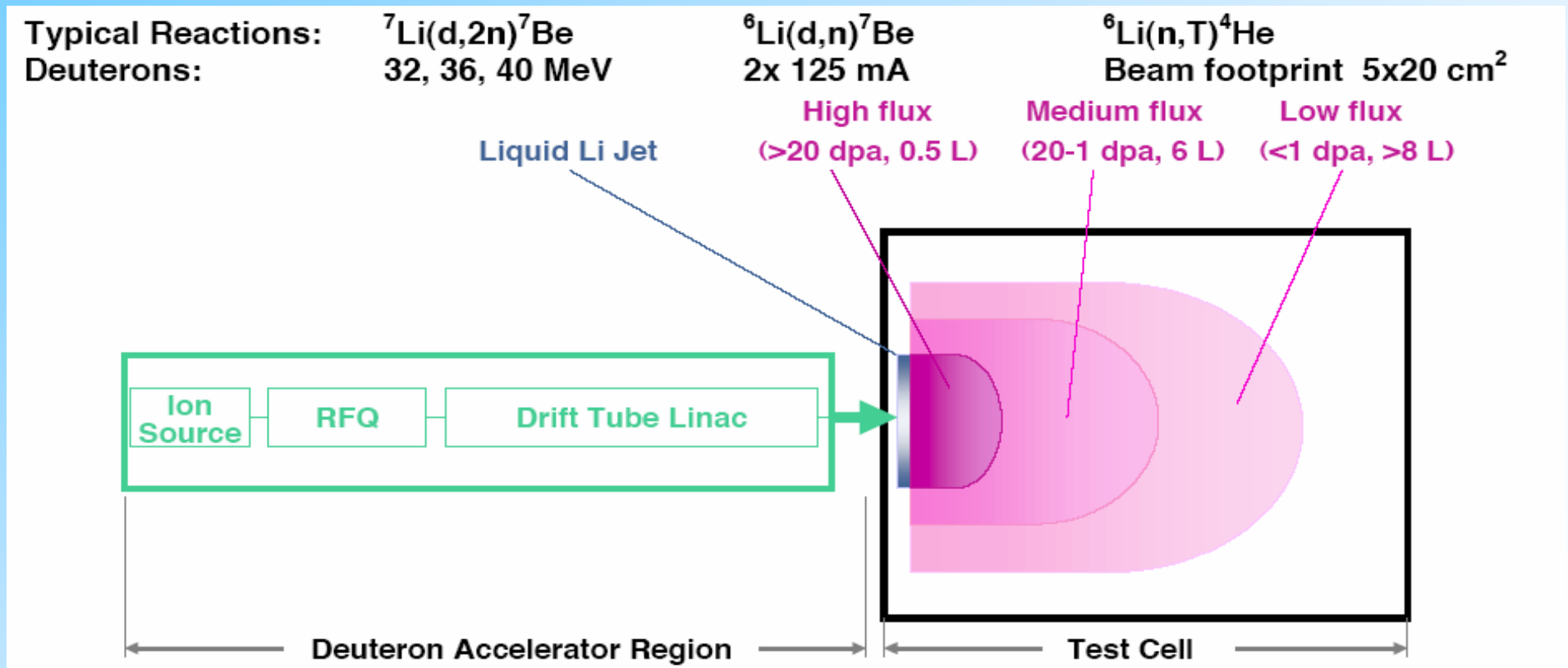
Different neutron spectra



W(T) function in the blanket represents the fraction of damage energy released by all PKA recoils with recoil energies lower than T (MeV).

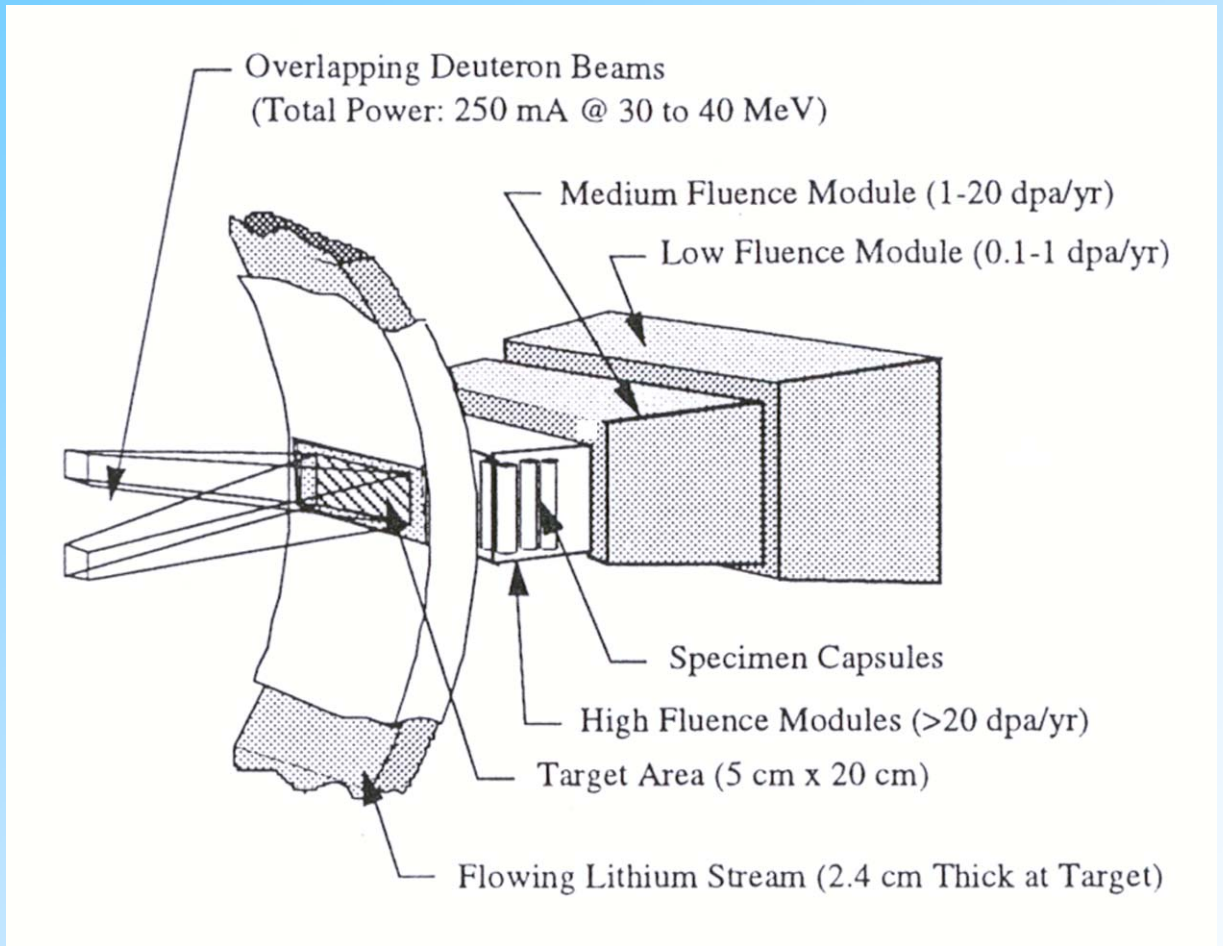
IFMIF - Schematic layout

IFMIF is an accelerator based D-Li neutron source



A. Möslang *et al.* 2000 Nucl. Fusion 40 6 19-627

IFMIF
Details of the target area and test cell



The high-flux test module volume is about 0.5 L.

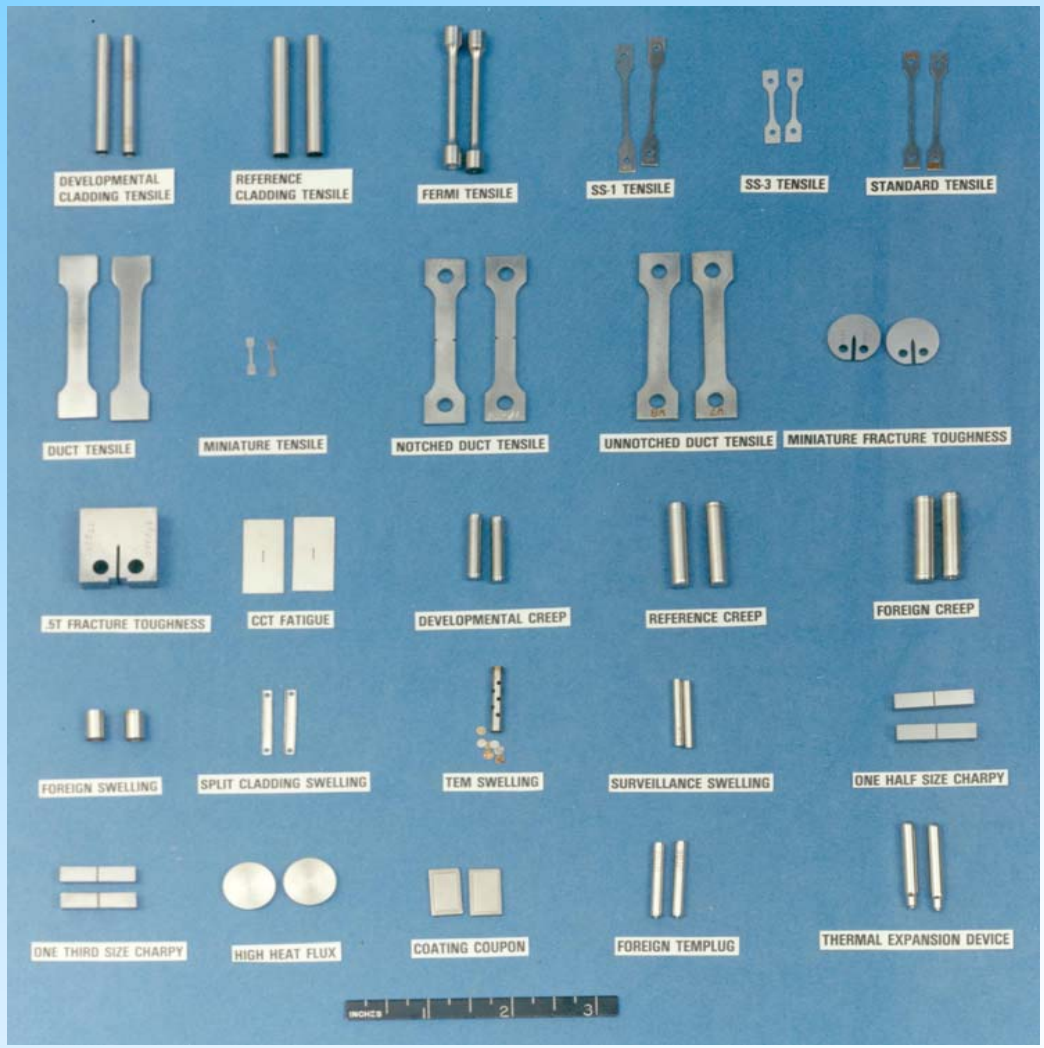
Small specimen test techniques (SSTT)

- Many small specimen techniques have been developed by the fusion material research community. Needs are mainly dictated by:
  - » Small volume irradiation facilities like IFMIF (but also accelerators, fission reactors)
- A large variety of specimen geometries have been developed. This includes either a scaling down of standard test specimens or the development of new tests for small specimens (punch tests with TEM discs).

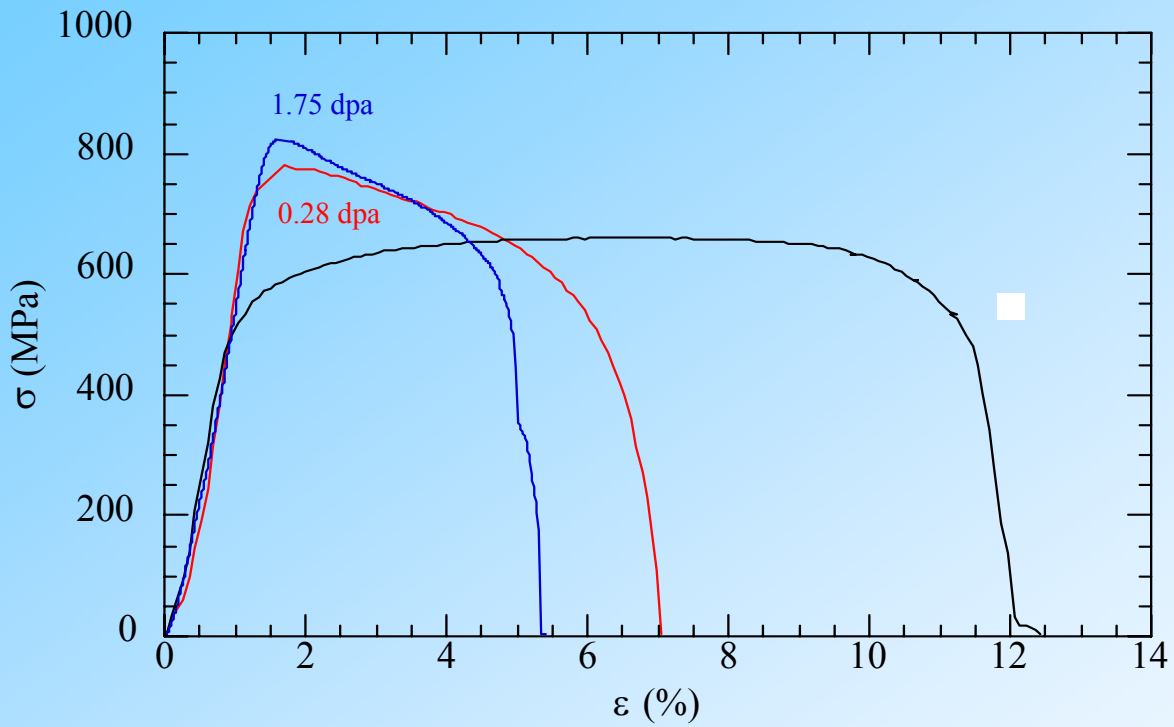
Small specimen test techniques (SSTT)

- Development of these specimens and techniques has led to collateral advantages:
  - » Minimize temperature uncertainties and flux gradient effects
  - » Optimize us of limited amounts of materials
  - » Reduce dose during PIE
- Application of SSTT forces the community to solve the issues related to transfer of the test data to structural integrity assessment.

Example of SSTT specimens for IFMIF



Irradiation effect on the tensile properties of tempered martensitic steels



F82H steel, $T_{test} = T_{irr} = 293K$

Yield stress increase

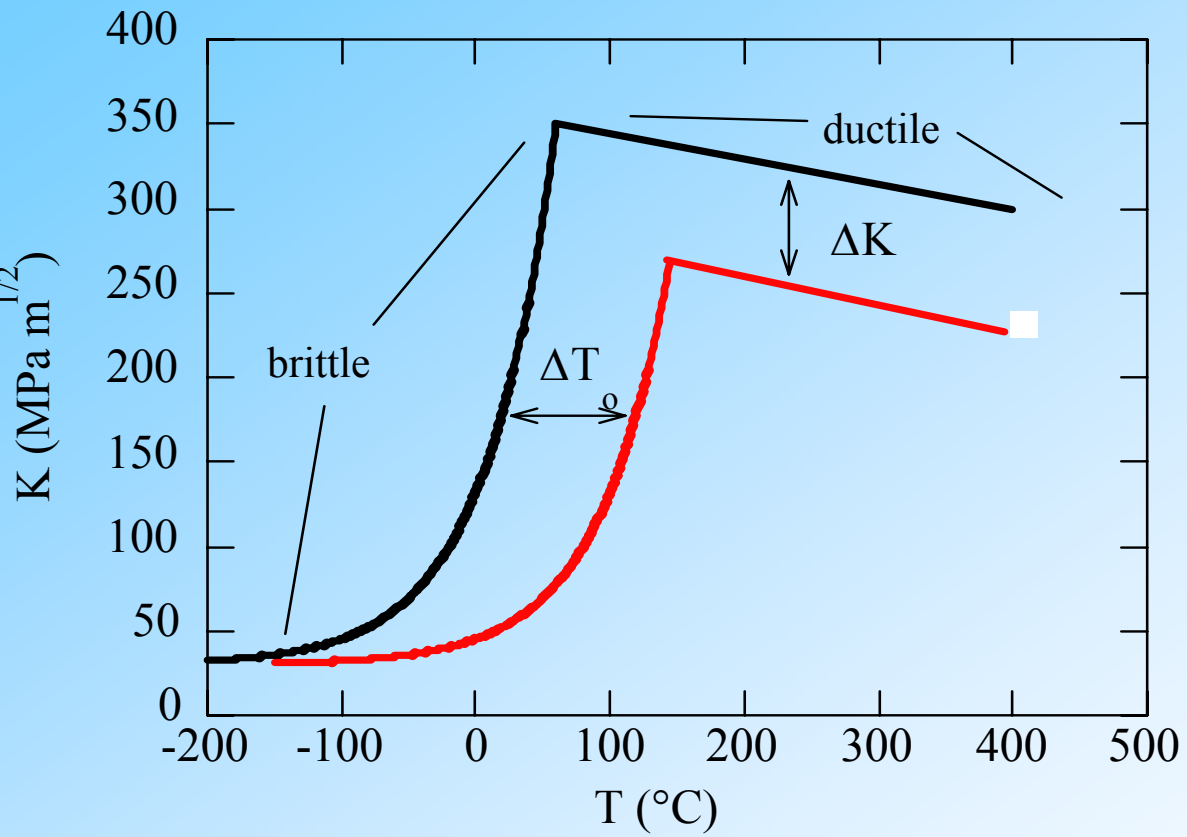
$\Delta\sigma_y(T_{irr},\Phi,d\Phi/dt\ldots)$

Uniform elongation reduction

$\Delta\varepsilon_u\ (T_{irr},\Phi,d\Phi/dt\ldots)$

resulting from the build-up of irradiation induced defects in the matrix (I-loops, micro-voids and precipitates).

Irradiation effect on the fracture properties of tempered martensitic steels



Tempered martensitic steels (bcc) exhibit a ductile-brittle transition

Two major effects of irradiation:

1) Shift of the brittle regime to higher $T + \Delta T_o$

2) Decrease of fracture toughness in the ductile regime ΔK.

Simplified roadmap to model fracture toughness in the transition (brittle) region

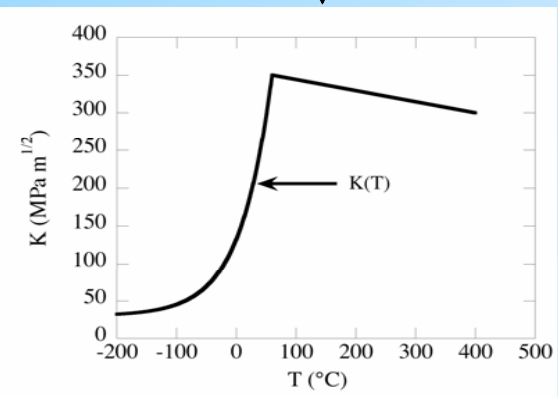
Fracture testing

Tensile testing

Constitutive behavior
$\sigma(\varepsilon, d\varepsilon/dt, T)$

Critical applied stress intensity factor
$K_{IC,}$ versus temperature

FEA, σ-ε fields at crack tip



Modeling of K(T) curve
in the transition

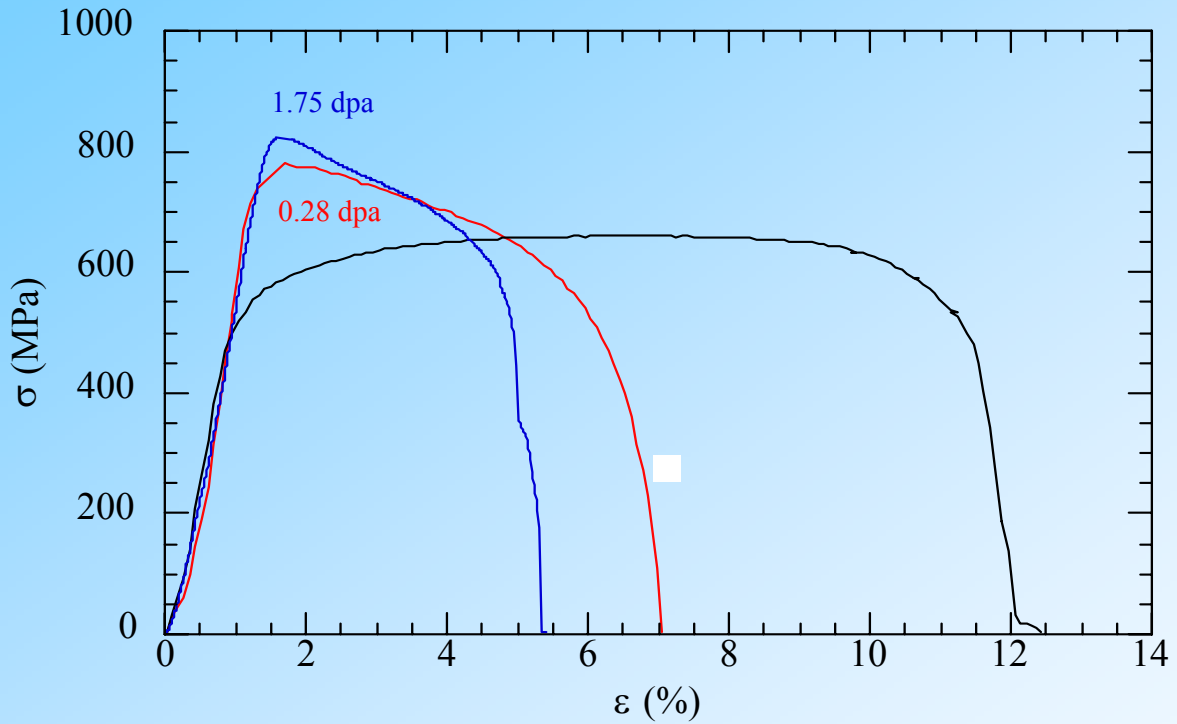
Critical condition
for cleavage, (σ*-A*) for K_{IC}

Therefore the fracture properties are intrinsically related to the plastic flow described by a constitutive law $\sigma(\varepsilon)$ usually determined by plain tensile test.

Thus we need to:

1. ***Establish the true stress - true strain relationship $\sigma(\varepsilon)$ over a significant plastic deformation range.***
2. ***Understand the plastic flow with physically-based models in order to…***
3. ***…gain insight into the micromechanisms controlling fracture.***

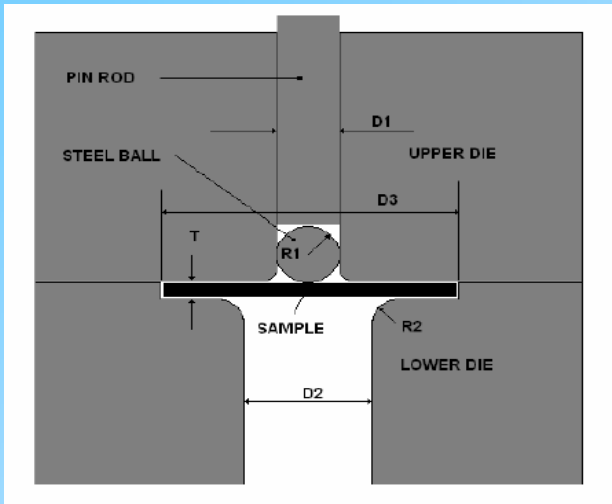
How to establish σ(ε) for irradiated materials?



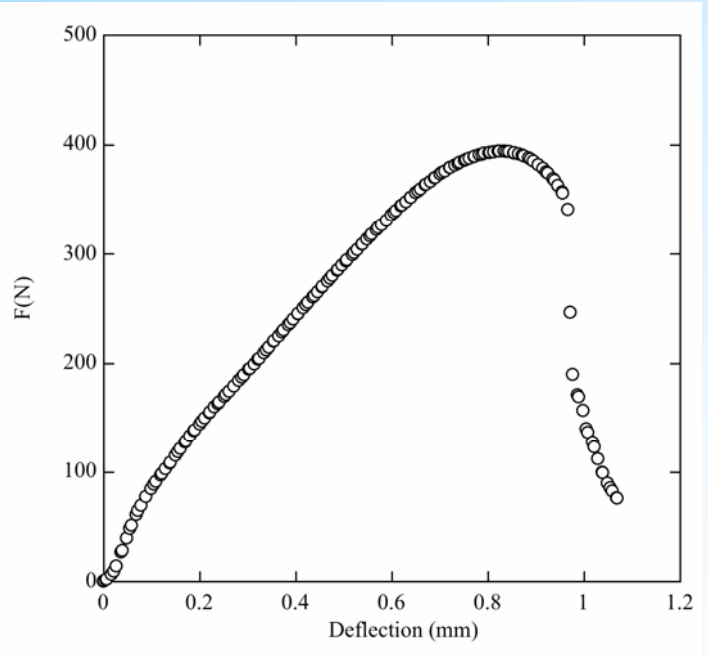
F82H steel, $T_{test} = T_{irr} = 293K$

Owing to the low uniform elongation measured with tensile tests after irradiation, this type of test is usually not suitable to determine σ(ε) for irradiated material.

Non-standard small ball punch test



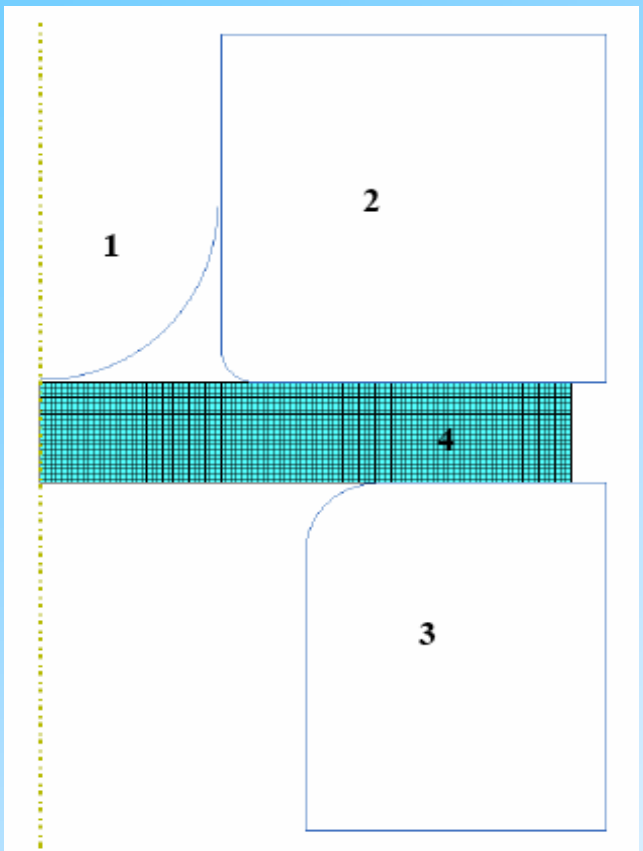
R1 = 1 mm
R2 = 0.2 mm
D1 = 1 mm,
D2 = 1.5 mm
D3 = 3 mm
T = 0.2 - 0.3 mm



Eurofer97 tested at room temperature

A 3 mm diameter disk is clamped between two dies and is deformed by bending. The load-deflection L-Δ curve is recorded.

Finite element axisymmetric model



Model implemented in ABAQUS 6.4-1.

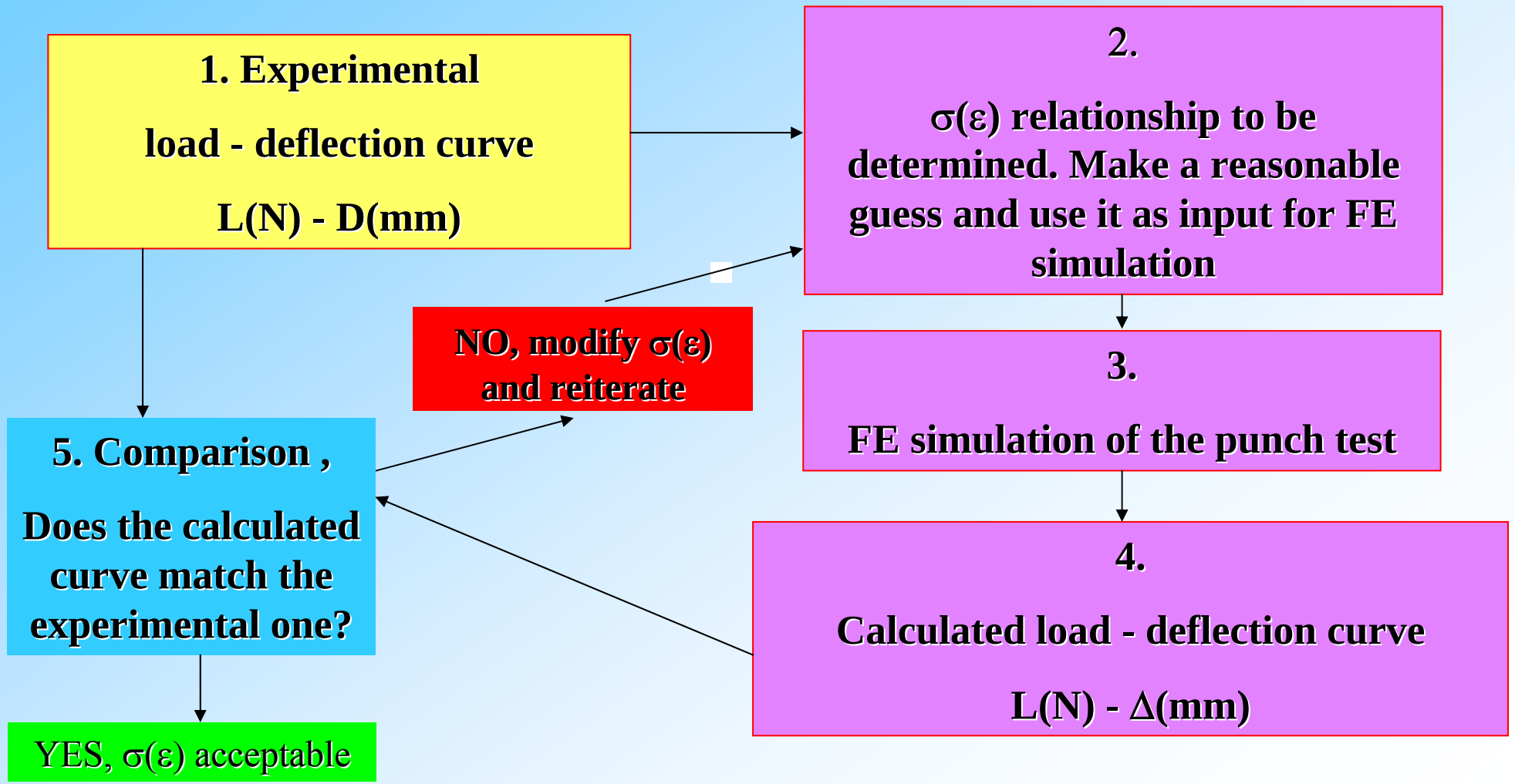
The ball and dies are rigid bodies.

The disk was modeled with 2000 axisymmetric linear reduced integration elements (CAX4R).

A force is applied between the upper and the lower dies during the deformation, this prevents the specimen from slipping. Friction between these dies and the disk constrains the latter in the same way as in the actual experimental device.

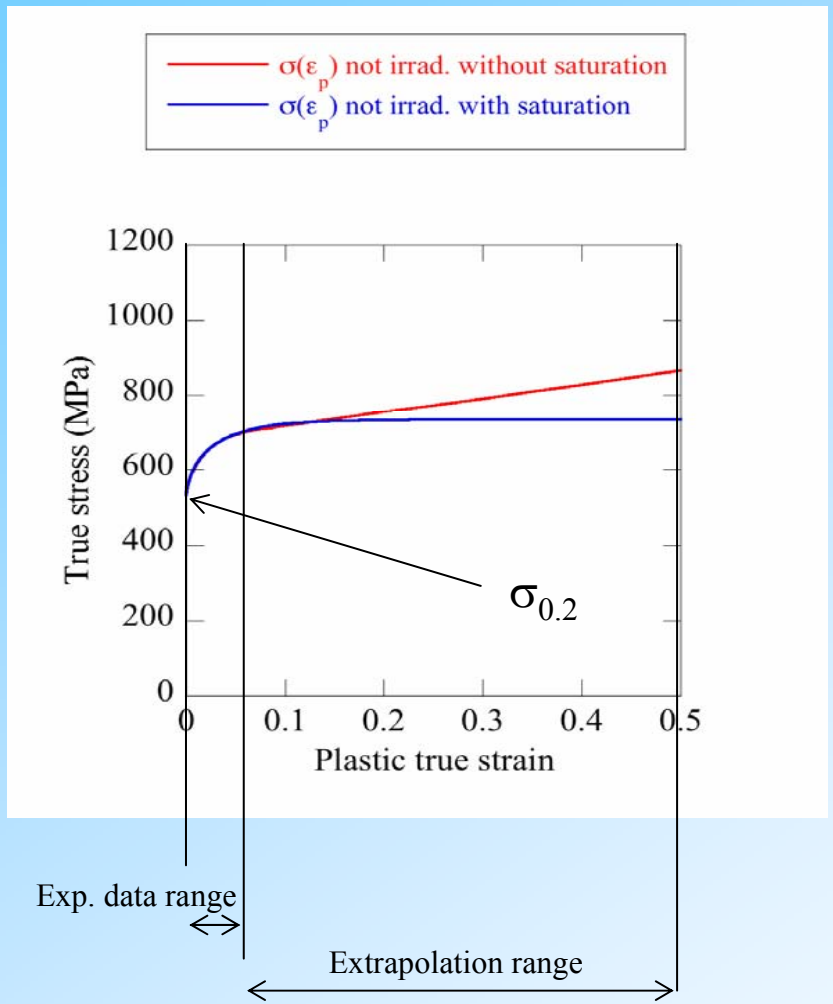
The calculations were run by imposing the vertical displacement of the ball.

On the determination of the σ(ε) relationship from small ball punch test

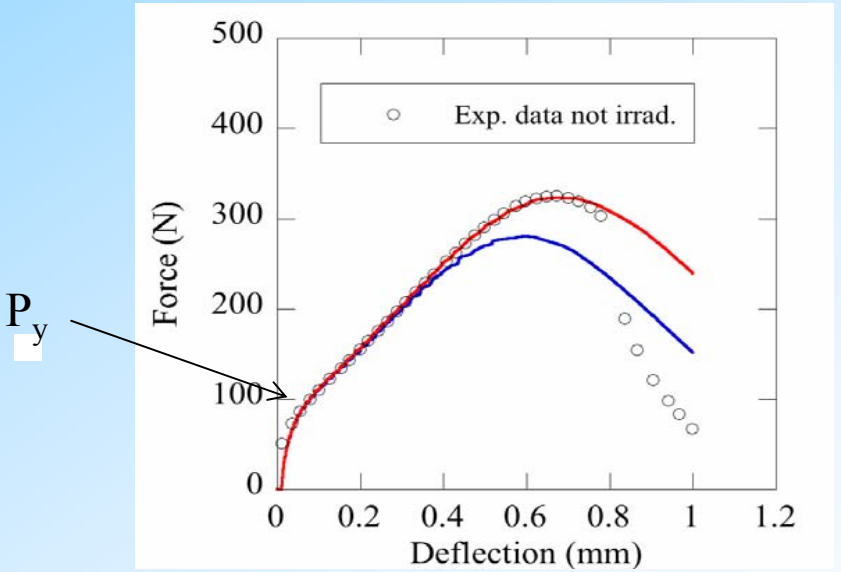


Validation of the FE model for the tempered martensitic F82H-mod steel

Tensile test curve



Small ball punch test curve

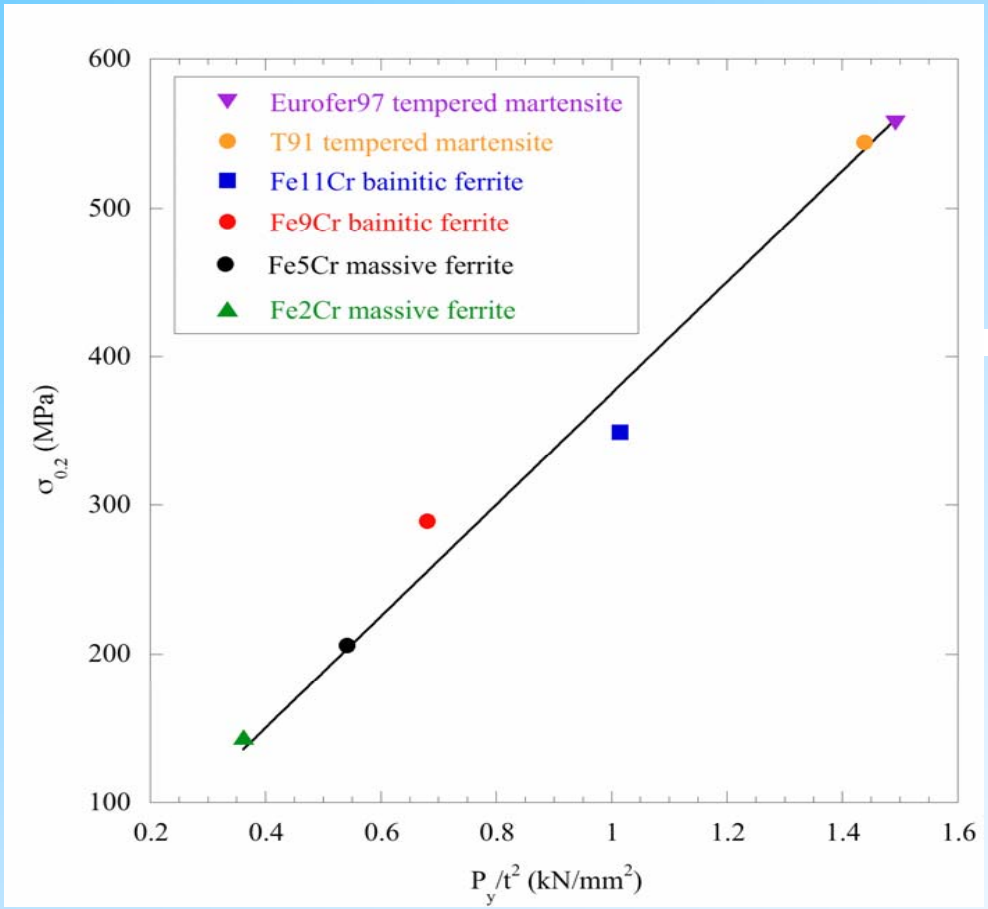


Equivalent plastic strain in the disk reaches about 0.6, so the $\sigma(\varepsilon)$ relationship measured with tensile test had to be extrapolated.

The non-saturating $\sigma(\varepsilon)$ curve fits better the punch curve.

Search a calibration between the yield load P_y and the yield stress $\sigma_{0.2}$

Calibration between the yield stress $\sigma_{0.2}$ (tensile test) and yield load P_y/t^2 (punch test)



$\sigma_{0.2}$: yield stress (MPa)

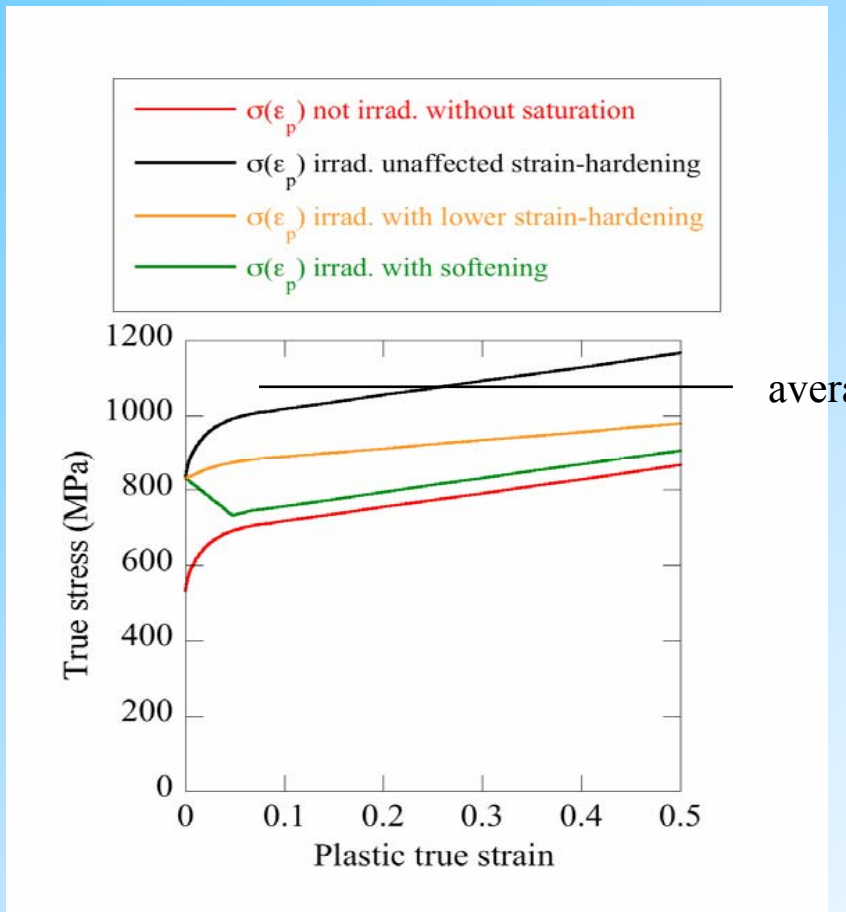
P_y: yield load (kN)

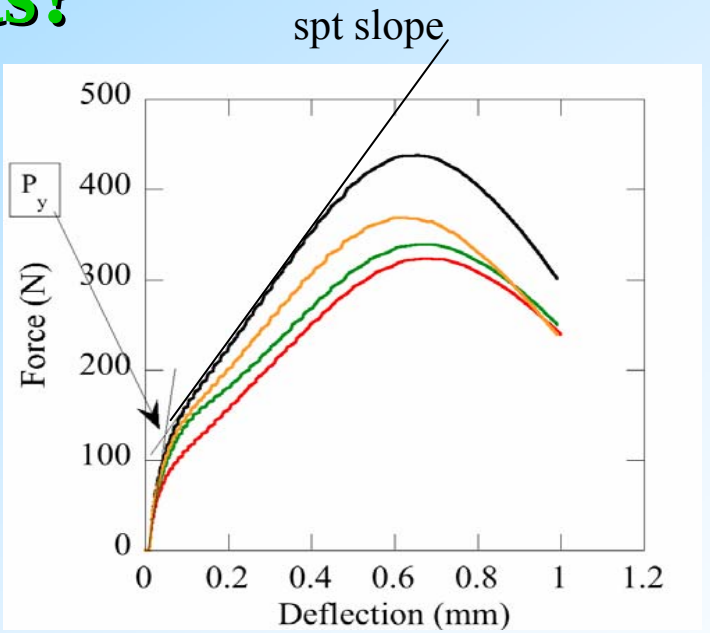
t: specimen thickness (mm)

A universal empirical linear relationship between $\sigma_{0.2}$ and P_y/t^2 was found for a variety of bcc materials with different morphologies covering a wide range of stresses.

$$\sigma_{0.2}\ \text{MPa} = 375\ P_y/t^2\ (\text{kN/mm}^2)$$

What irradiation induced changes in the σ(ε) constitutive behavior can we expect to measure from punch tests?



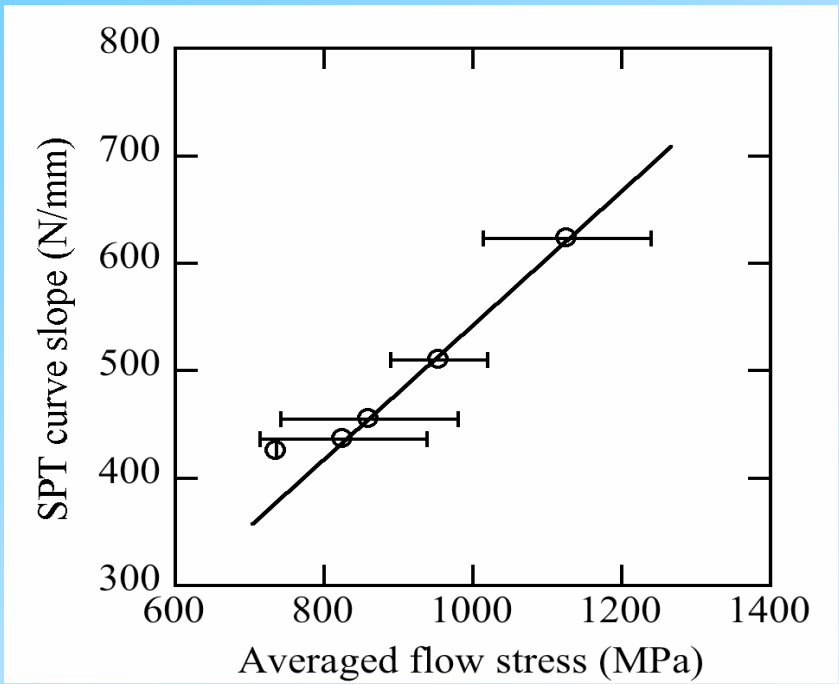


Clearly, there is a one-to-one correspondence between σ(ε) and F – Δ.

A calibration between the averaged flow stress and punch curve slope is proposed.

An irradiation-hardening of 300 MPa was selected, followed by three different post-yield behaviors. The corresponding punch curves were calculated.

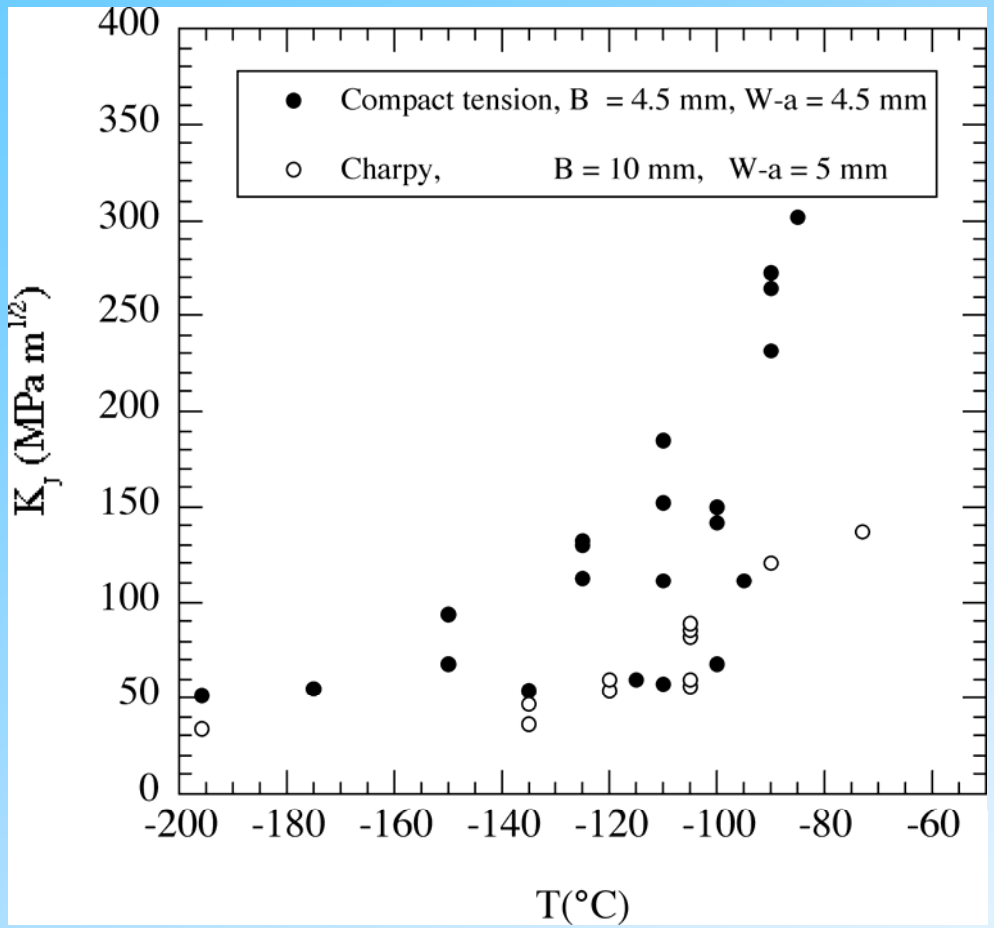
Investigation of the plastic flow properties from small ball punch test

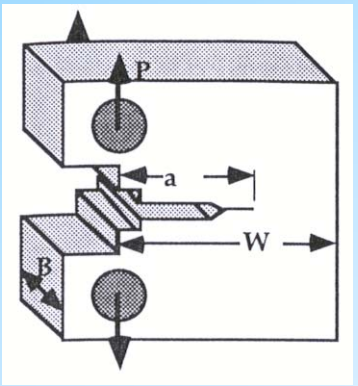


Also in this case, an empirical linear relationship between the SPT curve slope and the averaged flow stress was found.

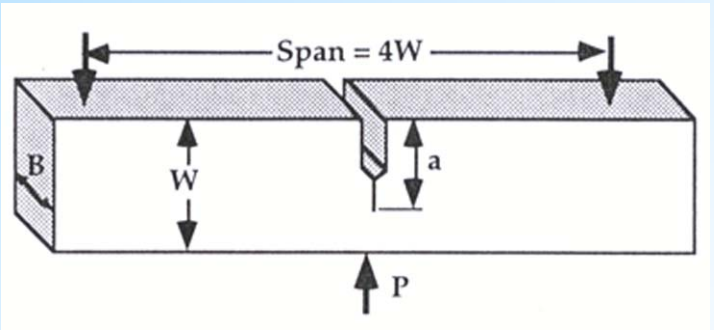
The strain-capacity can therefore be estimated form the punch test.

Specimen size effect on fracture toughness





Compact tension

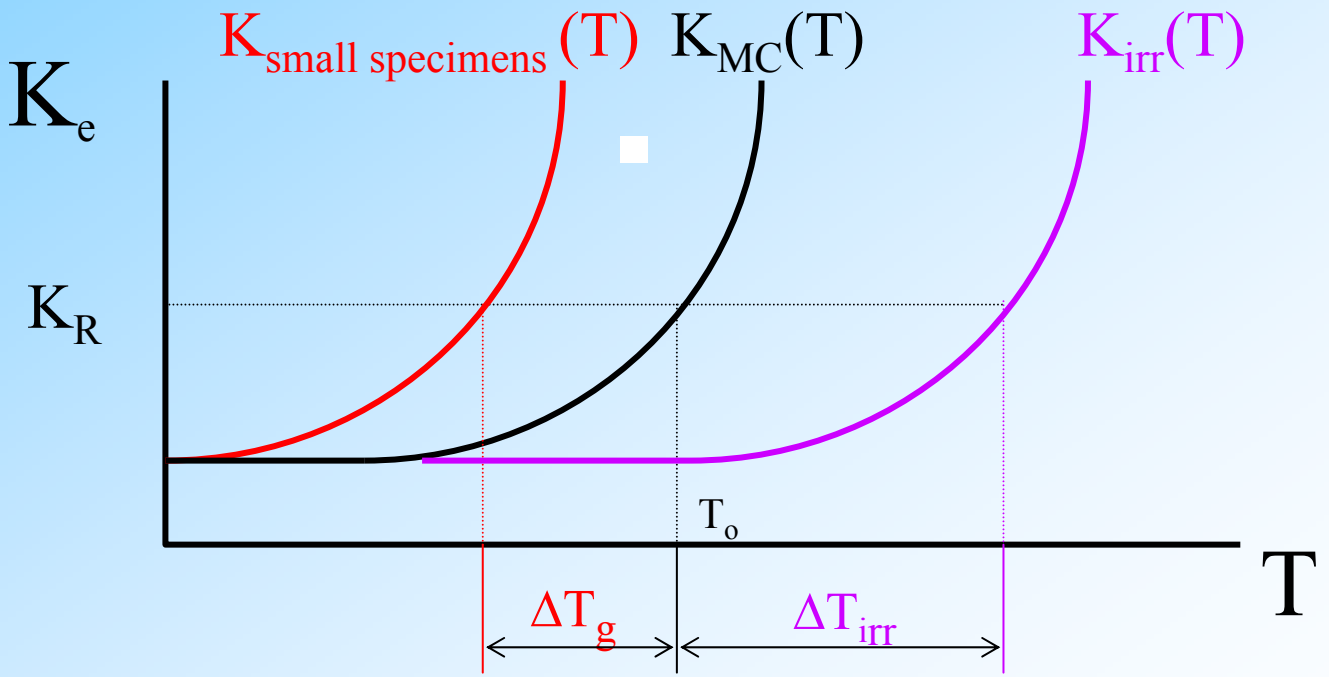


Bend bar

1. **The smaller the specimens, the higher the measured fracture toughness.**
2. **Large scatter in the transition, statistical nature of cleavage.**

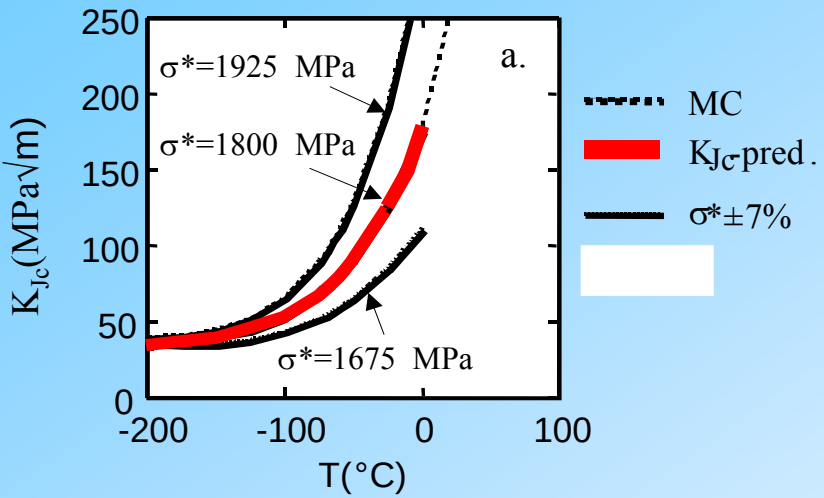
Fracture

Much of the recent work addresses use of Master Curve-Shift (MC-ΔT) method for fracture toughness. K(T) has a constant shape and is indexed at an absolute temperature T_o for K = 100 MPa $m^{1/2}$.



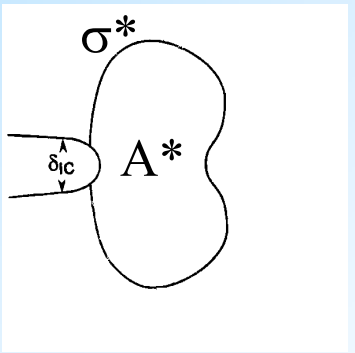
$$K_e(T) = K_{MC}(T-[T_o + \Delta T]) \qquad \Delta T = \Delta T_i + \Delta T_g + \Delta T_{sr} + \Delta T_m$$

Reconstruction of K(T) curve, local approach based on a critical criterion σ*-A* to trigger cleavage.



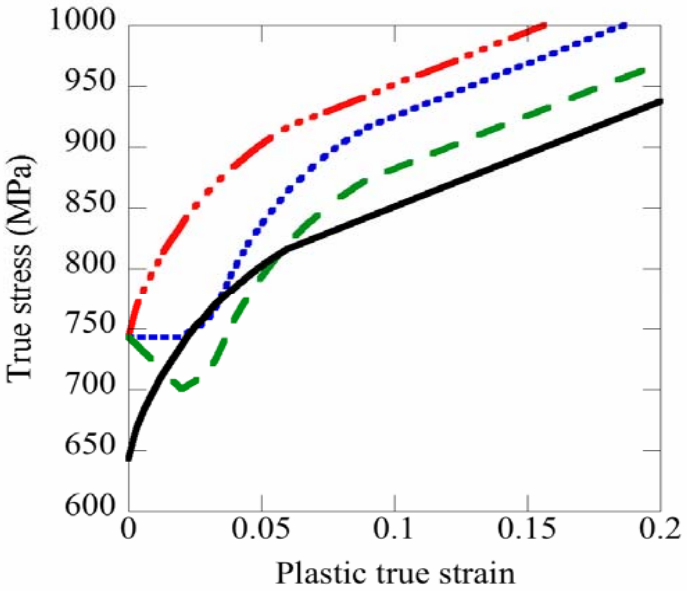
Cleavage criterion

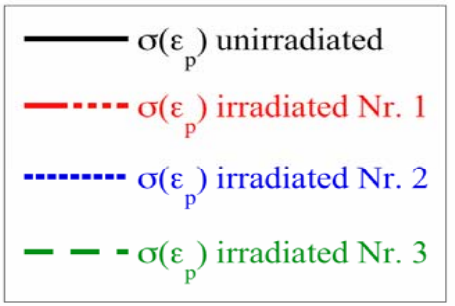
a critical stress σ* encompassing a critical area A*

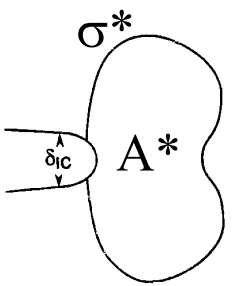


- Small specimens are used to develop micromechanics-based approach to fracture:
  - » Constitutive equations for use in Finite Element calculations of crack tip stress/strain fields
  - » Local fracture parameters -- e.g., critical stress (σ*) critical area (A*) descriptions of cleavage fracture
- These can in turn be used in combination with Finite Element Modeling (FEM) to estimate ΔT_g for various specimen/component sizes and geometries.

Drastic effect of the details of σ(ε) on the critical K to reach the criterion σ*-A*







Constitutive relationship	$\sigma^* = 2000$ MPa - $A^* = 1 \times 10^{-8}$ m^2
$\sigma(\varepsilon_p)$ unirradiated	100 MPa m$^{1/2}$
$\sigma(\varepsilon_p)$ irradiated Nr. 1	56 MPa m$^{1/2}$
$\sigma(\varepsilon_p)$ irradiated Nr. 2	66 MPa m$^{1/2}$
$\sigma(\varepsilon_p)$ irradiated Nr. 3	85 MPa m$^{1/2}$

Summary

The available irradiation volume of IFMIF makes the development and use small specimen test techniques (SSTT) necessary.

It was shown that SSTT like:

1. the non-standard ball punch test,

2. fracture testing with sub-sized specimens that do not meet the ASTM requirements

are pertinent to investigate the fundamental plastic flow and fracture properties and are applicable to the design of defect tolerant fusion structures if and only if

an appropriate approach based on physically-based models is used to rationalize the experimental results.

Conclusion

The success in the search for fusion materials depends on the existence of a suitable neutron source - IFMIF - and on our ability to develop predictive models of the irradiation environment on the material properties.