The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2055-38

Joint ICTP/IAEA School on Physics and Technology of Fast Reactors Systems

9 - 20 November 2009

Introduction to structural materials and their behaviour in a fast reactor fuel assembly

2 Radiation Damage

Principles of Design of Radiation Resistant Materials for Fast Reactor Fuel Assembly

M. Vijayalakshmi
Indira Gandhi Center for Atomic Research
Kalpakkam
India

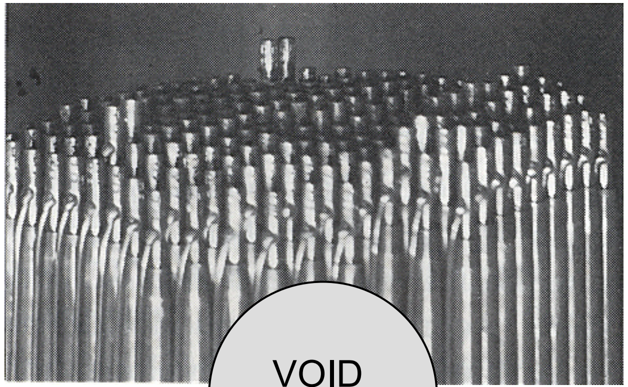
Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Introduction to structural materials and their behaviour in a fast reactor fuel assembly

2. Radiation Damage

Principles of Design of Radiation Resistant Materials for Fast Reactor Fuel Assembly

MODULE 2: RADIATION DAMAGE -SCOPE



- DOSE;
- TEMPERATURE;
- DOSE RATE;
- COLD WORK
- CHEMISTRY

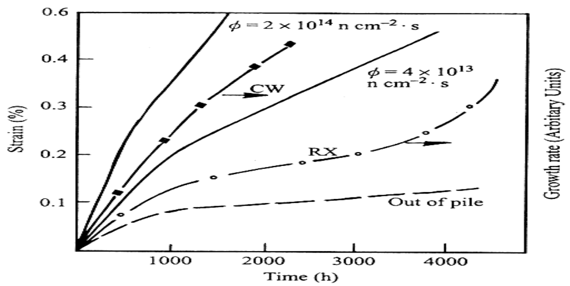
VOID SWELLING

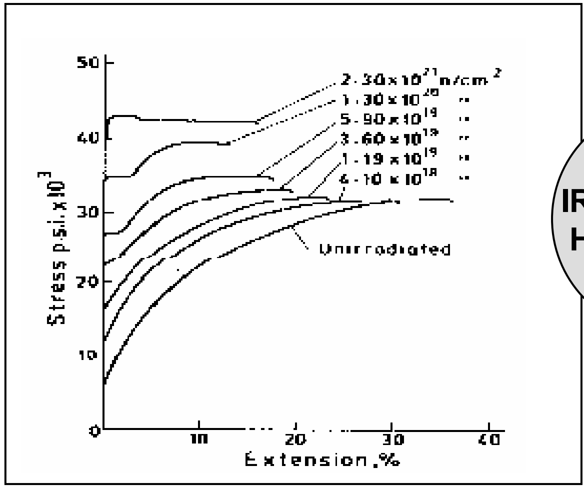
DISTORTION IN SHAPE RETAINING SAME VOLUME

IRRADIATION CREEP

MATERIALS DEGRADATION IN REACTORS

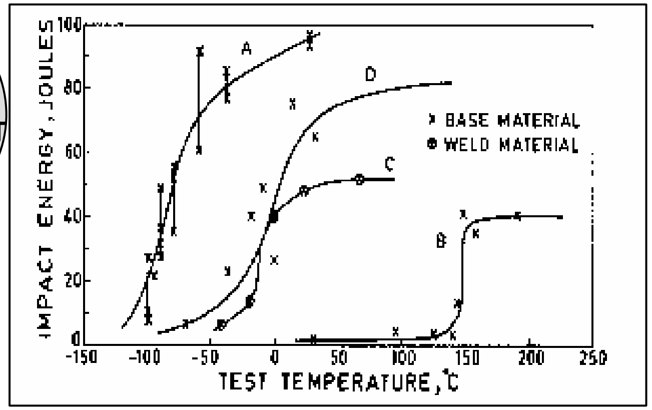
IRRADIATION GROWTH



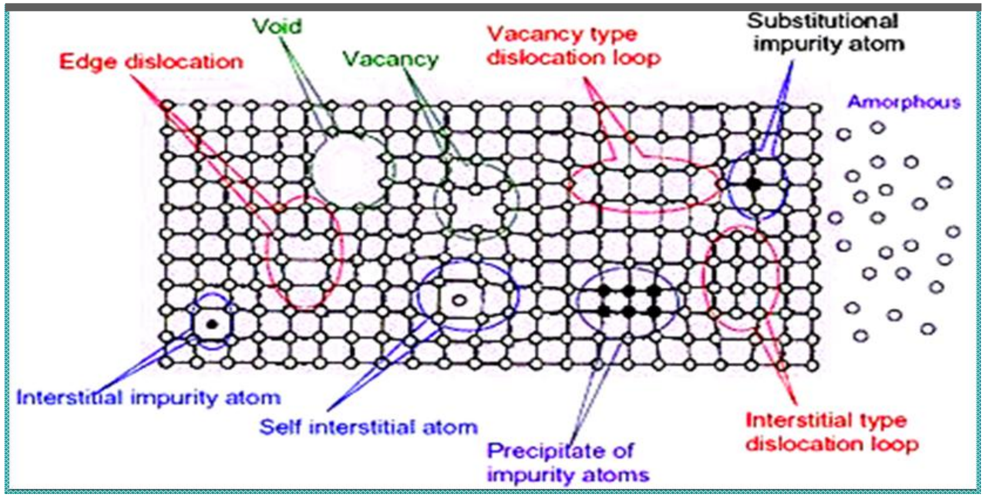


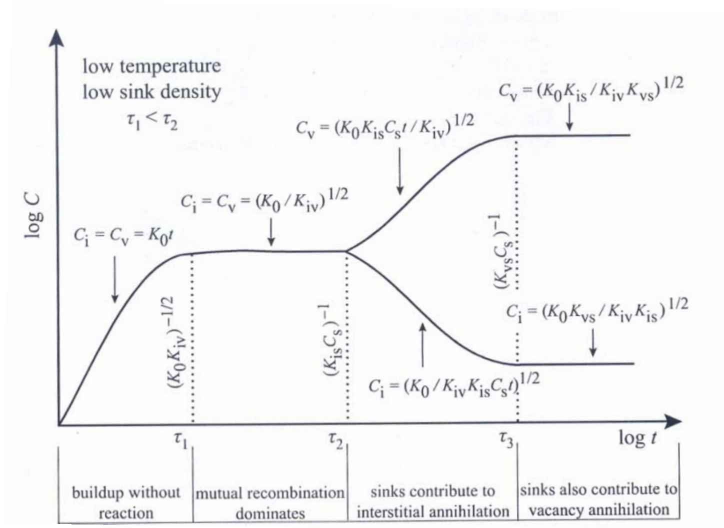
IRRADIATION HARDENING

IRRADIATION EMBRITTLEMENT



VOID SWELLING: NUCLEATION & GROWTH OF VOIDS



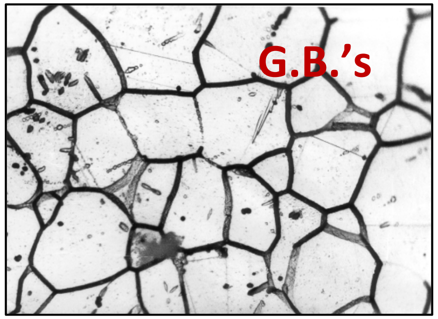


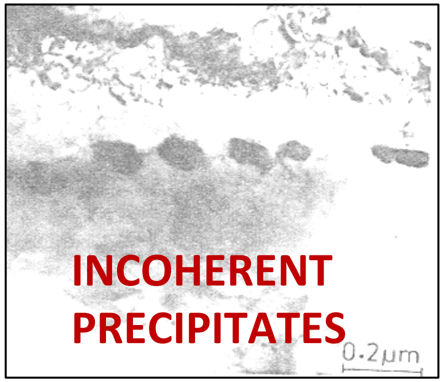
DO ALL SINKS REACT WITH DEFECTS THE SAME WAY?

NATURE OF SINKS IN VOID GROWTH;

TYPE OF SINKS: NEUTRAL, BIASED & VARIABLE BIAS

NEUTRAL





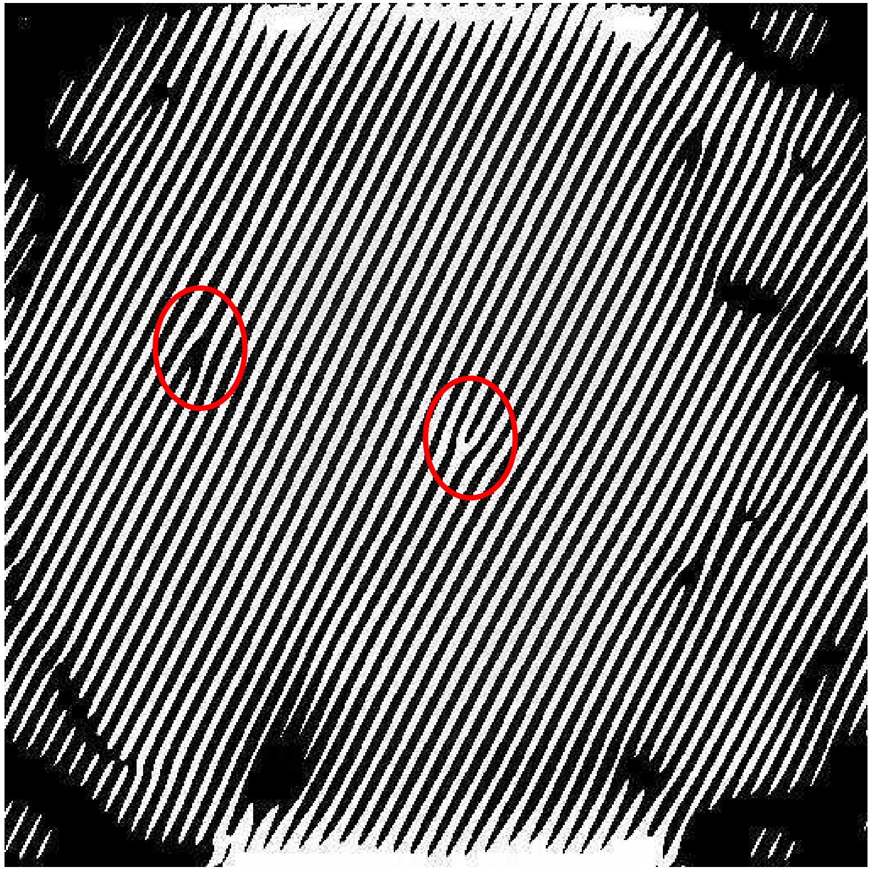
absorption α $D_{i.v}$ & ($C_{i/v}^{xal} - C_{i/v}^{sink\ surface}$)
rate

BIASED SINKS - DISLOCATIONS

2% more bias For I's than V's.

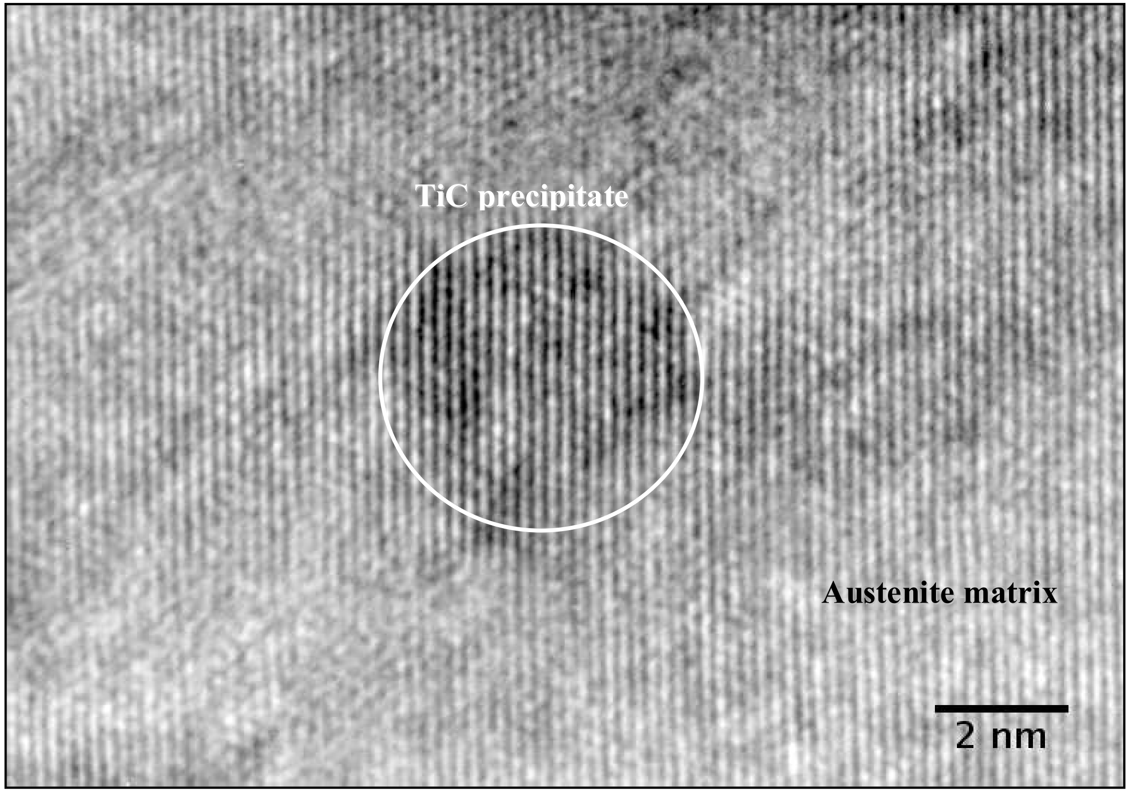
I's drift towards Core driven by Stress gradient

I's enhance climb; So unsaturable sink



TYPE OF SINKS

VARIABLE BIAS SINKS: COHERENT PRECIPITATES & IMPURITY ATOMS



CAPTURES I OR V's ; RETAINS ITS IDENTITY TILL IT ANNIHILATES WITH THE OPPOSITE !!!!

INCREASES RATE OF V + I → ☐ RECOMBINATION PROBABILITY

VOID SWELLING: solution to growth rate equations

$$\rho_V = \int \rho_V \text{®} \, dR$$

Total Number Density of voids

Number of voids / cm^2 of radii R & R+dR

$$R_{av} = (1/\rho_V) \int R \, \rho_V \text{®} \, dR$$

Volumetric swelling rate

$$dV/dt = 4\Pi R^2 (dR/dt)$$

$$\Delta V / V = (4/3) \Pi R_{av}^{3} \rho_V$$

VOID SWELLING

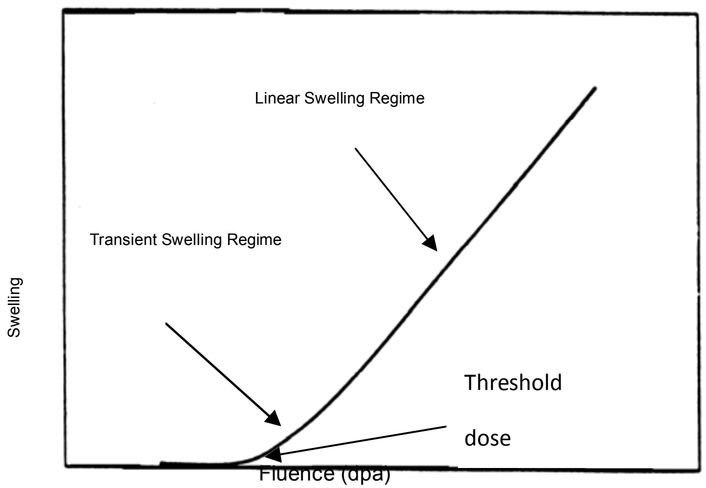
DOSE;

TEMPERATURE;

COLD WORK &

DOSE RATE.

Void swelling – dose dependence



- LOW DOSES -→ LOW AMOUNT PRODUCTION OF POINT DEFECTS ; NOT ENOUGH TO FORM MORE VOIDS & ALLOW THE AMBRYOS TO GROW.

- HIGH DOSES --→ LOSSES TERM TO (RECOMBINATION + SINKS) IS OFFSET BY PRODUCTION

JOB OF MATERIALS SCIENTISTS --→ IDENTIFY A MATERIAL WITH AS HIGH THRESHOLD AS POSSIBLE

VOID SWELLING: TEMPERATURE DEPENDENCE

STRONG DEPENDENCE ON TEMPERATURE

- VACANCY DIFFUSION COEFFICIENT - D_v
- EQUILIBRIUM THERMAL VANCANCY CONCENTRATION – C_v^0

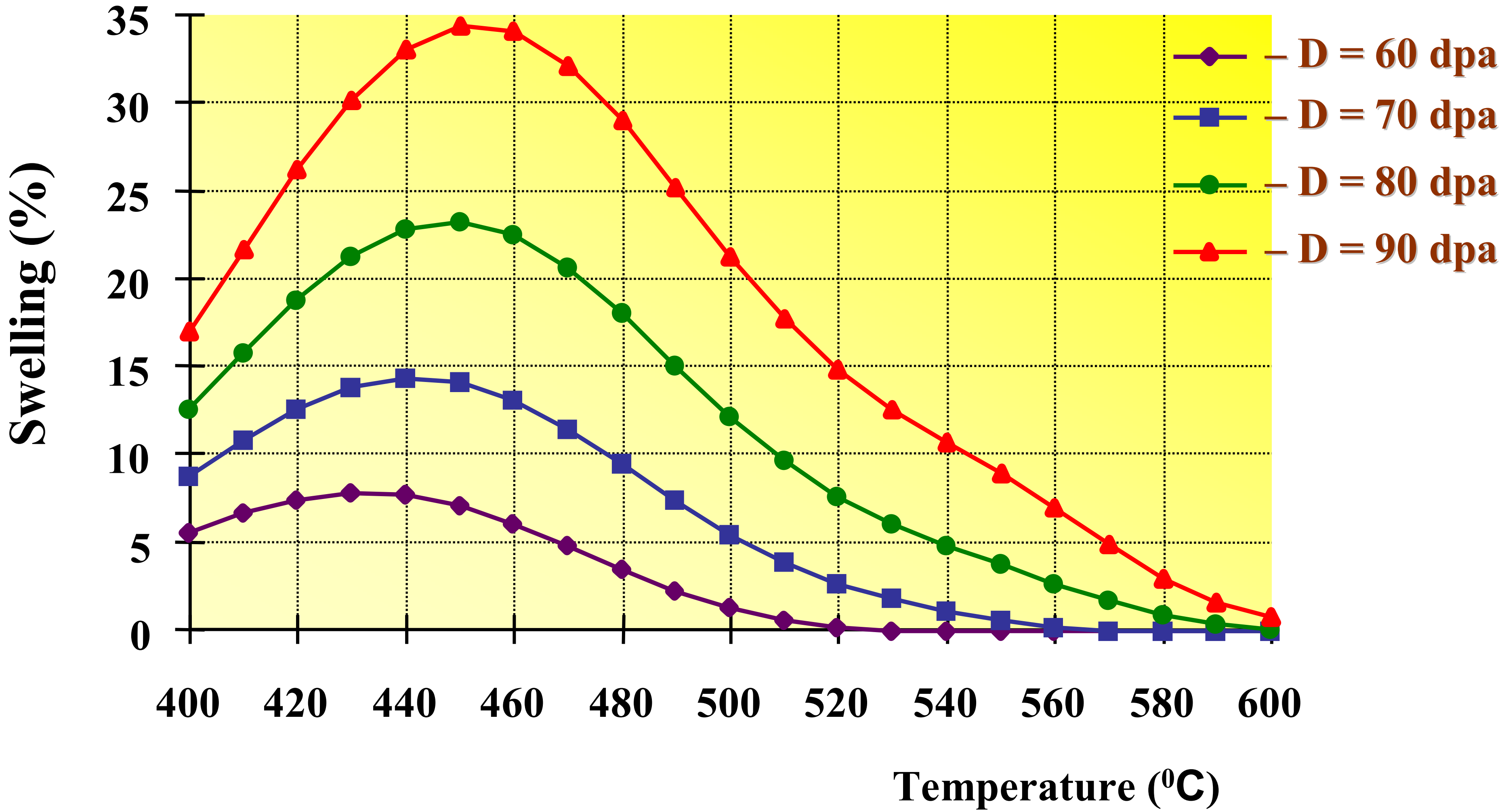
LOW TEMPERATURE

- LOW (D_v)MOBILITY OF VACANCY CONCENTRATION
- BUILD UP OF FREE VACANCIES & INTERSTITIALS
- HIGHER RECOMBINATIONS
- NO EXCESS CONCETRATION OF VACANCIES
- LESS VOIDS

HIGH TEMPERATURE

- DEFECT CONCENTRATION ~ THERMAL EQUILIBRIUM CONCENTRATION
- LESS SUPERSATURATION ($S = C_V / C_V^0$)
- LESS DRIVING FORCE FOR VOID FORMATION
- EMISSION OF VACANCIES FROM VOIDS;
- LESS NO OF VOIDS

Regularity of swelling



The dependence of swelling on irradiation temperature of steel ChS-68 of fuel pin cladding material of the first modernization core of BN-600.

TEMPERATURE EFFECT

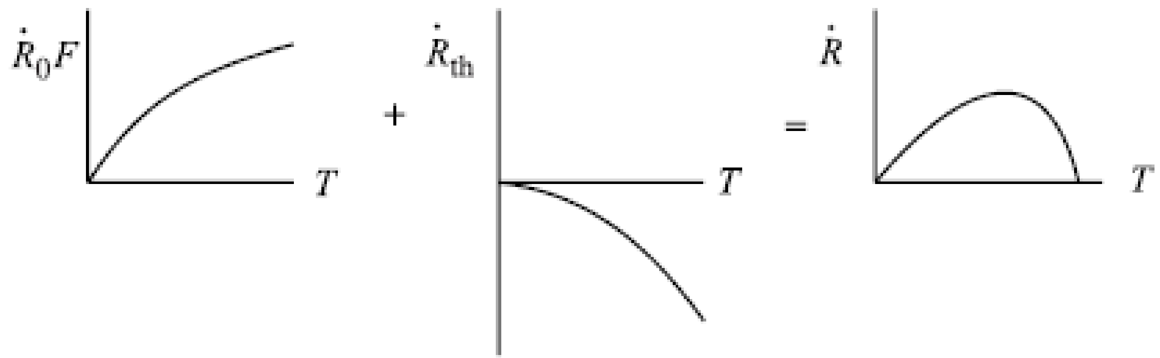


Fig. 8.17. Construction of the total void swelling rate $\dot{R}$ from its components $\dot{R}_0F$ and $\dot{R}_{th}$

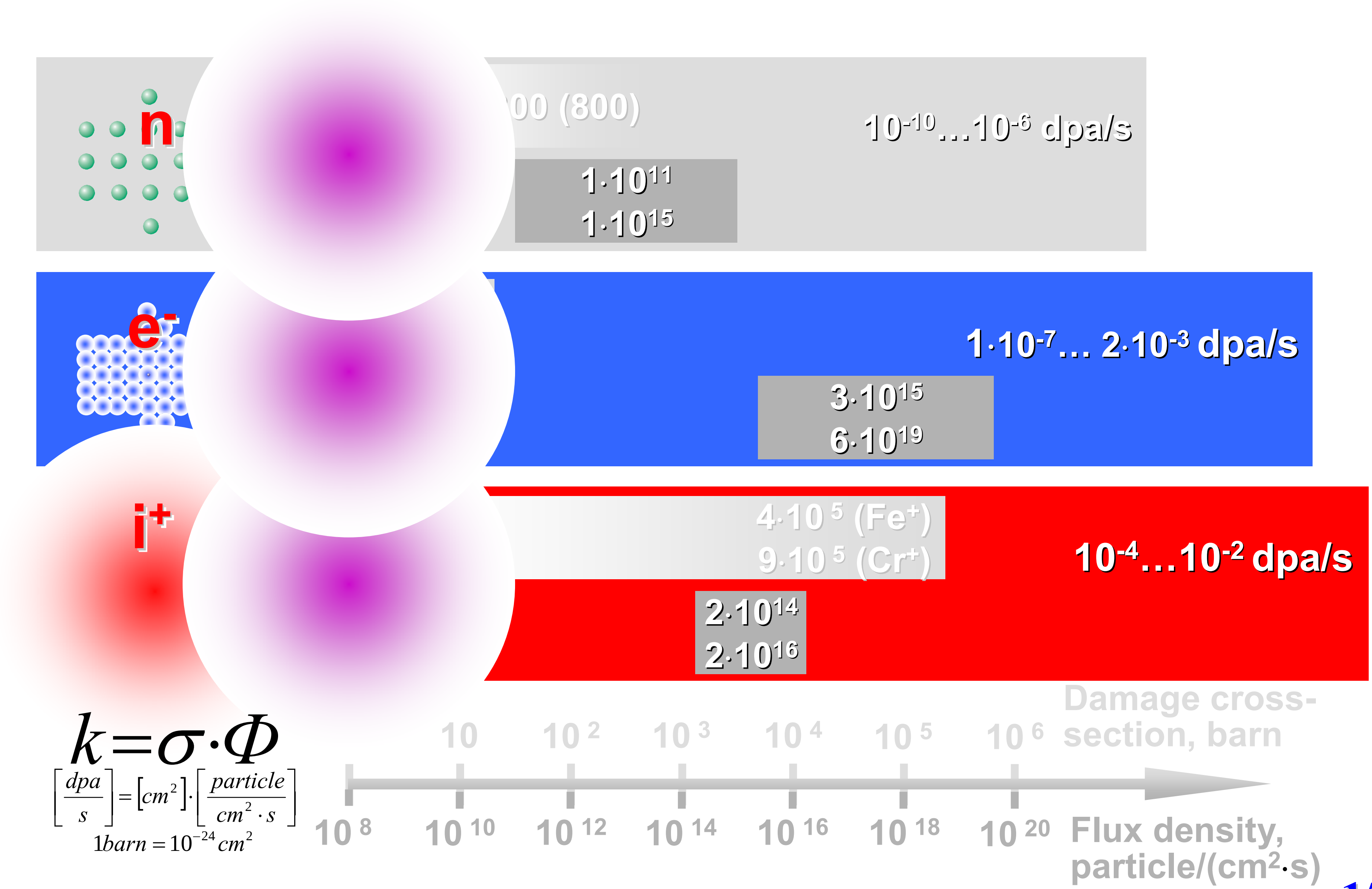
- AS ‘T’ INCREASES, VACANCIES BECOME MORE AND MORE MOBILE; NET ARRIVAL OF VACANCIES TO VOIDS INCREASE; VOIDS GROW.

- AT HIGH ENOUGH TEMPERATURES, C_V^0 INCREASES, S REDUCES, THERMAL EMISSION OF VACANCIES FROM VOID SURFACE INCREASES. VOID SHRINKS.

- BALANCE IS VOID GROWTH.

VOID SWELLING: EFFECT OF DOSE RATE

DOSE RATE DIFFERENCE USING DIFFERENT INCIDENT PROJECTILES



$$k=\sigma\cdot\Phi$$

$$\left[\frac{dpa}{s}\right]=\left[cm^2\right]\cdot\left[\frac{particle}{cm^2\cdot s}\right]$$

$$1barn=10^{-24}cm^2$$

➢Electrons

➢High dose rate (10-3 dpa/s)

➢no cascades

➢Insitu analysis (TEM)

➢Light ions

➢moderate dose rate (10-4 dpa/s)

➢Good depth of penetration

➢Flat damage profile over tens of µm

➢Smaller, widely separated cascades

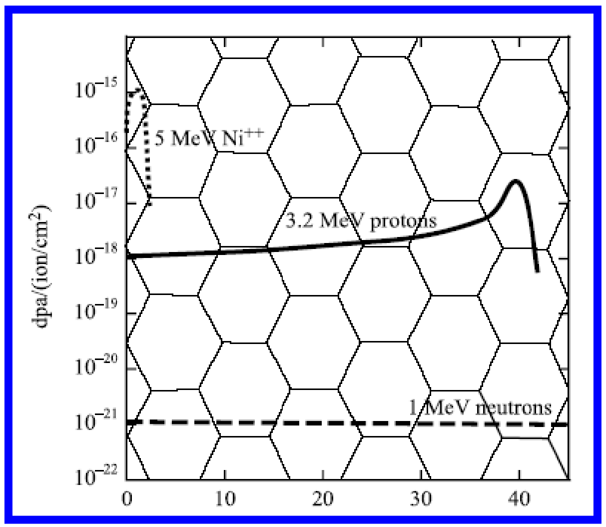
➢Heavy ions

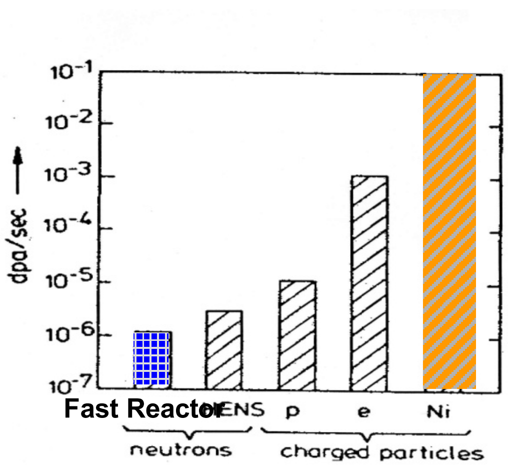
➢Very limited depth of penetration

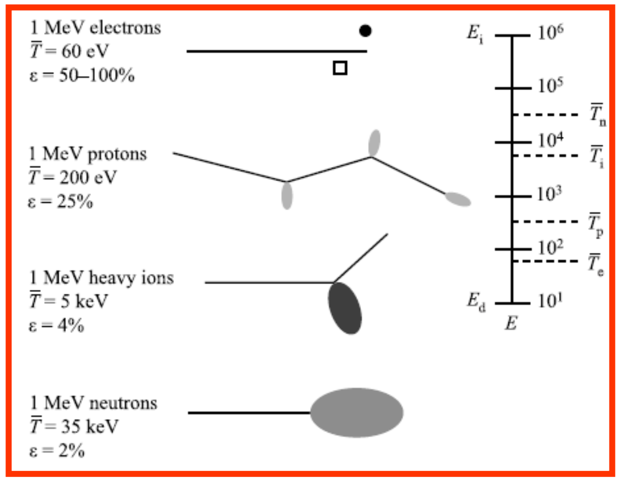
➢Strongly peaked damage profile

➢High dose rate

➢Cascade production



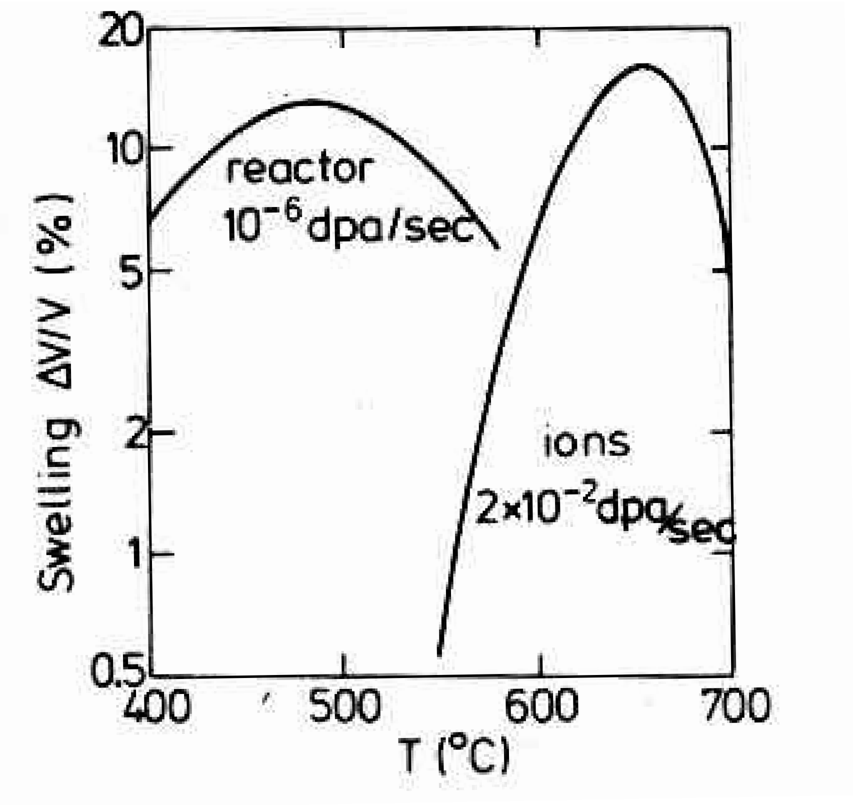




Time to build up dose: Reactor vs other irradiation sources

- 10-6 to 10-7 dpa/s in a reactor
- Time for 10 dpa – 4 to 5 months against one day in heavy ion accelerator
- few hrs in HIGH VOLTAGE electron microscope

Void Swelling : - Dose Rate



Peak Swelling Temperature depends on Irradiation Dose rate

$$\frac{T_1}{T_2} = A \ln\left(\frac{\Phi_2}{\Phi_1}\right)$$

WHY ? OF DOSE RATE BEHAVIOUR

- **HIGHER DOSE RATE INCREASES RATE OF PRODUCTION OF CONCENTRATION OF POINT DEFECTS ;**
- **RECOMBINATION RATE α PRODUCTION RATE -→ DOSE RATE;**
- **SUPERSATURATION REDUCES & HIGHER TEMPERATURE IS REQUIRED TO INTRODUCE THE DIFFERENCE IN THE PRODUCTION / LOSS TERM, TO ACHIEVE REQUIRED SUPERSATURATION**
- **T_{max} SHIFTS TO HIGHER TEMP.**

EFFECT OF DISLOCATIONS

Void growth rate in a lattice with biased sinks, like dislocations

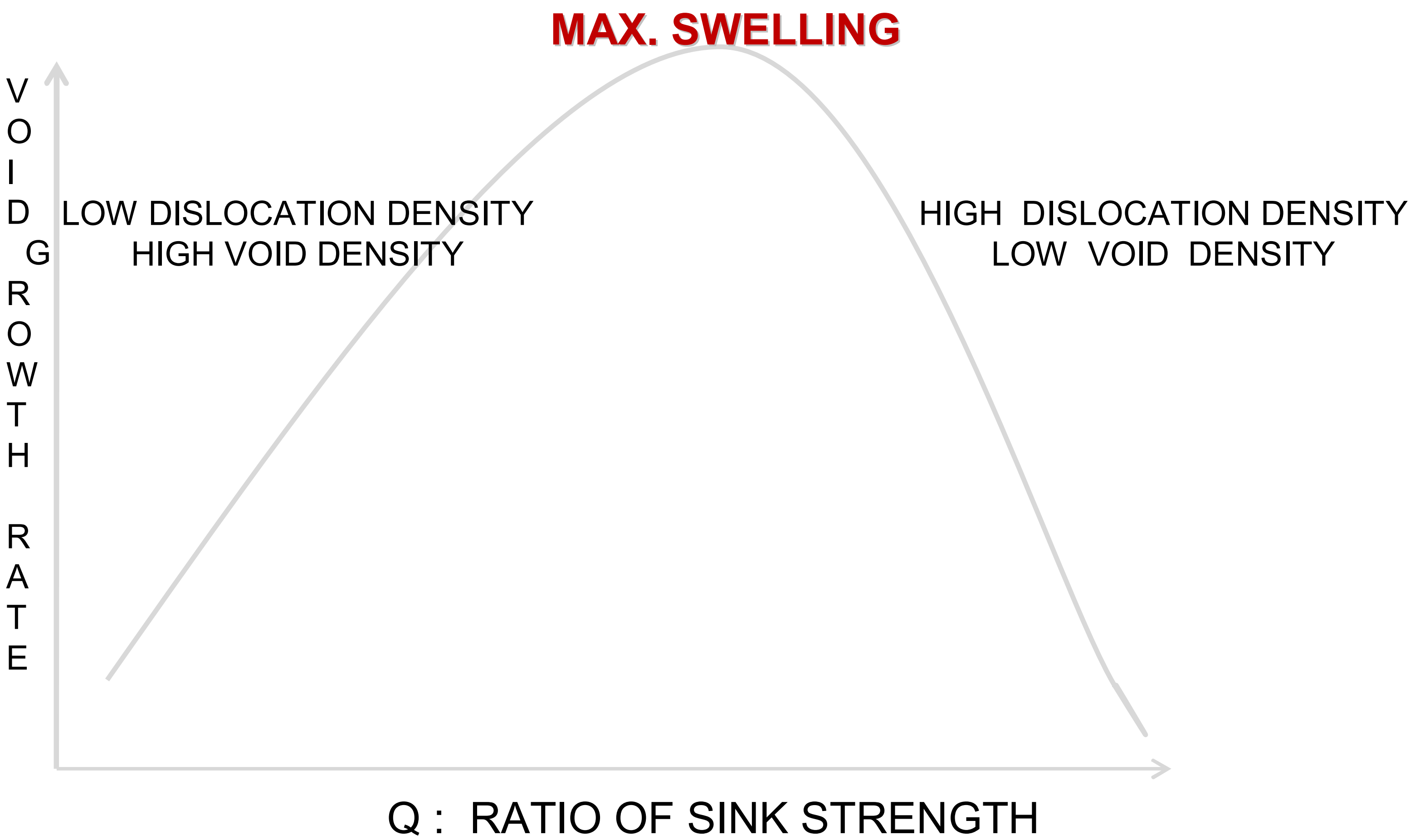
$$dR_o/dt = [(K_o (Z_i - Z_v)\rho_d \, \Omega] / [R (Z_v \rho_d + 4\pi R \rho_v + 4\pi R_{cp} \rho_{cp})]$$

Bias due to dislocations

Vacancies absorption at dislocations

If $Z_i = Z_v$, voids do not grow.

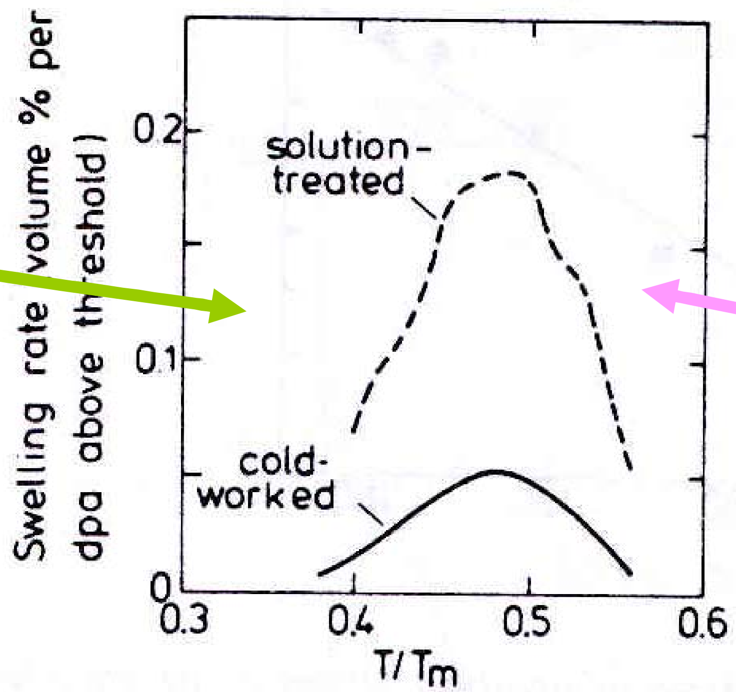
EFFECT OF DISLOCATIONS



Let Q = dislocation sink strength / void sink strength

Void Swelling : Temperature & Dislocation Density

Low Mobility



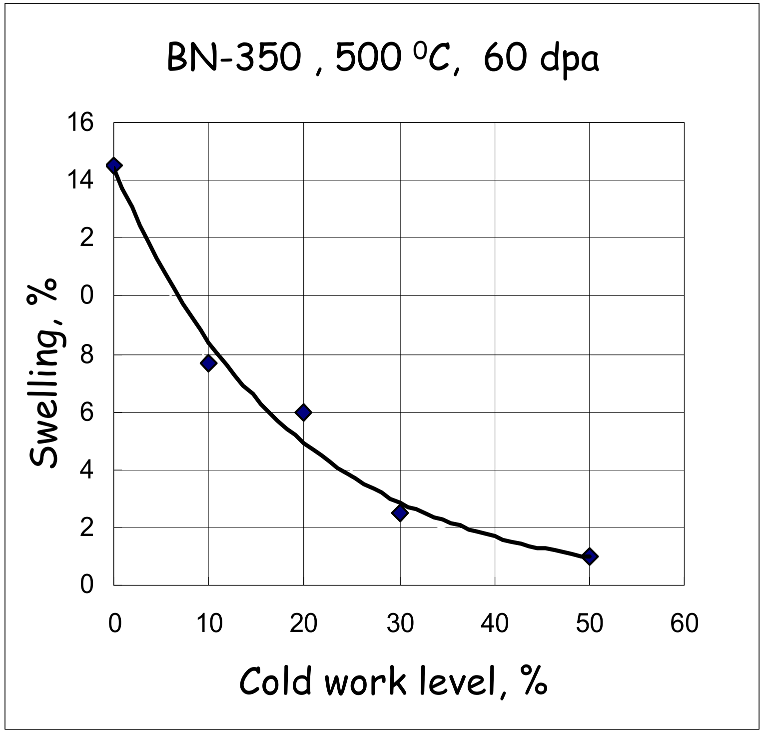
Super saturation difficult

Thermal Emission of Vacancies from voids

VNIINM

Structural approach – dislocation factor

Effect of cold work level on EI847 swelling



Progress in c.w. level of austenitic steel

ε = 15 %

ε = 18 ±2 %

ε = 20 ±3 %

ε = 20-25 %

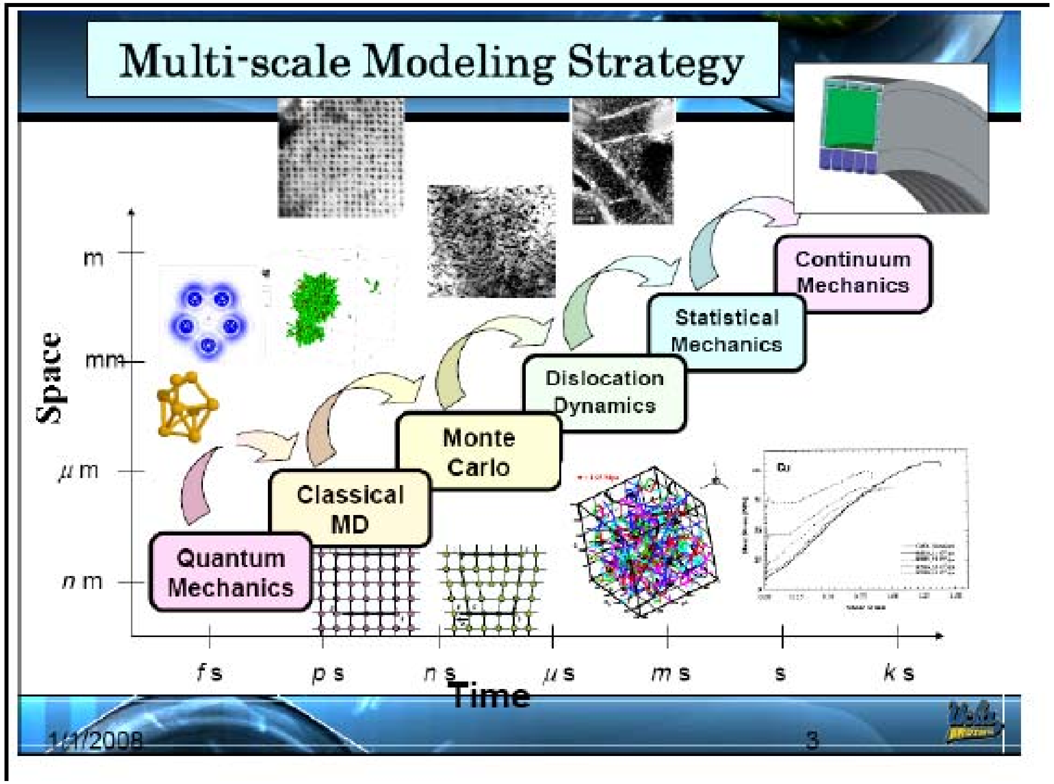
What is the limiting dose at which the favourable effect of C.W. increase disappears?

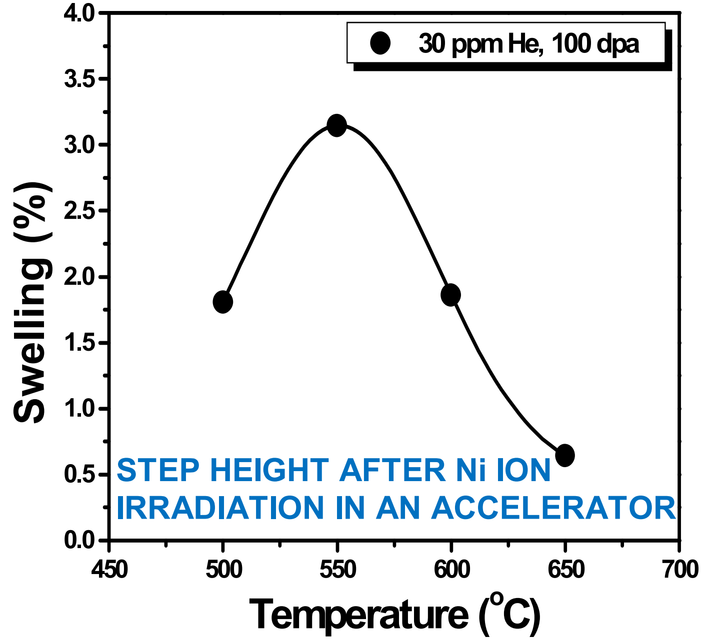
METHODS TO STUDY VOID SWELLING

- **MODELLING :** MONTE-CARLO METHODS, MOLECULAR DYNAMICS, CONTINUUM MECHANICS, RATE THEORY, DISLOCATION DYNAMICS

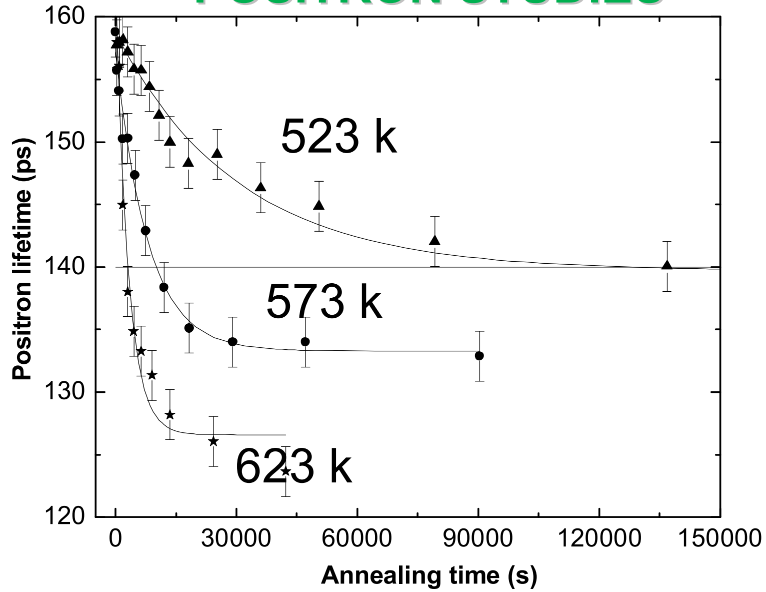
- **EXPERIMENTAL METHODS:** DENSITY MEASURE-MENTS, STEP-HEIGHT , POSITRON ANNIHILATION, RESISTIVITY, TEM UNDER NEUTRON, ION IRRADIATION CONDITIONS.

METHODS TO STUDY VOID SWELLING





POSITRON STUDIES



Materials Modeling

MDCASK

Car- Parinello MD

Density Functional Theory calculation of Physical Properties

ABINIT

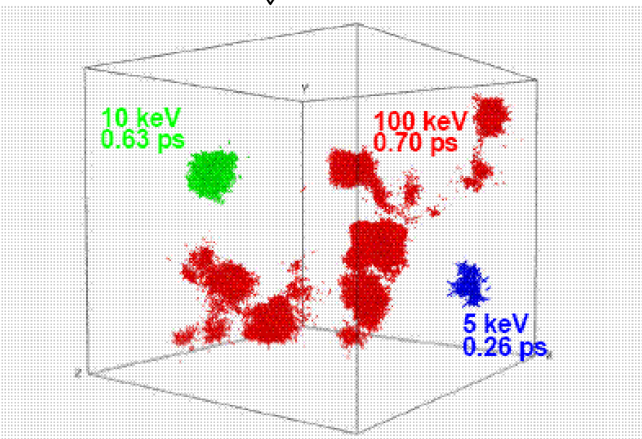
VASP

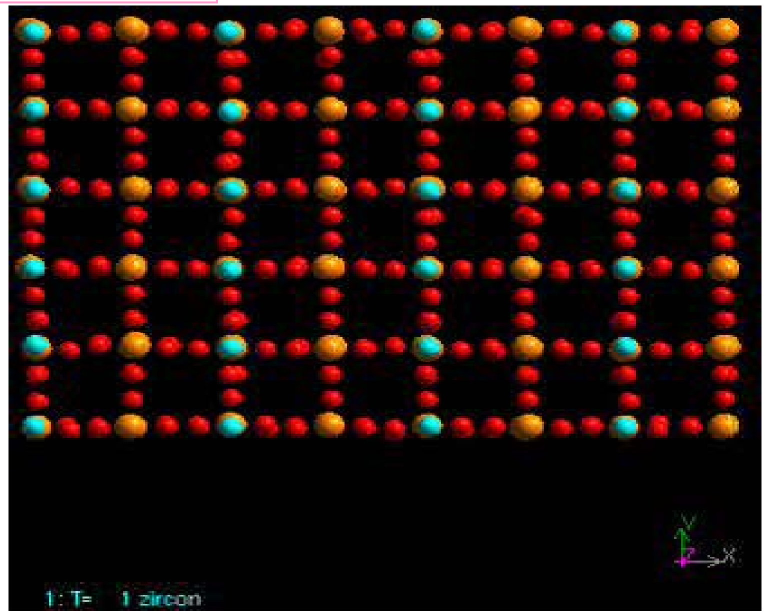
SIESTA

WIEN-2K

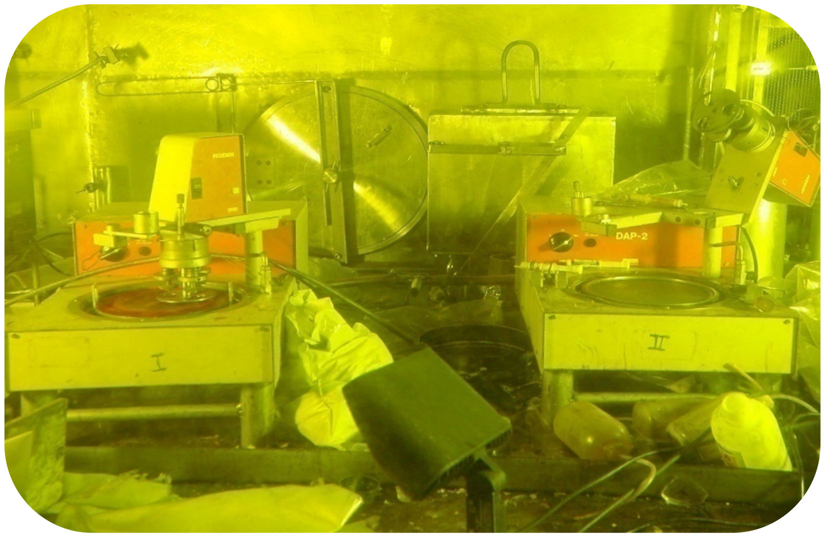
Cascades for 5, 10, and 100 keV cascades in Cu at 100K

Codes Installed, Parallelised

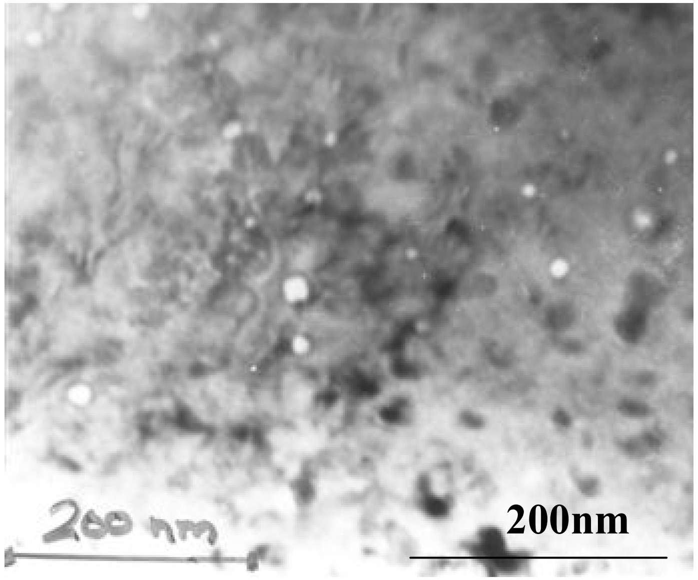




Hot cells at for PIE of FBTR Fuel & Structural Materials

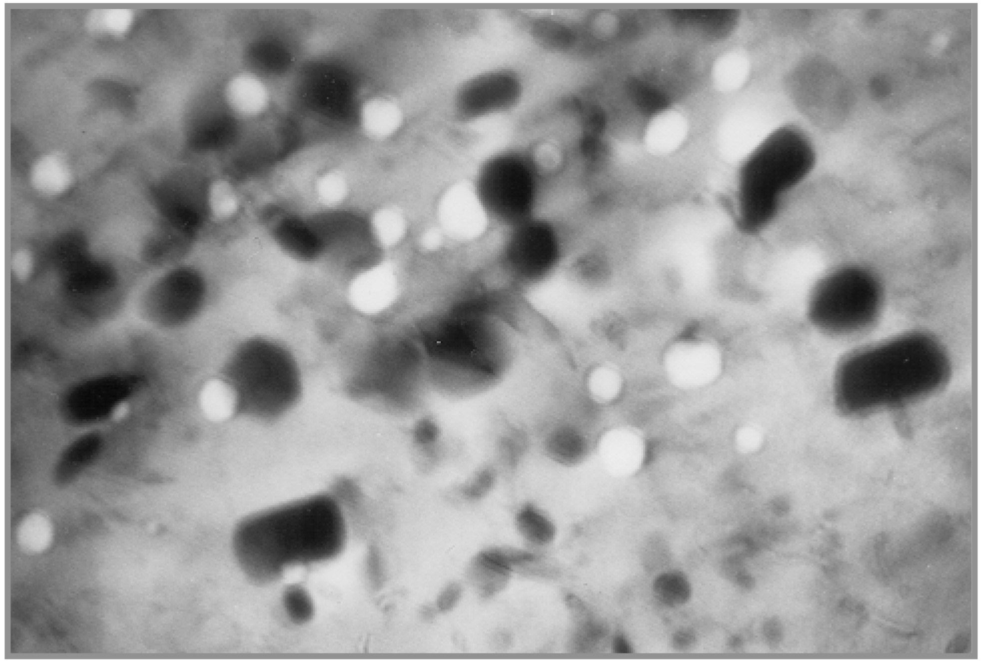


IN-SERVICE PERFORMANCE – WRAPPER OF FBTR



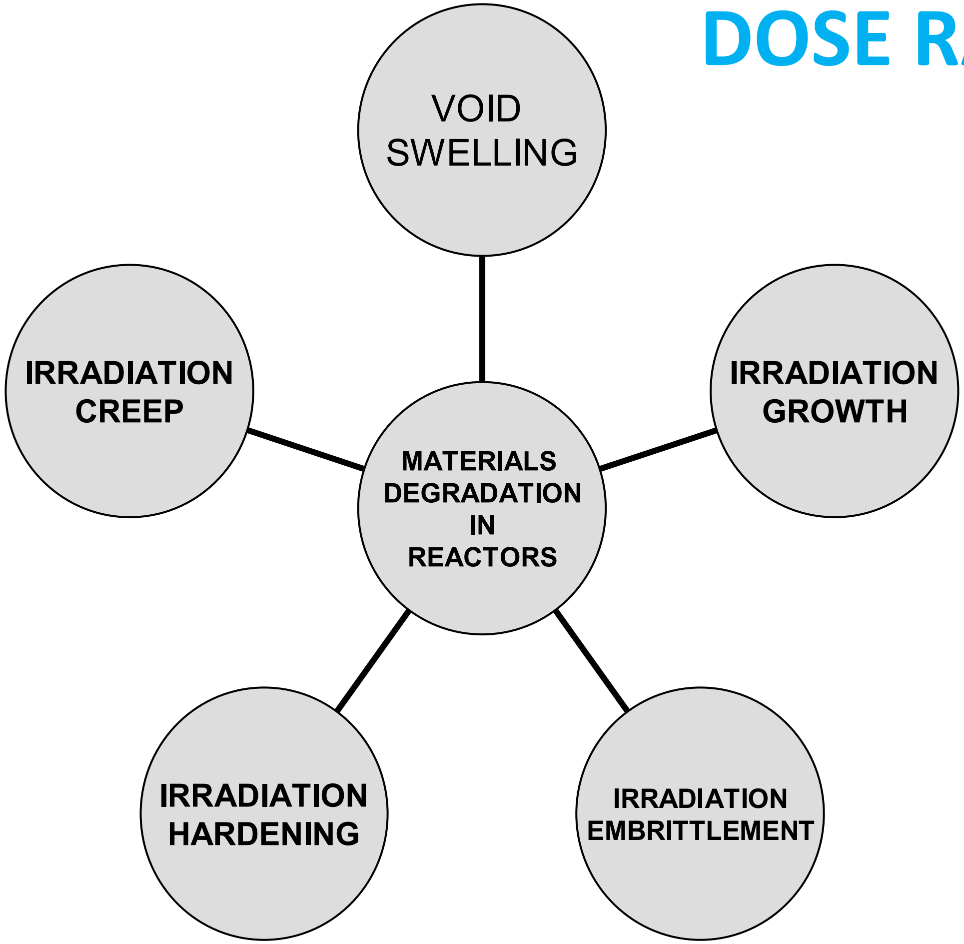
VOIDS in 20 % CW 316 SS AFTER 40 dpa

Ni3Si – G Phase formed ONLY during irradiation – due to RIS

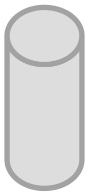


VOID SWELLING

DOSE; TEMPERATURE; COLD WORK & DOSE RATE.



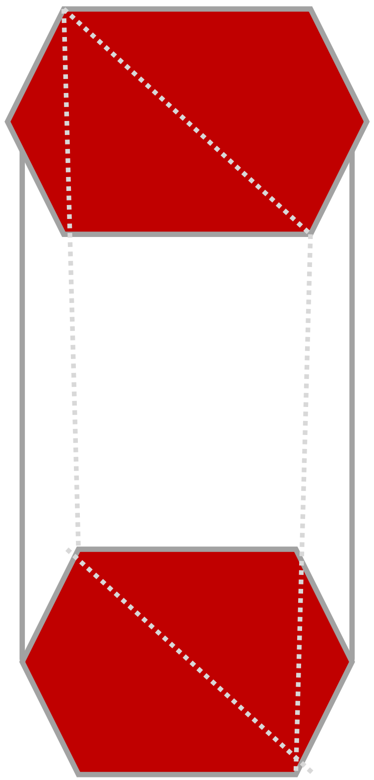
IRRADIATION GROWTH



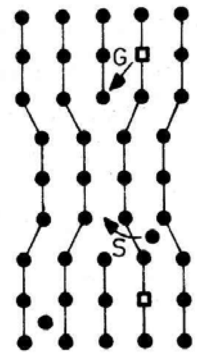
10^{20} n/cm^2

Volume remains same
Distortion increases
shape changes

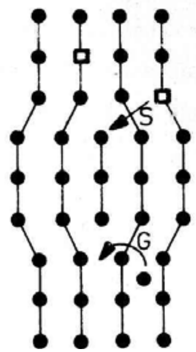
HCP
LATTICE



BASAL PLANE – (0001) - VACANCY LOOPS



PYRAMIDAL PLANE –
(11. 0) –
INTERSTITIAL LOOPS



ATOMS ARE REMOVED FROM BASAL PLANES & DEPOSITED IN THE (11-0) PLANES

IRRADIATION HARDENING

MECHANICAL BEHAVIOUR OF MATERIALS
(FORGET IRRADIATION FOR A MOMENT)

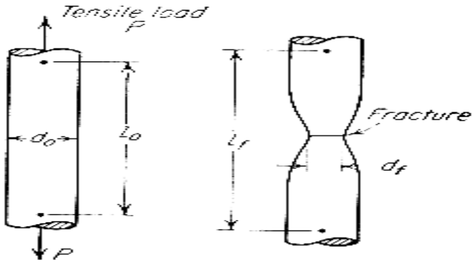
Generation of dislocations

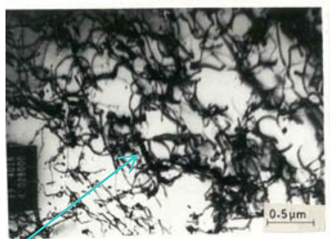
Pinning by obstacles

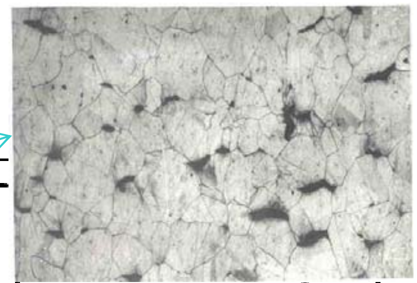
Unpinning of immobile dislocations

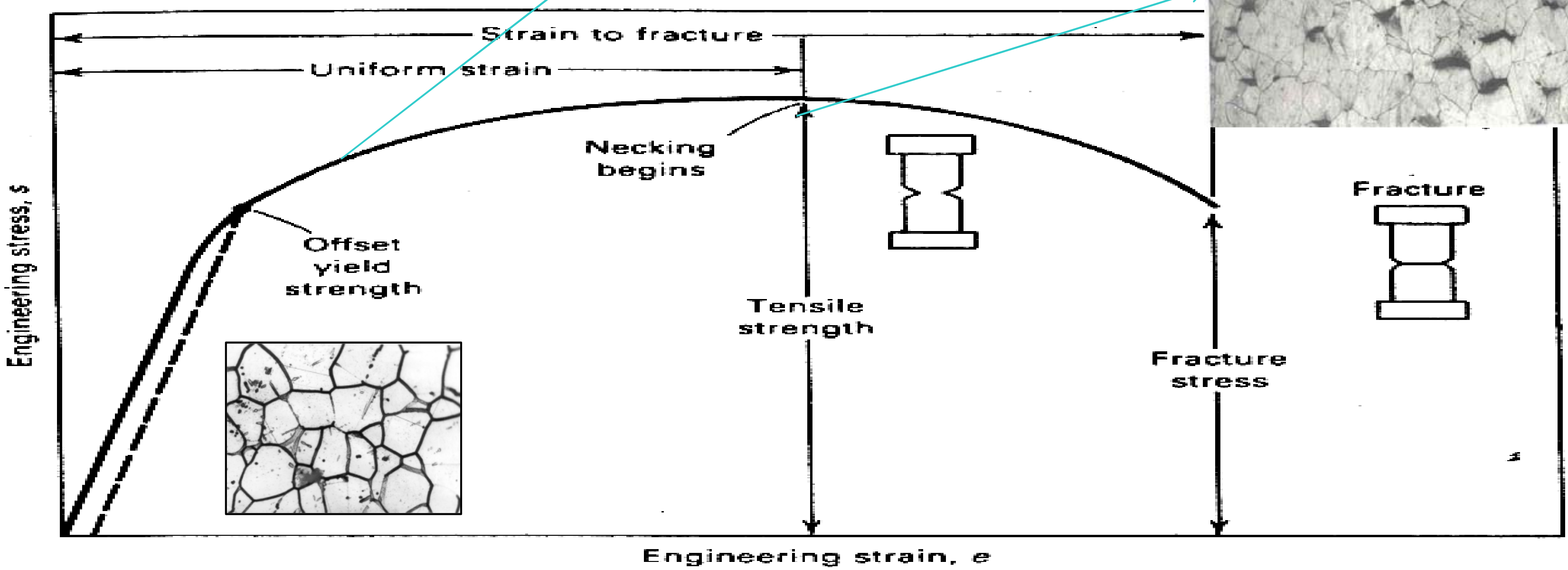
Build up of stress ahead of pile-up

cracking

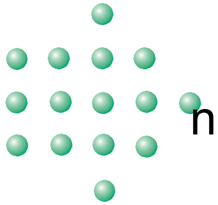




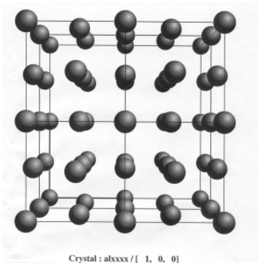




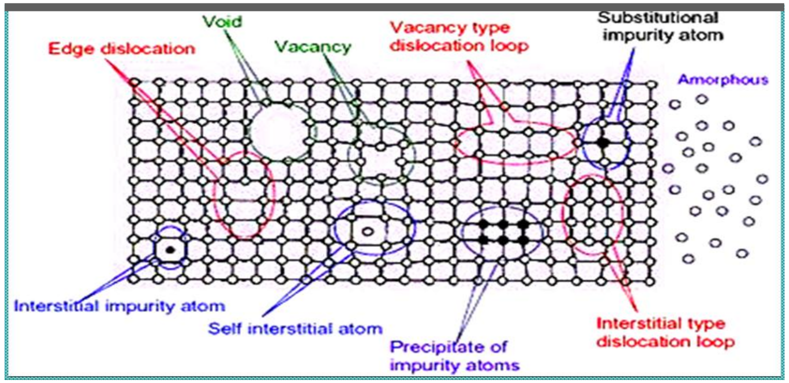
IRRADIATION HARDENING

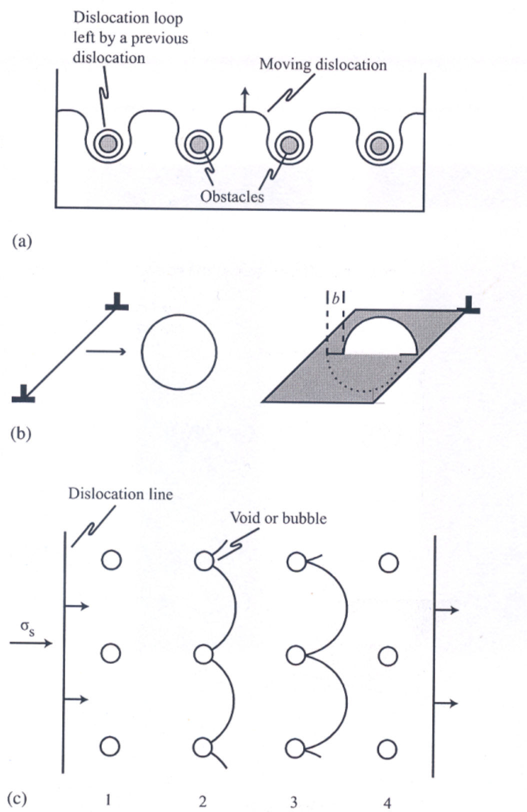


n +



=



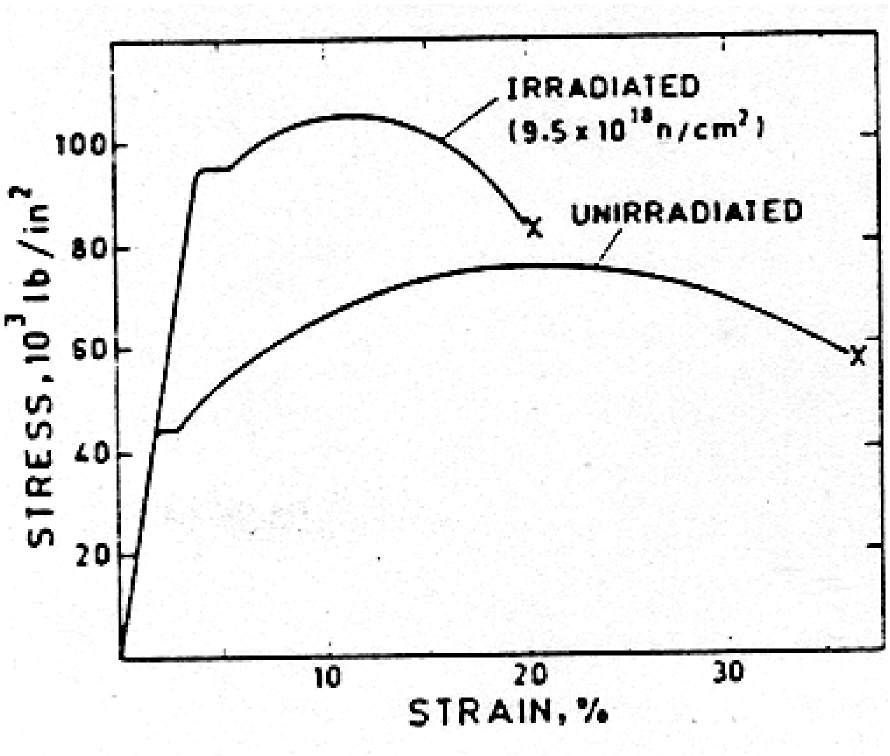


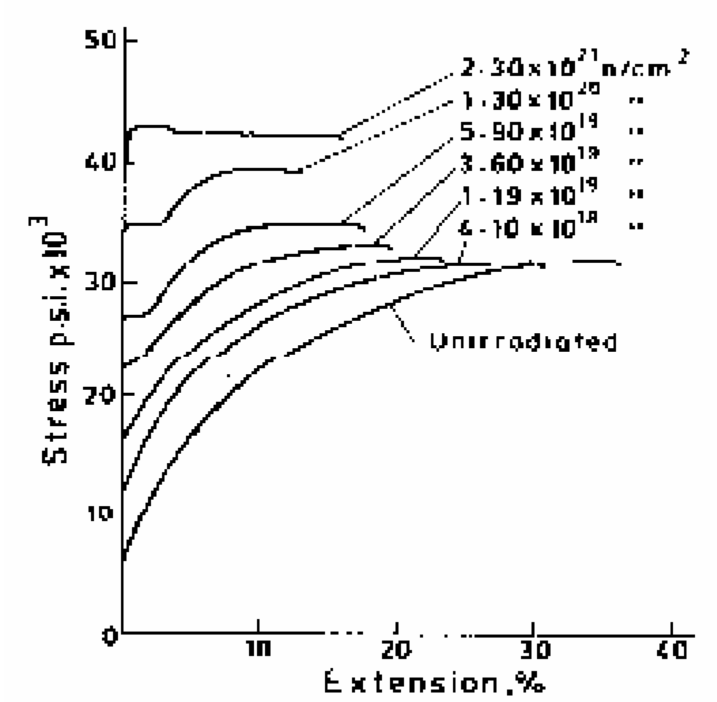
= source hardening + friction hardening

Unpin the immobile dislocations

Obstacle to mobile disolcations

IRRADIATION HARDENING



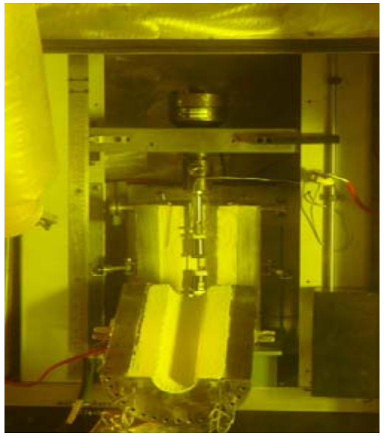


$$\Delta\sigma_s^{\text{irrad.}} = (\varphi\, t)^{1/2}$$

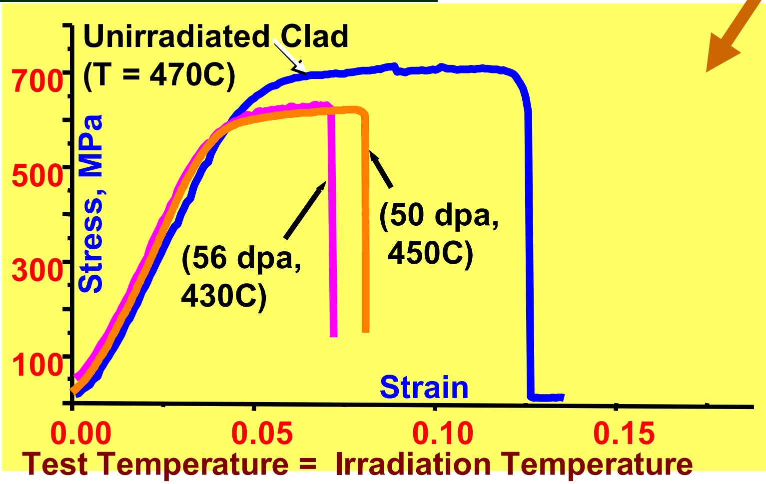
IN-SERVICE PERFORMANCE – WRAPPER OF FBTR

Tensile Testing of Irradiated Cladding

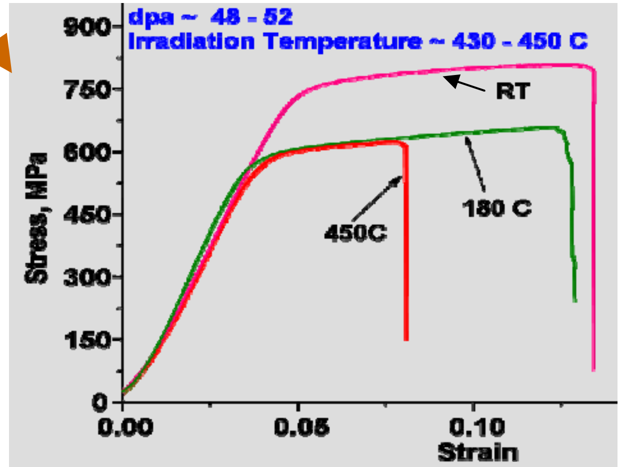
Stress-strain curves for various dpa and test temperatures



Remote tensile test system



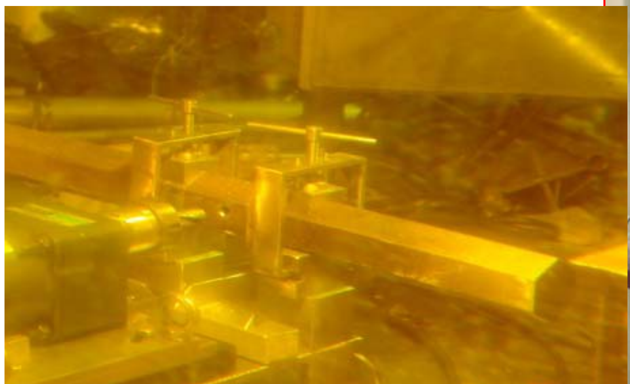
Effect of dpa

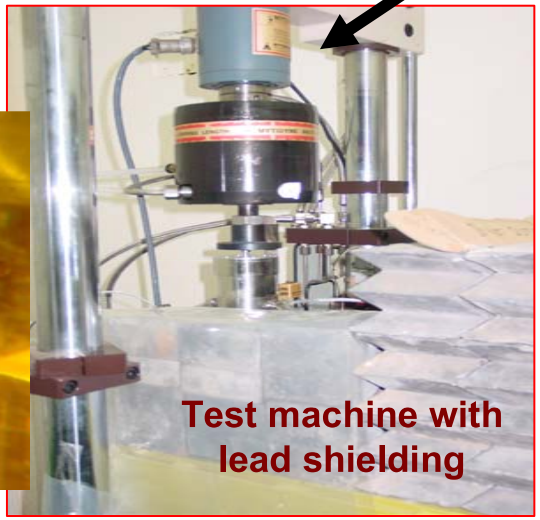


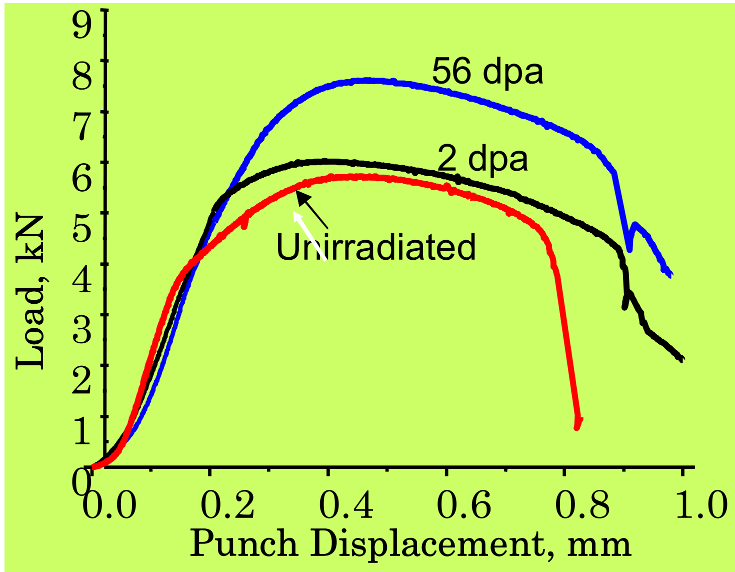
Effect of Test Temperature

Shear Punch testing of Irradiated Wrapper

Small disk specimen extracted in hot cell



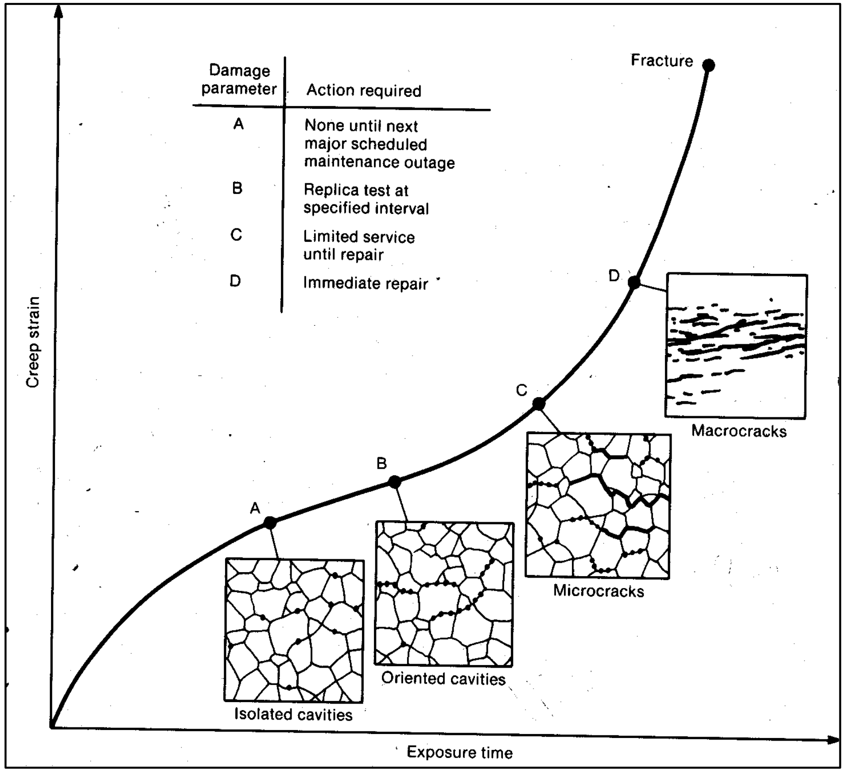




Shear punch test plot for various dpa

IRRADIATION CREEP

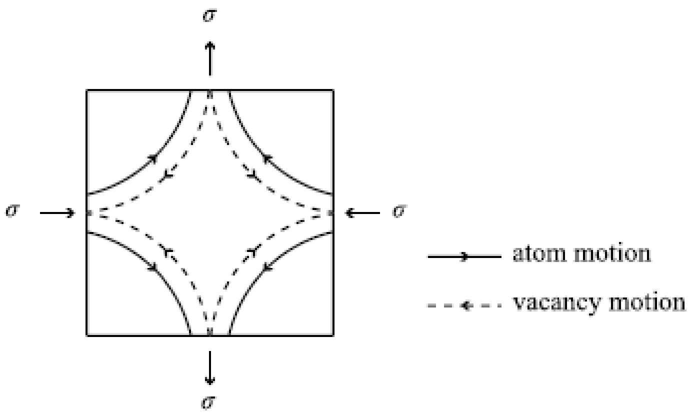
- WHAT IS CREEP ?
- WHAT ARE CREEP MECHANISMS ?
- WHAT IS IRRAD. CREEP ?
- SIPN & SIPA – IRRAD. CREEP MECHANISMS
- IDENTIFICATION OF IRRAD. CREEP



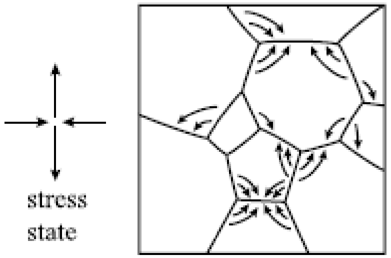
Typical Creep-curve: THERMAL ONLY

CREEP MECHANISMS

GRAIN BOUNDARY CREEP MECHANISMS



(a)



(b)

HARDENING MECHANISMS

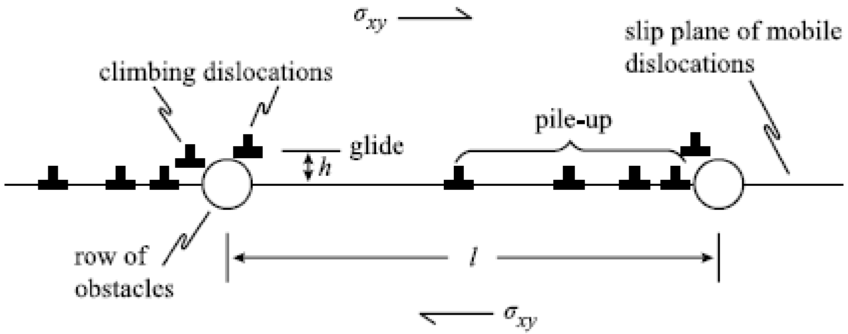


Fig. 14.4. Schematic showing the pile-up of dislocations behind an obstacle on the glide plane of the dislocations

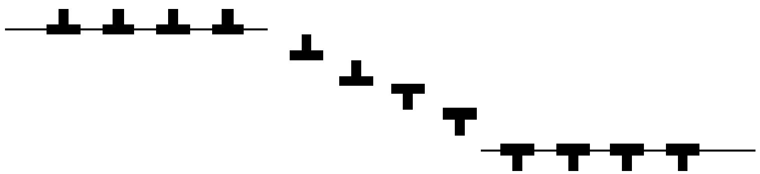


Fig. 14.7. Arrangement of a network of Frank–Read sources that produce dislocations that climb to annihilation (after [5])

IRRADIATION CREEP

- AUGMENTATION OF THERMAL CREEP BY IRRADIATION OR
- INTRODUCING CREEP AT T's WHERE THERMAL CREEP IS KNOWN 'NOT TO OCCUR'
- CREEP RATE CHANGED WITH DOSE, DOSE RATE – SIGN OF IRRAD. CREEP

IRRADIATION CREEP IN EBR-II

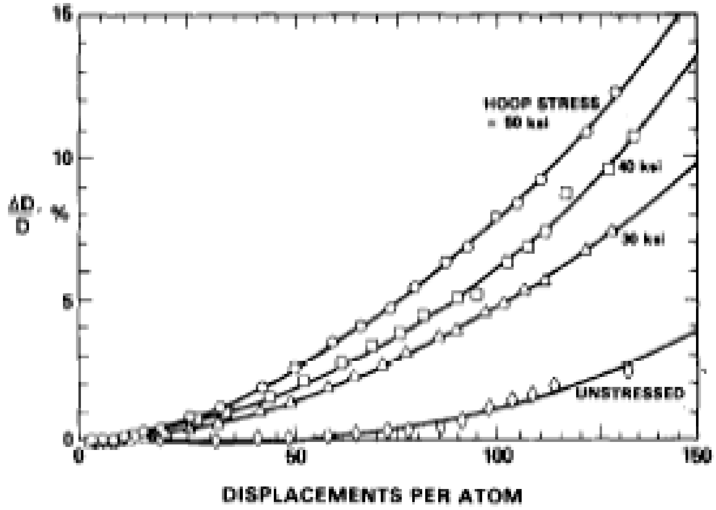
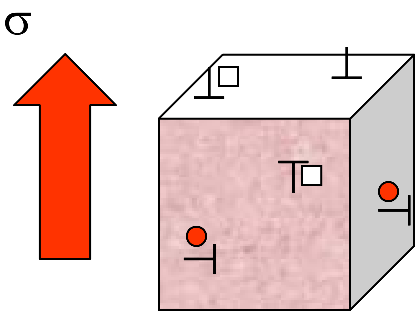


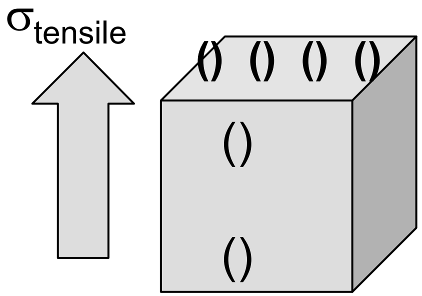
Fig. 2. Diameter changes induced at capsule center in four selected creep capsules constructed from 20% cold-worked AISI 316 stainless steel and irradiated in EBR-II. The hoop stress levels ranged from 0 to 343 MPa (0–50 ksi).

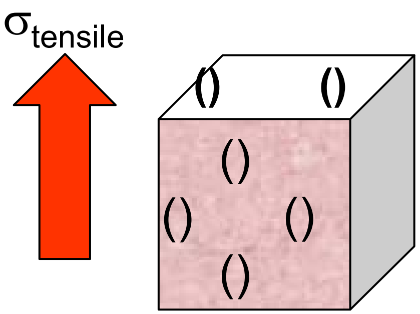
IRRADIATION CREEP MECHANISMS: SIPA & SIPN

- V 's & I's ABSORBED PREFERENTIALLY
- I's TO $\perp$ s WITH EXTRA HALF PLANE $\perp$ σ



- V's TO OTHER $\perp$s

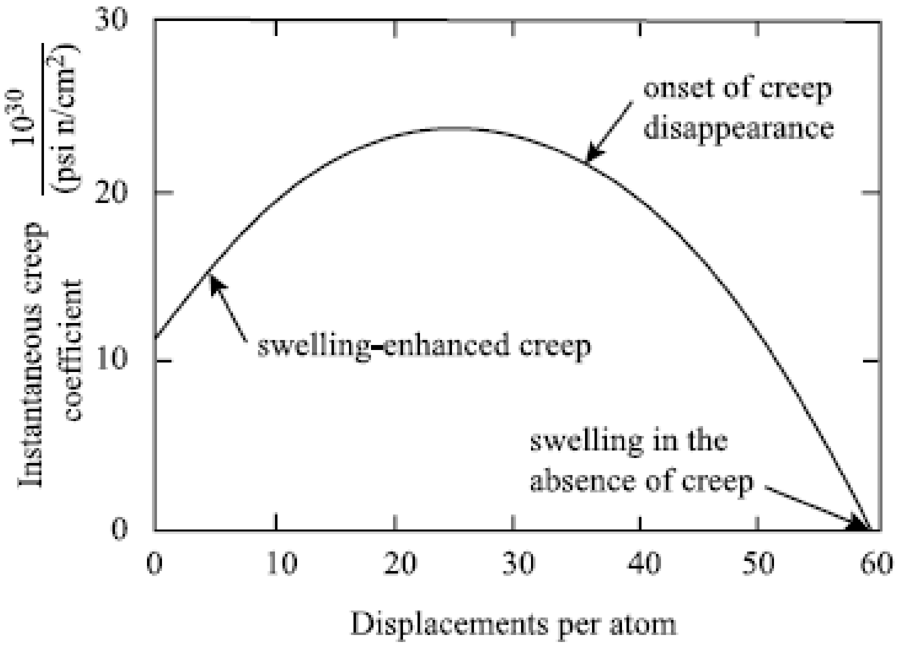




- LOOPS NUCLEATE PREFERENTIALLY
- $(\text{INT.LOOPS})_{\text{PLANES} \perp \sigma\text{tensile}}$ >>> same in planes ll σ_{tensile}
- $(\text{VAC.LOOPS})_{\text{PLANES} \perp \sigma\text{tensile}}$<<<<< same in planes ll σ_{tensile}

Swelling assisted creep

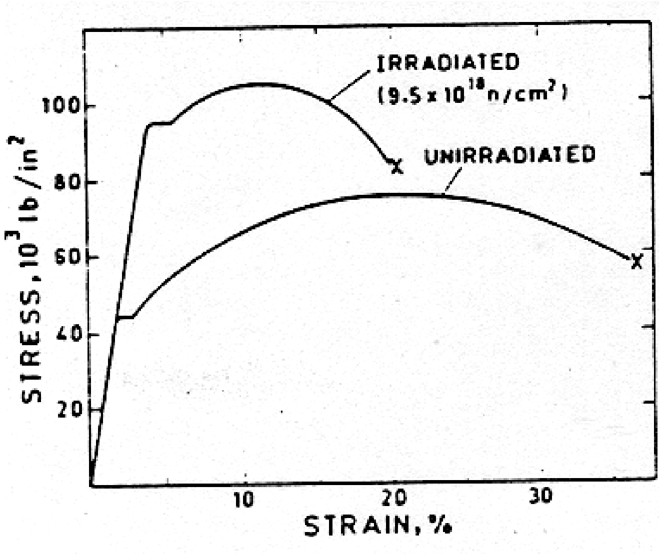
- **Swelling enhances creep rate at smaller dose levels**
- **Creep disappears beyond certain dose**
- **After this dose, swelling continues, creep disappears**

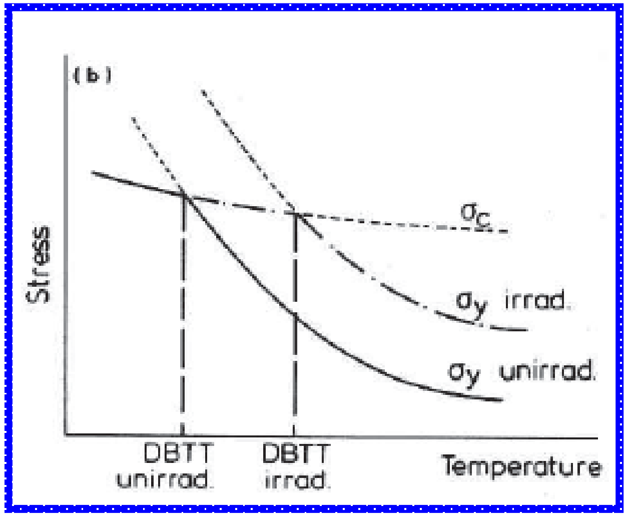


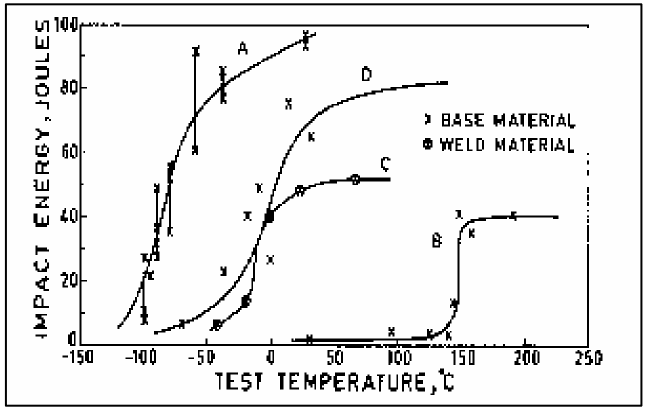
Swelling assisted creep: Mechanisms

- **when voids form, V + I are absorbed in large numbers by the voids.**
- **Less I flow to dislocations -→ creep reduces**
- **Swelling saturates due to low excess vacancy absorption**

Irradiation embrittlement

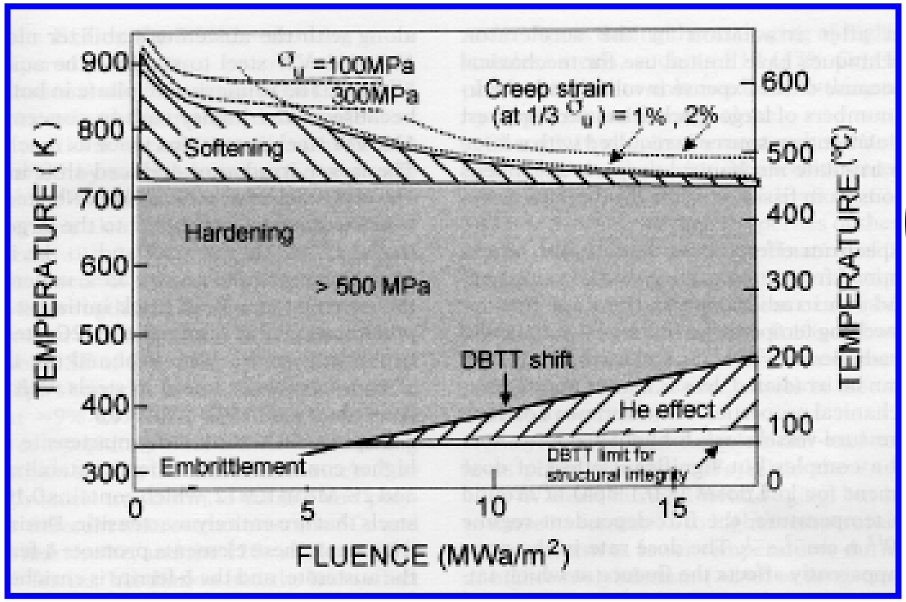






$$T_c = C^{-1} [\ln Bk_s d^{1/2} / (\beta\gamma\mu - k_y k_s)$$

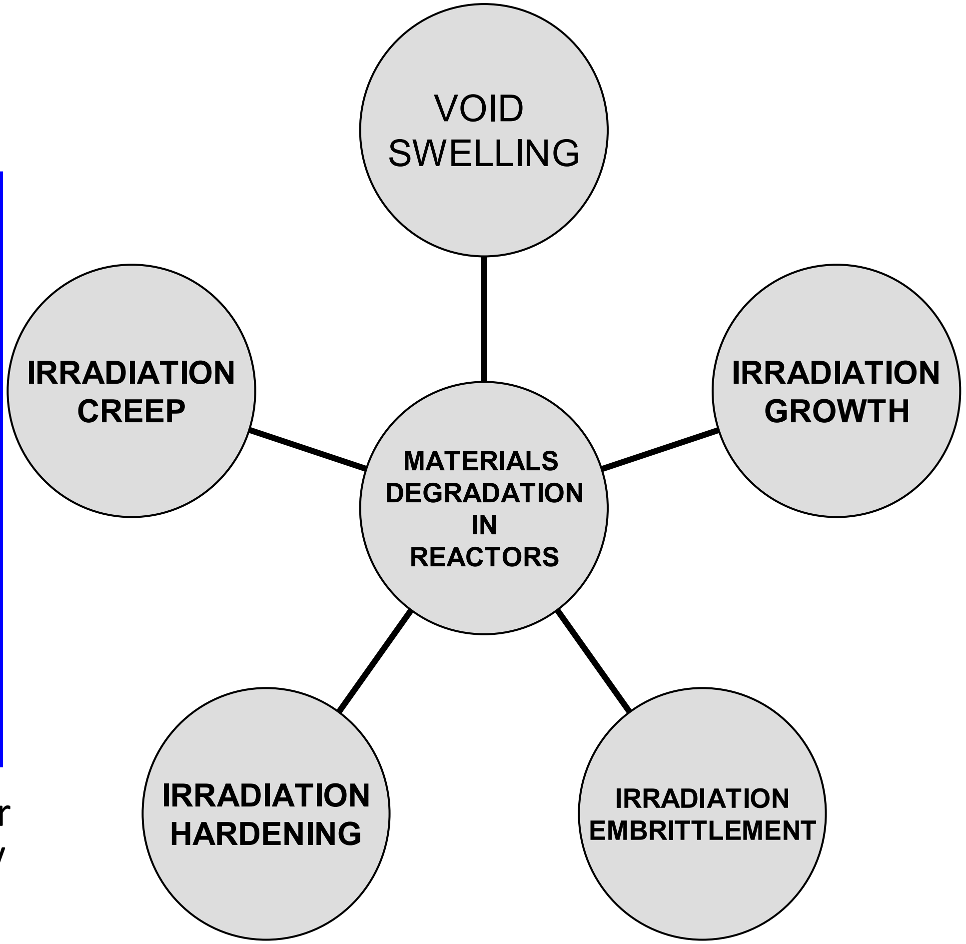
RADIATION DAMAGE



Introduction to structural materials and their behaviour in a fast reactor fuel assembly

Radiation Damage

Principles of Design of Radiation Resistant Materials for Fast Reactor Fuel Assembly



THANQ 4 UR ATTENTION