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Radiation damage of structural materials for fast reactor fuel assembly

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RADIATION DAMAGE OF STRUCTURAL MATERIALS FOR FAST REACTOR FUEL ASSEMBLY

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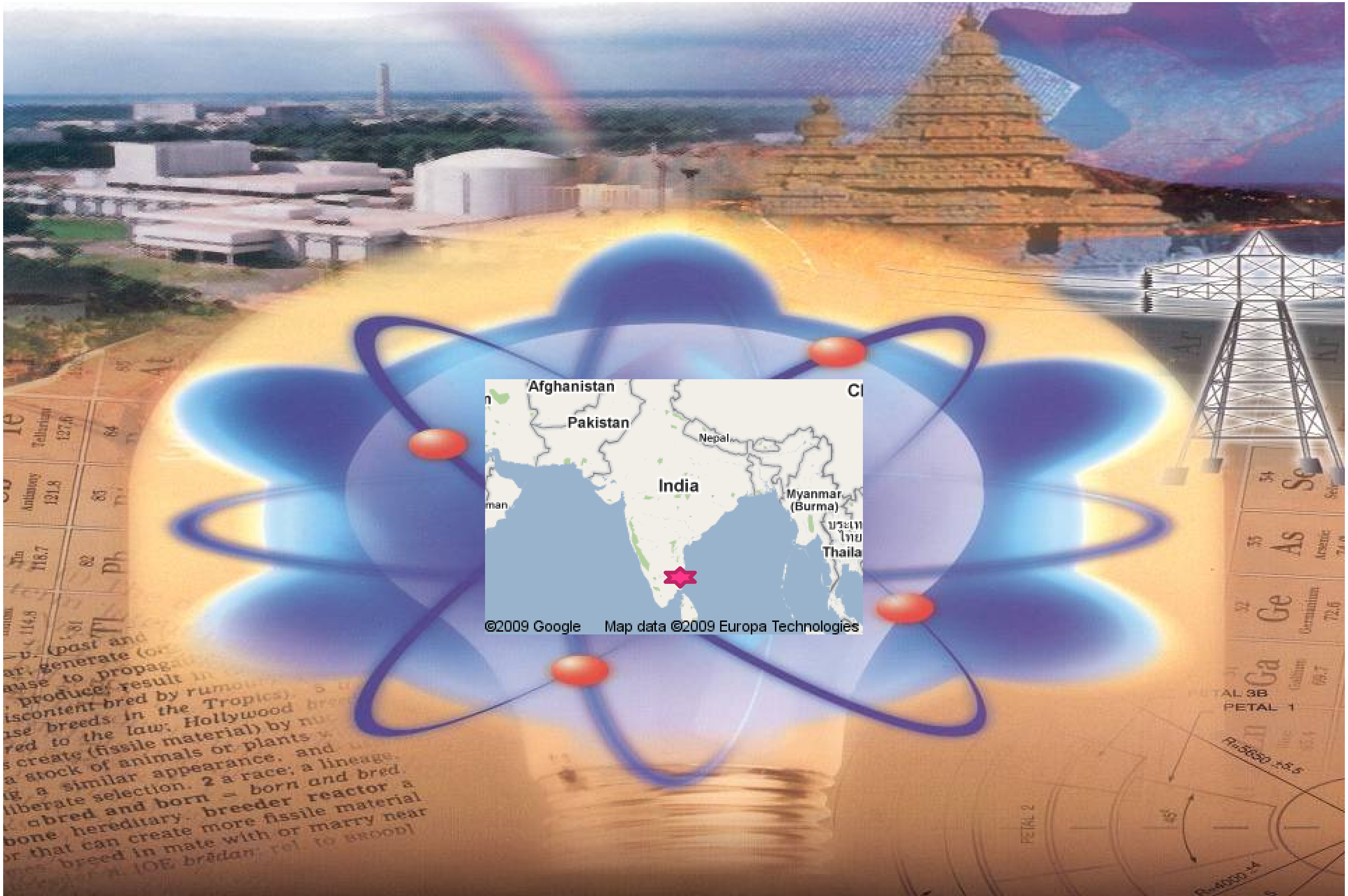
1. **Introduction to structural materials and their behaviour in a fast reactor fuel assembly**

2. Radiation Damage

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



FAST BREEDER REACTORS

Energy Security for Country's Prosperity

About Indira Gandhi Centre for Atomic Research, KALPAKKAM, INDIA

SOUTHERN PART OF INDIA ;

SECOND LARGEST ORGANISATION IN DEPARTMENT O F ATOMIC ENERGY;

SINCE 70’s, DEVELOPING FAST REACTOR TECHNOLOGY;

COMMISSIONED FAST BREEDER TEST REACTOR IN 1985;

COMMERCIAL PROTOTYPE FAST BREEDER REACTOR IS TO BE COMMISSIONED;

EXPERTISE BUILT IN : REACTOR PHYSICS, DESIGN, CONSTRUCTION, COMMISSIONING, OPERATION & MAINTENANCE,

SAFETY, POST-IRRADIATION EXAMINATION, IN-SERVICE MONITORING, ROBOTICS, REPROCESSING & WASTE MANAGEMENT;

MATERIALS SCIENCE, RADIATION DAMAGE, METALLURGY & MATERIALS TECHNOLOGY

SCOPE OF MODULE 1

- **TARGETS FOR MATERIALS SCIENTISTS**
- CLASSIFICATION & ENGINEERING PROBLEMS
- INTERACTION OF NEUTRONS WITH LATTICE ATOMS
- POINT DEFECTS & THEIR CLUSTERS

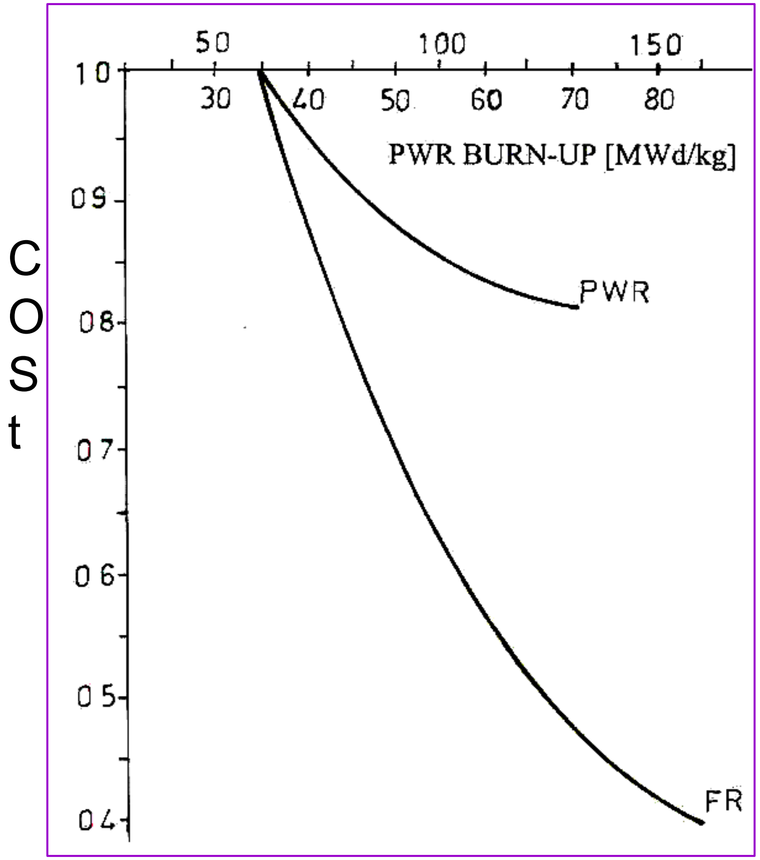
TARGETS FOR MATERIALS SCIENTISTS FOR NUCLEAR REACTORS

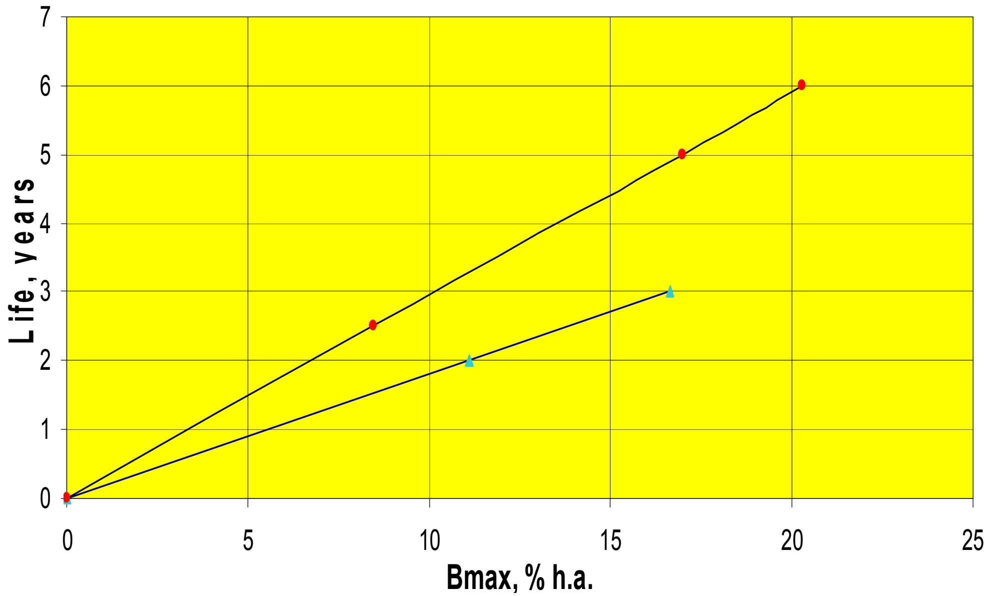
HIGH BURN-UP MATERIALS;

LONG LIFE – 100 YEARS;

HIGH TEMPERATURE CAPABILITIES

WHY INCREASE BURN-UP?





INCREASE BURN-UP--→ INCREASES RESIDENCE TIME IN CORE --→ REDUCES COST

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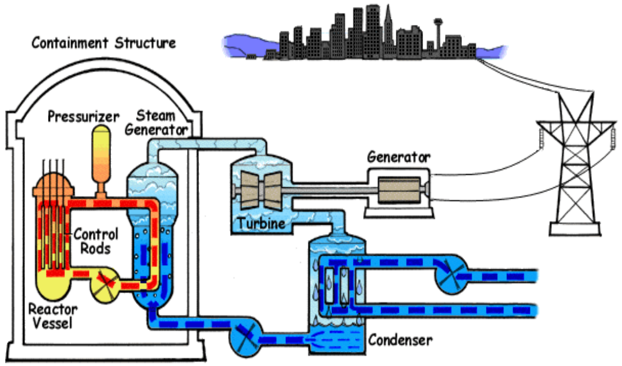
CLASSIFICATION OF STRUCTURAL MATERIAL IN FAST REACTOR FUEL ASSEMBLY



-- CORE

-- BALANCE-OF-PLANT (CONVENTIONAL)

-- OUT-OF- CORE

HIGHEST RADIATION

MAXIMUM TEMPERATURE

MAXIMUM TEMP. GRADIENT

FISSION PRODUCT RELEASE

SODIUM COMPATIBLE

LESS RADIATION

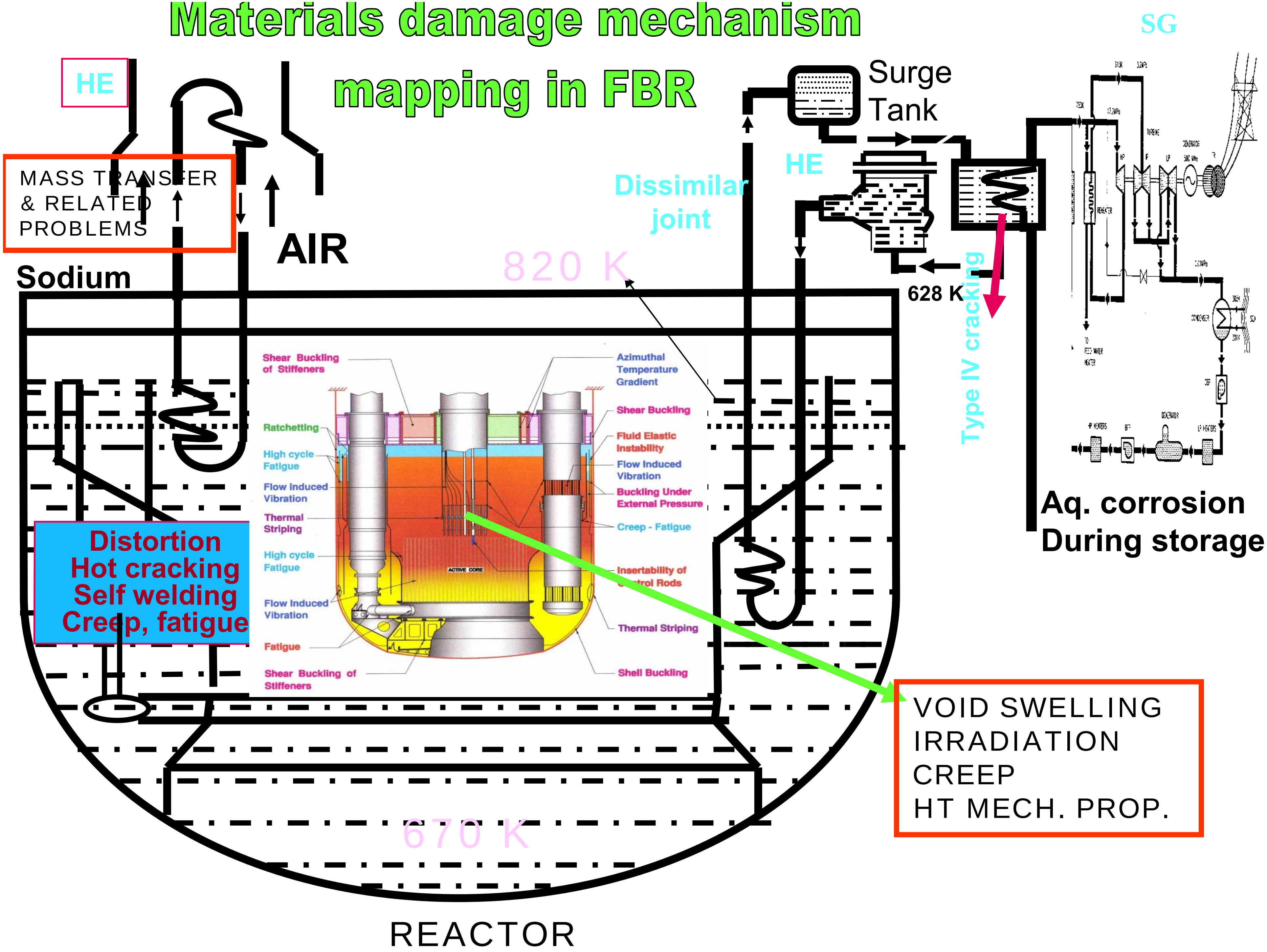
LESS TEMPERATURE

SODIUM COMPATILE

FATIGUE LIFE

FABRICABILITY

Materials damage mechanism mapping in FBR



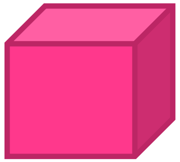
MATERIALS SELECTION CRITERIA:
FAST REACTOR CORE COMPONENT MATERIALS

Criterion	Clad Tube	Wrapper Tube
Irradiation effects	Void swelling Irradiation creep Irradiation embrittlement	Void swelling Irradiation creep Irradiation embrittlement
Mechanical properties	Tensile strength Tensile ductility Creep strength Creep ductility	Tensile strength Tensile ductility
Corrosion	Compatibility with sodium Compatibility with fuel Compatibility with FP	Compatibility with sodium
Corrosion	Resistance under normal Na chemistry, Na-H2O reaction, fretting, wear	
Good workability		
International irradiation experience as driver or experimental fuel subassembly		
Availability & Cost		

MACROSCOPIC EFFECT OF RADIATION ON STRUCTURAL MATERIALS

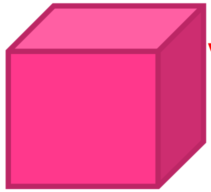
BEFORE | **AFTER IRRADIATION**

- 1 cm



1.06 CM

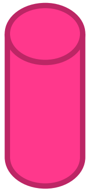
10^{22} n/cm^2



Volume increases;
Density reduces

- HCP lattice,

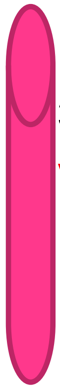
1 CM



10 CM

0.58 CM

10^{20} n/cm^2

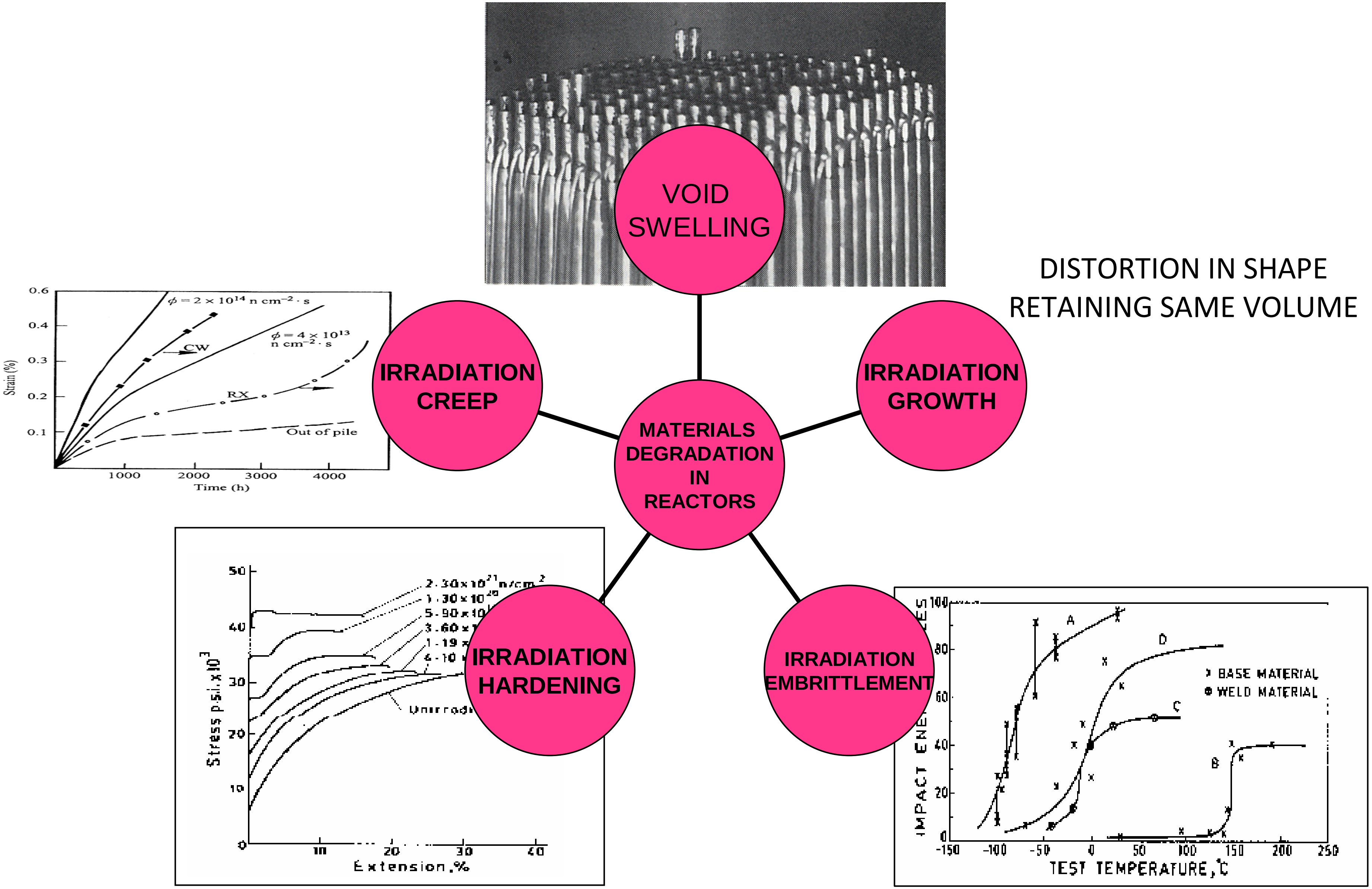


30 CM

Volume remains same
Distortion increases
shape changes

CHANGES IN
MECHANICAL BEHAVIOUR

RADIATION DAMAGE IN CORE COMPONENT MATERIALS



ENGINEERING PROBLEMS ----→ ATOMISTIC DEFECTS PRODUCED DURING IRRADIATION

SCOPE OF MODULE 1

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RADIATION DAMAGE : TYPES

.RADIATION DAMAGE

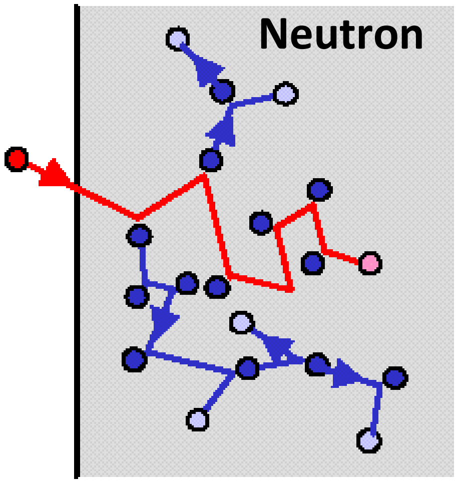
- **DISPLACEMENT**

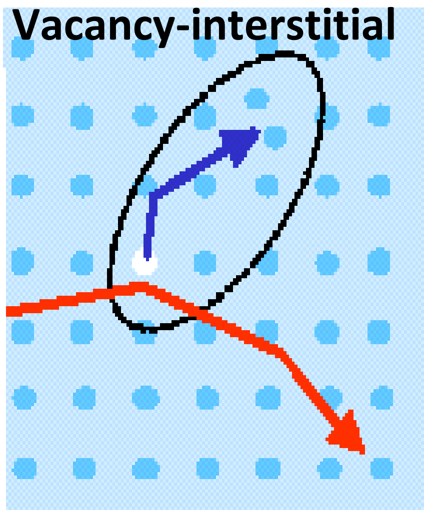
  Displacement of Lattice Atoms From Their Equilibrium positions

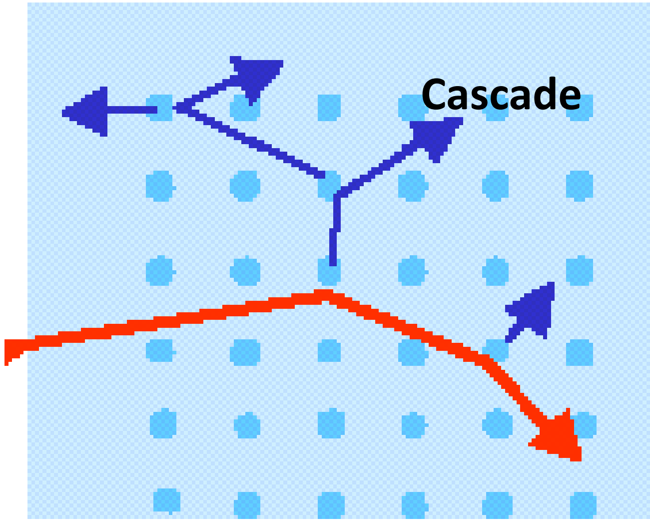
- **TRANSMUTATION**

  Production of Helium by (n,α) Reactions

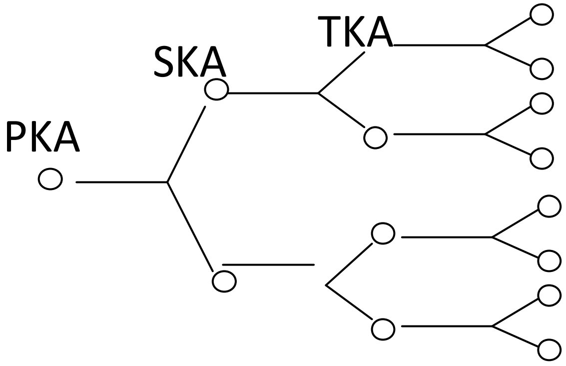
Radiation Damage : CASCADE FORMATION

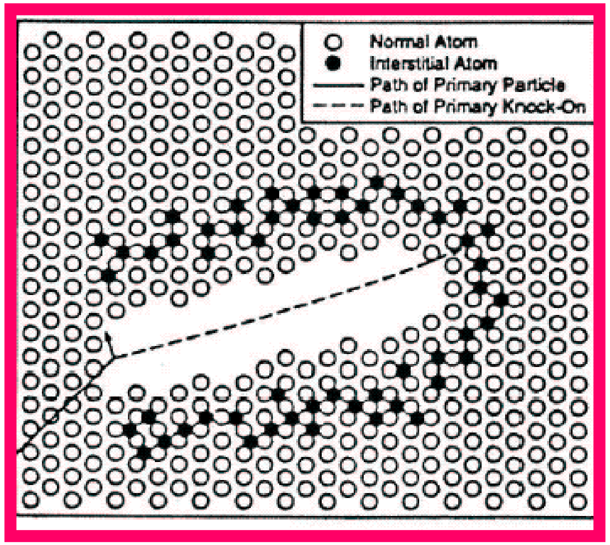




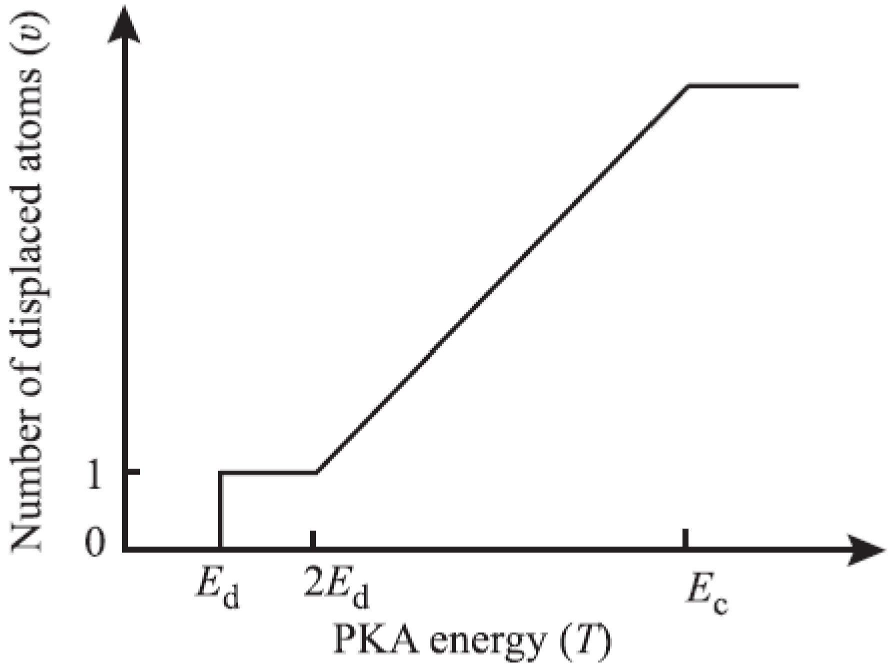


$$E = E_0\, 4\{(m_1 x\ m_2)/\ [m_1 + m_2]^2\ \}$$





ANIMATION



NUMBER OF DISPLACED ATOMS

DEPEND ON

T – PKA ENERGY

$$\nu(T) = \begin{cases} 0 & \text{for } T < E_d \\ 1 & \text{for } E_d < T < 2E_d \\ \dfrac{T}{2E_d} & \text{for } 2E_d < T < E_c \\ \dfrac{E_c}{2E_d} & \text{for } T \geq E_c \end{cases}.$$

TIME SCALES OF DAMAGE EVENTS

Time (s)	Event	Result
10^{-18}	Energy transfer from incident pcle	Primary Knock On generated
10^{-13}	Displacement of lattice atoms by PKO	Displacement cascade
10^{-11}	Energy dissipation, spontaneous recombination & clustering	Stable Frenkel pairs & defect clusters
10^{-8}	Defect reactions by thermal migration	Single interstitial atom & vacancy recombination, clustering, trapping & defect emission

Four stages of damage & the final structure

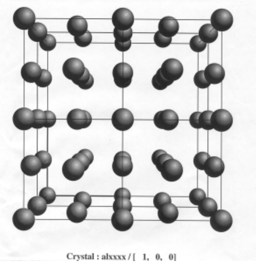
Collisional

Thermal Spike

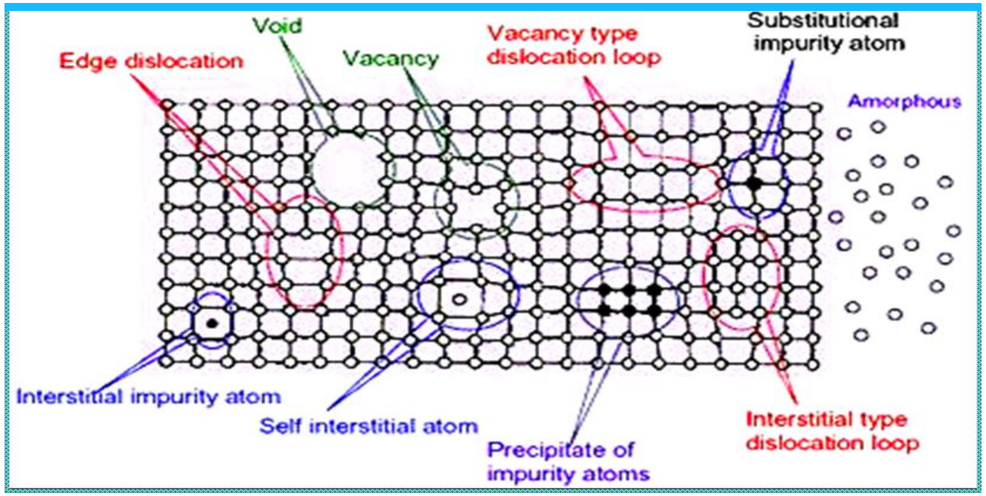
Quenching

Annealing.

NEUTRONS +



= 0, 1, 2 and 3 dimensional defects



TRY ANSWERING

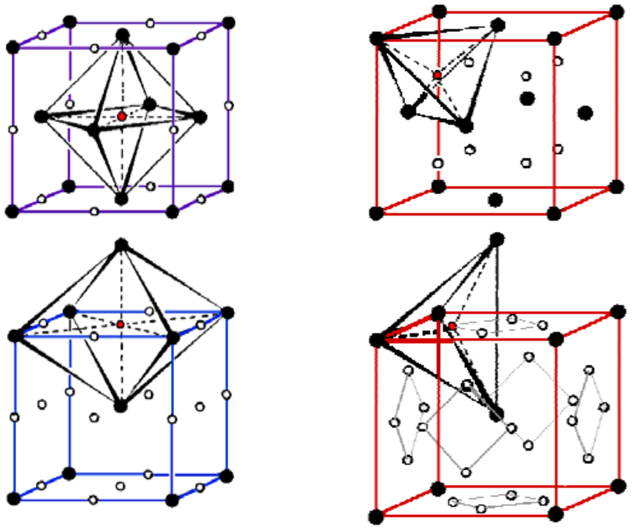
- CONSIDER LATTICE OF ALUMIUNIUM AND TUNGSTEN. WHICH LATTICE WILL HAVE MORE DISPLACEMENTS, GIVEN THE SAME IRRADIATION CONDITIONS.

- TAKE AN ALUMINIUM LATTICE. IMPINGE ON IT A NEUTRON AND A NICKEL ION OF SAME ENERGY. WHICH OF THE TWO PRODUCE MORE DAMAGE

0-D defects: point defects – VACANCIES & INTERSTITILAS

A vacant lattice site is a vacancy

INTERSTITIALS IN FCC & BCC



Thermodynamics of point defects

$F \sim G = U + pV - TS = H - TS$

$\nabla S_{mix} = k \ln \omega$

FOR n defects & N sites,

$w = \{ [N (N-1) (N-2)....(N-n+1)] / n!\}$

$C = n / N = \exp (-\nabla G_f / kT)$

Under thermal equilibrium, vacancies are necessarily present: why ?
They reduce the total free energy of the system.

$C_v = \exp (-E_{fv} / kT) \times \exp (S_{fv} / k)$

INTERSTITIALS ARE NOT EQUILIBRIUM DEFECTS

SOME IMPORTANT BEHAVIOUR OF POINT DEFECTS

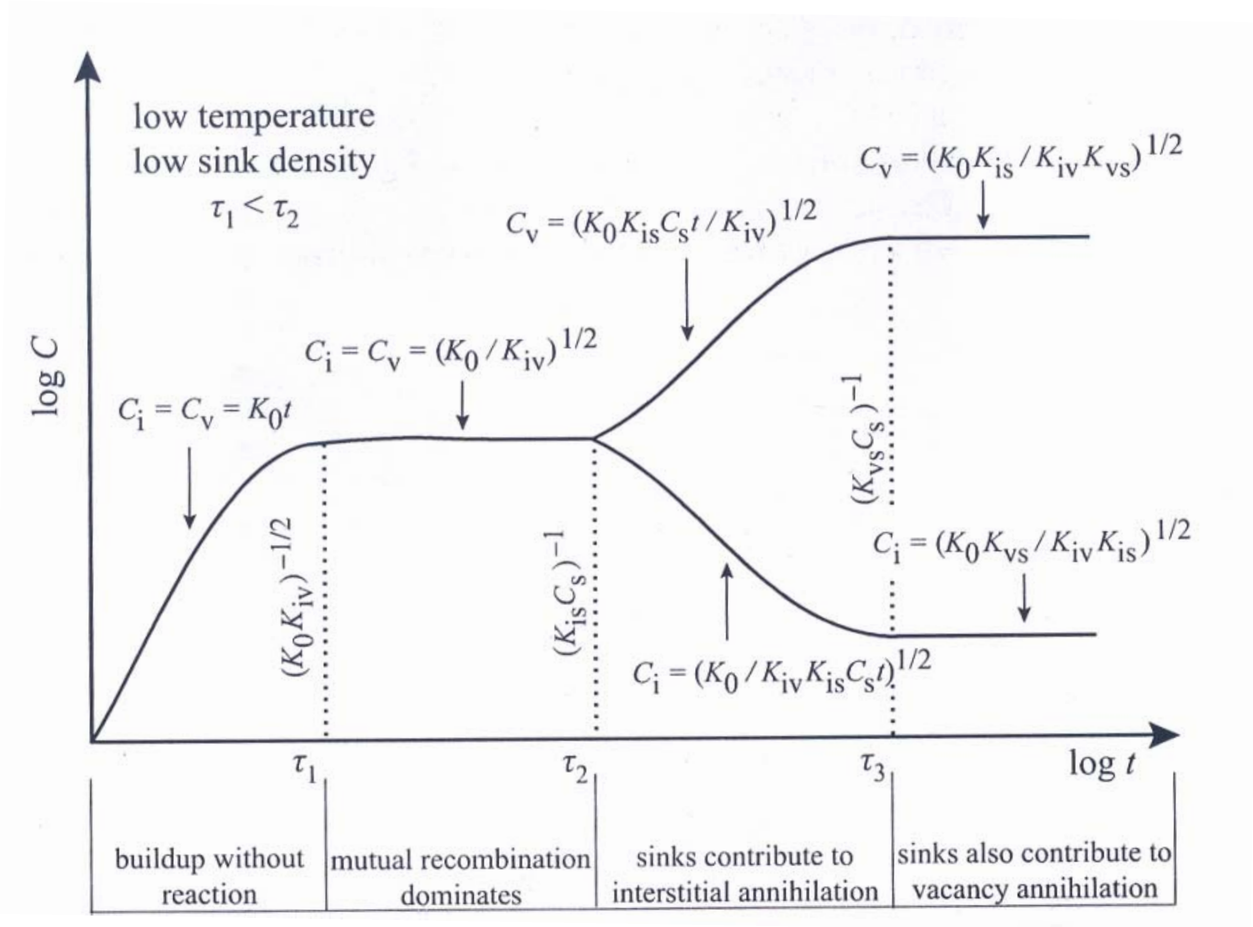
- FORMATION ENERGY OF VACANCIES < 0.6 - 1 eV
- SAME FOR INTERSTITIALS ~ 3-4 eV

- Migration energy for vacancies ~ 0.6 to 1 eV
- Same for interstitials ~ 0.06 eV

DIFFICULT TO FORM INTERSTITIALS THAN VACANCIES;

EASY TO MOVE INTERSTITIALS THAN VACANCIES

Point Defect evolution under irradiation:

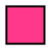


Point Defect Balance Equations under irradiation:

INCREASES WITH RATE OF PRODUCTION;

DECREASES WITH RECOMBINATION REACTIONS; MOBILITY

DECREASES WITH LOSS TO SINKS DEPENDENT

- V + I -→ 
- V + s -→ s or I + s -→ s
- $dC_v / dt = K_o - K_{iv}\, C_i\, C_v - K_{vs}\, C_v\, C_s$
- $dC_i / dt = K_o - K_{iv}\, C_i\, C_v - K_{is}\, C_i\, C_s$,

POINT DEFECTS: segregation & phase instability

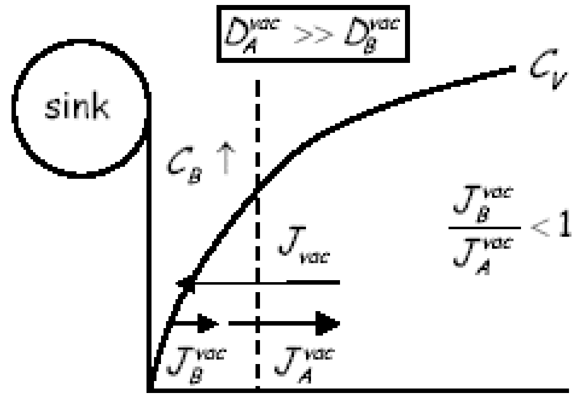
PHASE TRANSFORMATION
DUE TO DEFECTS

Free energy –
crystal + defects

Free energy –
parent crystal

Free energy –
amorphous

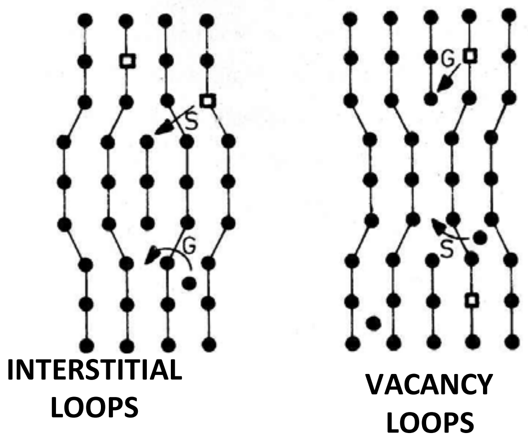
RADIATION INDUCED SEGREGATION

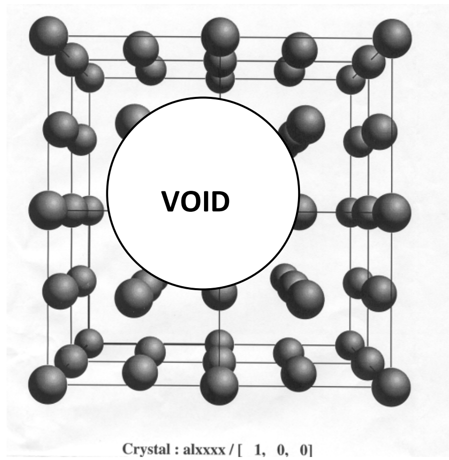


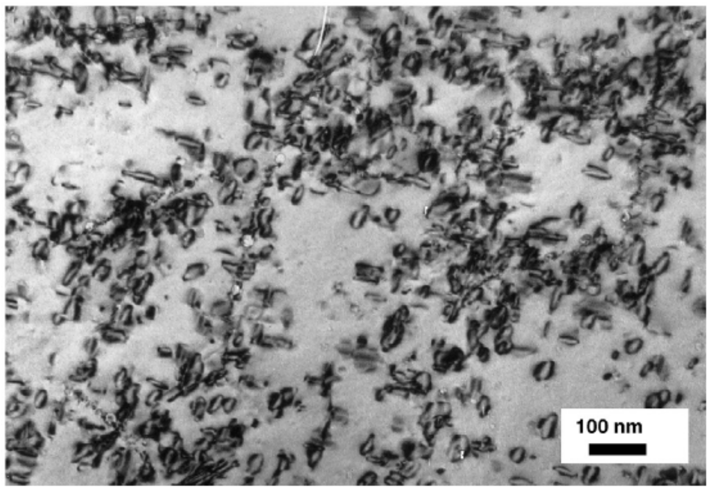
SCOPE OF MODULE 1

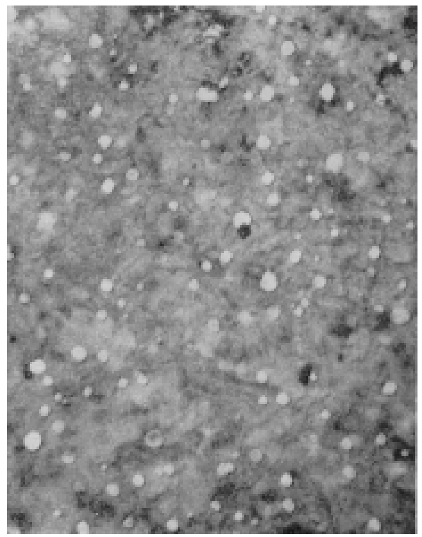
- TARGETS FOR MATERIALS SCIENTISTS
- CLASSIFICATION & ENGINEERING PROBLEMS
- INTERACTION OF NEUTRONS WITH LATTICE ATOMS
- **CLUSTERING OF POINT DEFECTS**

CLUSTERING OF POINT DEFECTS: 2 and 3 D defect clusters









CLUSTERING OF POINT DEFECTS

RELAXATION OF STRAIN OR
REDUCTION IN STRAIN ENERGY OF THE LATTICE

INTERSTITIAL LOOPS

+

VACANCY LOOPS

VOIDS

VOID GROWTH

RECAP

- REACTOR : CORE, OUT-OF-CORE & BALANCE OF PLANT
- CORE COMPONENT MATERIALS – WRAPPER & CLAD – MAX. DOSE, TEMP.
- IRRADIATION BY n's CAUSE CASCADE

Point Defects

Recombine

Migrate to Sinks

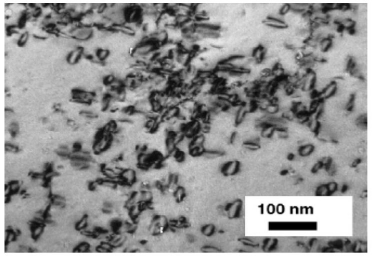
Clustering

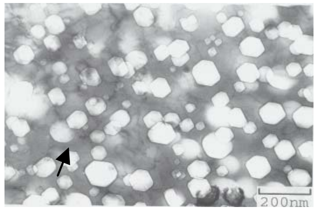
Voids

Dislocation loops

$$\frac{dc_i}{dt} = K - \alpha C_i C_v - k_i^2 D_i C_i$$

$$\frac{dc_v}{dt} = K - \alpha C_i C_v - k_v^2 D_v C_v$$

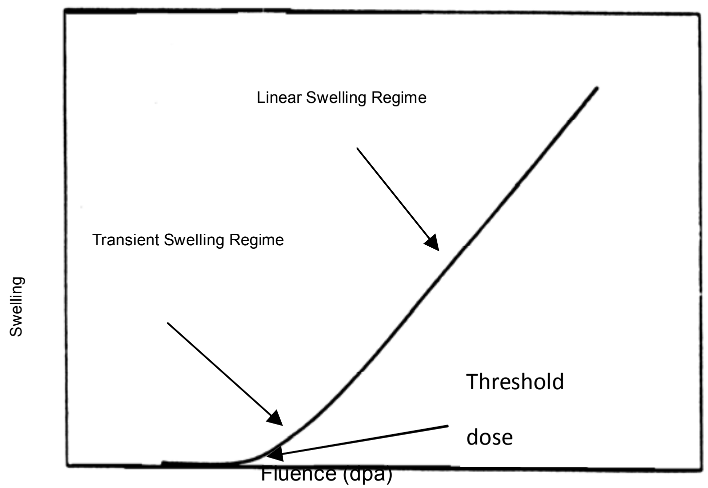




GROWTH RATE OF VOIDS – FUNDAMENTAL TO VOID SWELLING

VOID SWELLING ---

$$(\nabla V/V) = [(4/3)\,\pi\, R^3\,] \times N_f\,(R)$$

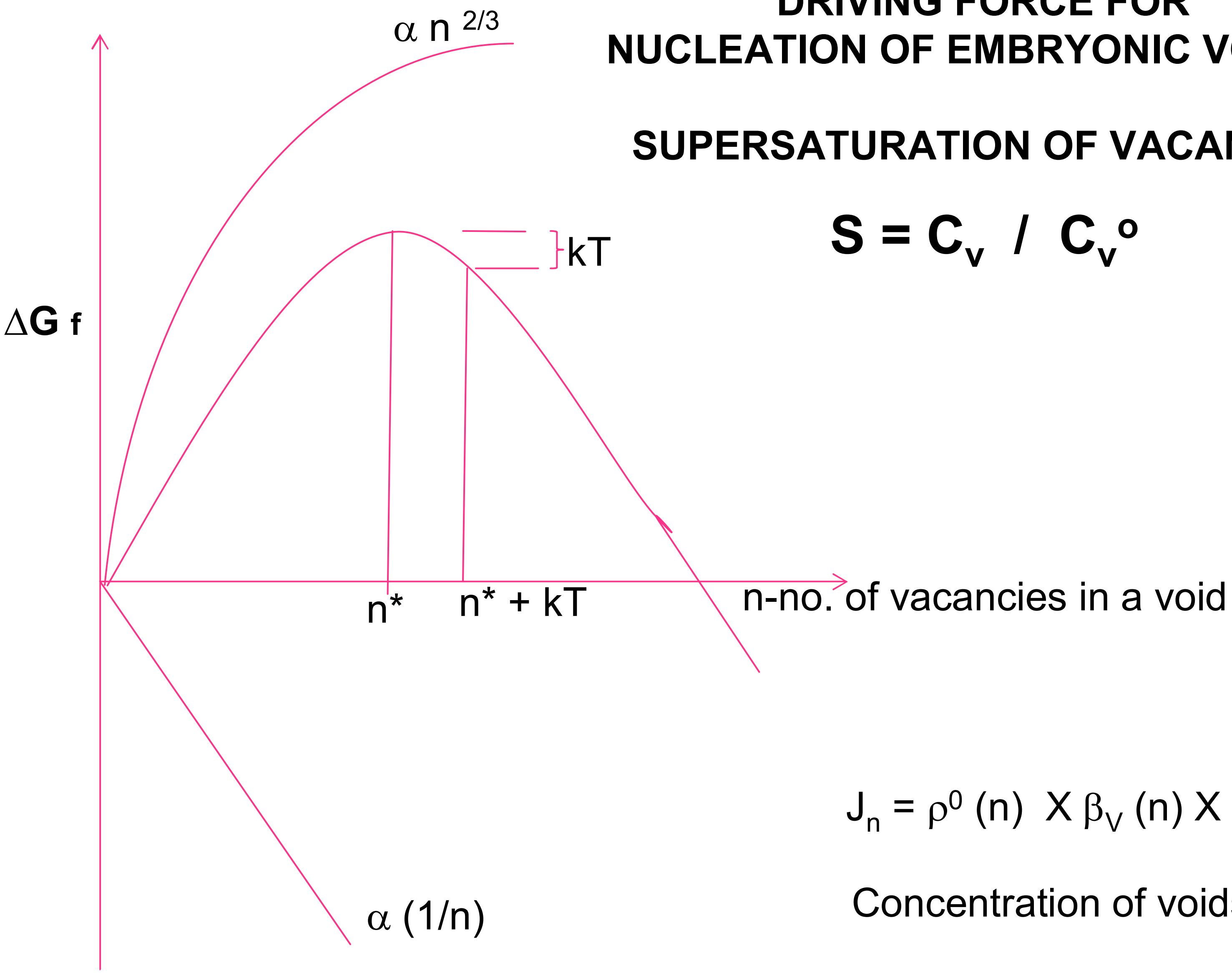


NUCLEATION (SUPERSATURATION OF VACANCIES)

+

GROWTH (Arrival rate of net vacancies on void surface)

NUCLEATION OF EMBRYONIC VOIDS



DRIVING FORCE FOR NUCLEATION OF EMBRYONIC VOIDS –

SUPERSATURATION OF VACANCIES

$$\mathbf{S = C_v \ / \ C_v^o}$$

$$J_n = \rho^0 (n) \ X \ \beta_V (n) \ X \ Z$$

Concentration of voids

$$\rho^0(n) = N_0 \exp\left(- \Delta G^0{}_n / kT\right)$$

NUCLEATION OF VOIDS : CERTAIN FEATURES

- DIRECTLY PROPORTIONAL TO HEIGHT OF ACTIVATION ENERGY;
- IRRADIATION INTRODUCES INTERSTITIALS & INCREASES THE ACTIVATION AND REDUCES NUCLEATION RATE
- CRITICAL VOID RADIUS ALSO DEPENDS ON ACTIVATION ENERGY;
- HIGHER SUPERSATURATION REDUCES CRITICAL VOID RADIUS.

GROWTH RATE OF EMBRYONIC VOIDS: RATE THEORIES

$$A_{net}{}^{V} = A_v{}^{void} - A_i{}^{void} = 4\pi R D_v (C_v - C_v{}^{void}) - 4\pi R D_i (C_i - C_i{}^{void})$$

$$dR/dt = (\Omega/R)[D_v(C_v - C_v{}^{Void}) - D_i C_i]$$

RATE THEORY

SET UP POINT DEFECT BALANCE EQUATIONS;

GROWTH RATE EQUATIONS &

SOLVE TO ARRIVE AT THE

VOID GROWTH RATE-→ R

VOID SWELLING ---

$$(\nabla V/V) = [(4/3)\pi \mathbf{R}^3] \text{ X } N_f(R)$$

SUMMARY OF MODULE 1

MATERIALS WITH HIGH BURN-UP, LONG LIFE AND HIGH TEMPERATURE CAPABILITY FOR LOWER COST, BETTER THERMAL EFFICIENCY;

CATEGORISE THE DIFFERENT CIRCUITS IN A REACTOR AS CORE, OUT-OF-CORE & BALANCE OF PLANT; FOCUS ON CORE.

VOID SWELLING, IRRADIATION GROWTH, IRRADIATION HARDENING, IRRADIATION CREEP, IRRADIATION EMBRITTLEMENT – FIVE EFFECTS IN CORE;

ALL THE ABOVE EFFECTS ---→ RADIATION DAMAGE DUE TO NEUTRONS

SUMMARY.... (contd...)

CASCADE FORMATION: COLLISIONS, THERMAL SPIKE, QUENCHING & ANNEALING

POINT DEFECTS & THEIR CLUSTERS; CHARACTERISTICS OF VACANCIES AND INTERSTITIALS

POINT DEFECTS CLUSTER INTO HIGHER DIMENSIONAL CLUSTERS-LOOPS AND VOIDS

SWELLING : NUCLEATION & GROWTH OF VOIDS

RATE THEORY : SETTING UP OF POINT DEFECTS BALANCE EQUATIONS, GROWTH RATE EQUATIONS & SOLVE FOR R.

ENJOY FINDING OUT, WHY?

It is difficult to create interstitial than vacancy.

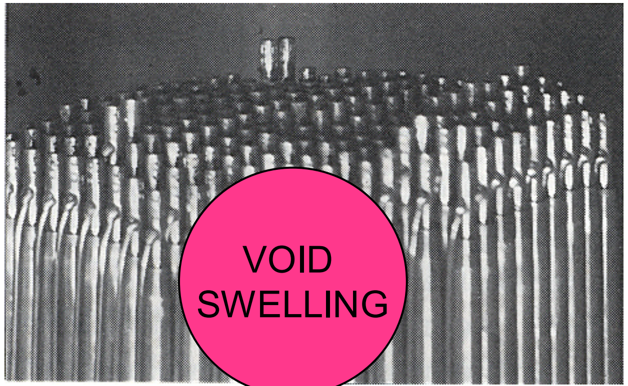
Displacement cascade does not form during electron irradiation.

It is easy to form vacancy in Nickel than the intermetallic, Nickel Aluminide.

Vacancies are thermodynamically stable defects, while interstitials are not.

MODULE 2: RADIATION DAMAGE

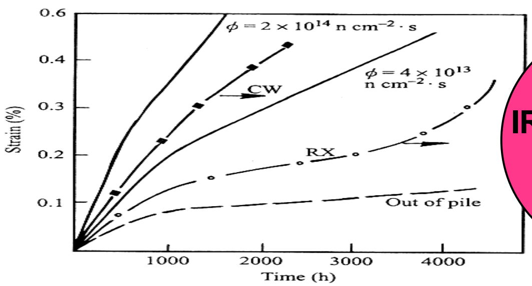
- DOSE;
- TEMPERATURE;
- DOSE RATE;
- COLD WORK
- CHEMISTRY



VOID SWELLING

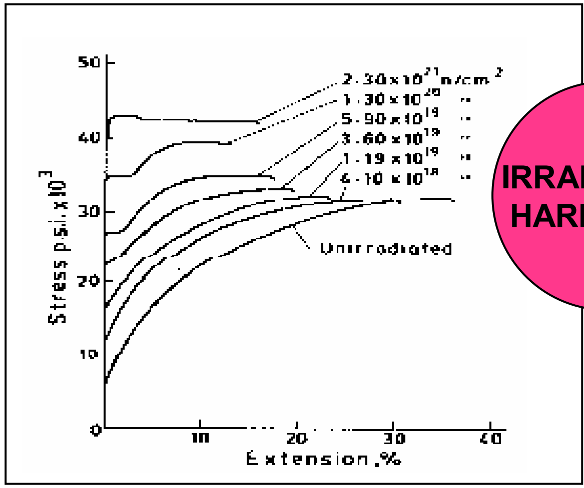
DISTORTION IN SHAPE RETAINING SAME VOLUME

IRRADIATION GROWTH



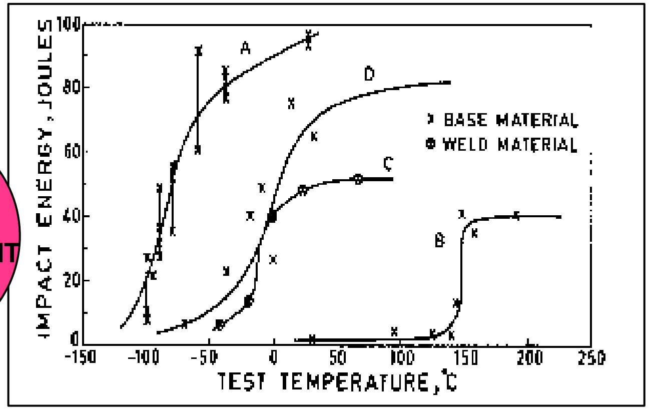
IRRADIATION CREEP

MATERIALS DEGRADATION IN REACTORS



IRRADIATION HARDENING

IRRADIATION EMBRITTLEMENT



THANQ FOR YOUR ATTENTION

HOPE U NJOYED & LEARNT MORE