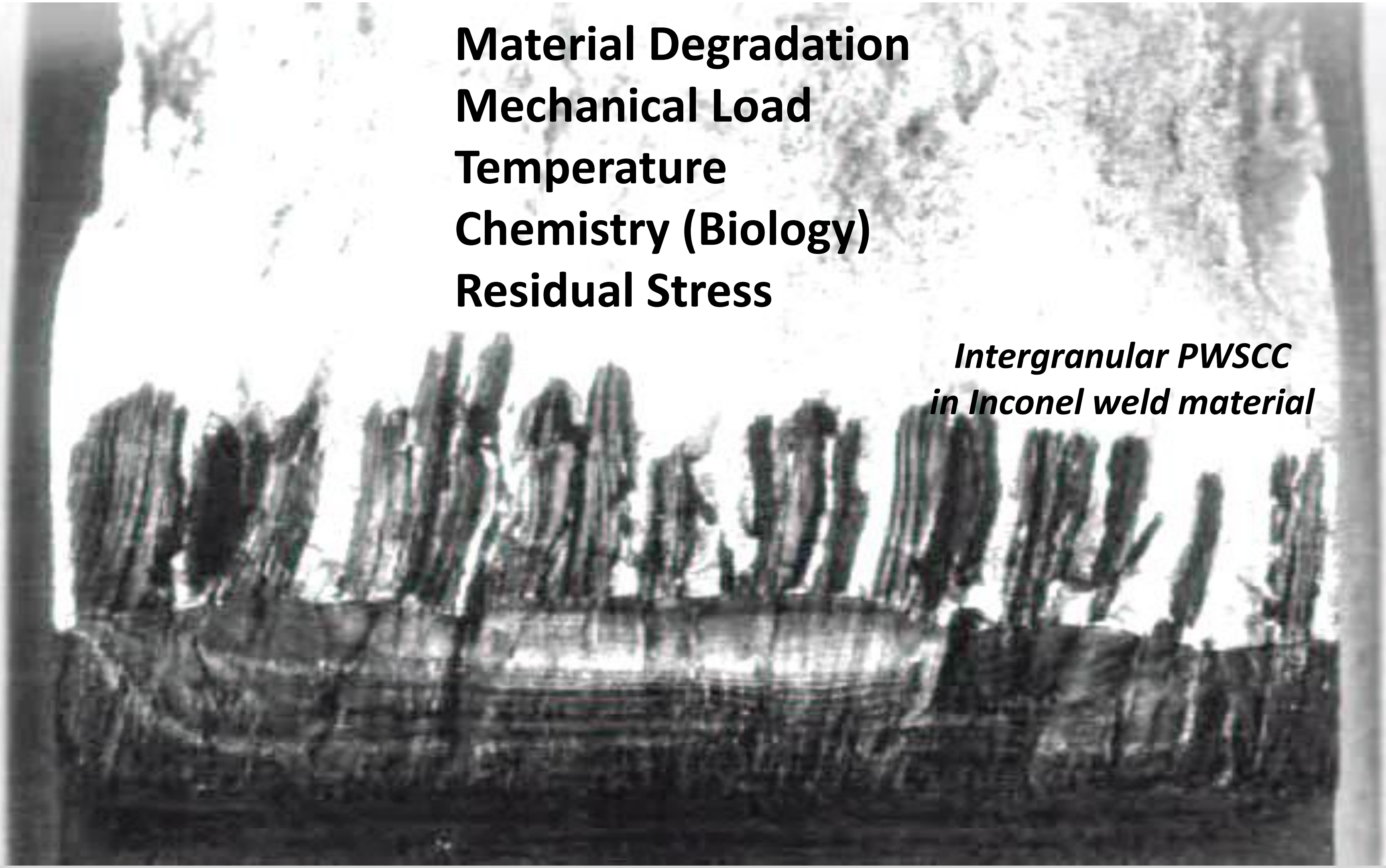
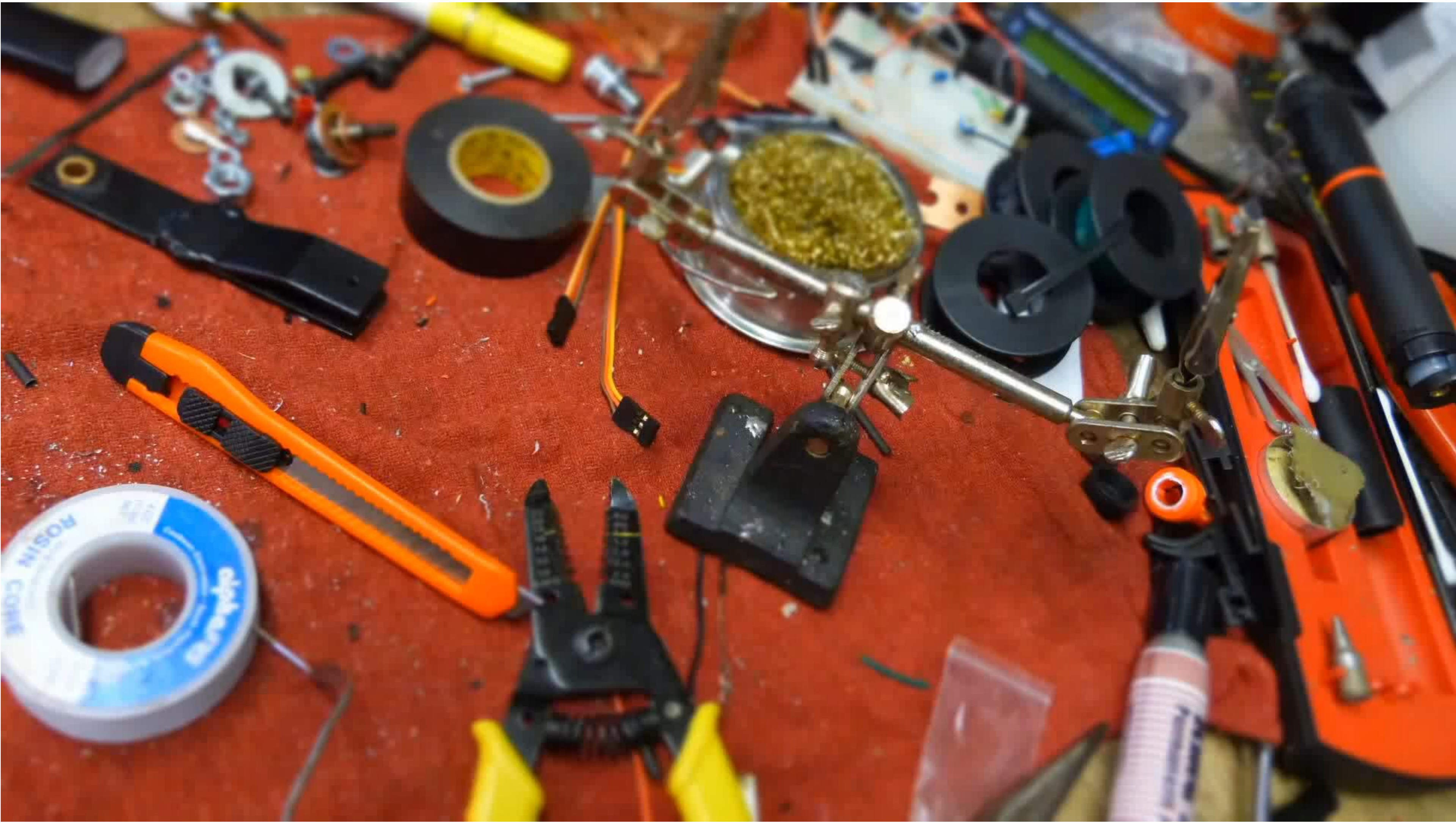
Degradation of nuclear structures during operation



2.	Degradation of nuclear structures during operation
2.1.	**Aging, Neutron Embrittlement, Structural Material Parameters**
2.2.	Stress Corrosion Cracking
2.3.	Fatigue
2.4.	(Unexpected events)

Degradation of nuclear structures during operation



AGING

everybody and everything are becoming older by time
life-time is limited by aging

challenging issues
for long-term operation of nuclear power plants

materials aging
cable/piping

Two-thirds of 47 US nuclear utility executives
polled on the most challenging issues facing further life extension
cited plant reliability as the key issue
with materials aging and cable/piping as the top concerns (EPRI Study)

Research Thrust Areas

There are many forms of materials degradation
in a nuclear power reactor.
They are highly dependent upon a number of different variables,
creating a complex scenario for evaluating lifetime extensions.

Mechanisms of degradation

Mitigation strategies

Modeling and simulation

Monitoring

New material characterization methods

Improved crack detection techniques

New NDE techniques for monitoring

(pressure vessel embrittlement or swelling of core internals)

Management

EPRI Poll

A recent EPRI-led study interviewed 47 US nuclear utility executives to gauge perspectives on long-term operation of nuclear reactors.

Nearly 90% indicated that:

- **extensions of reactor lifetimes to beyond 60 years were likely**
- **two-thirds cited plant reliability as the key issue**
- **with materials aging and**
- **cable/piping as the top concerns for plant reliability.**

Ageing and Life Management of Systems and Components

Ageing means:

- Change of material properties and component behaviour during operation due to degradation by irradiation, thermal load, fatigue, corrosion ...

Plant Life Management means:

- Understanding of aging mechanisms
- Knowledge on actual condition of the component (weak-point-analysis)
- Realization of preventive or corrective measures

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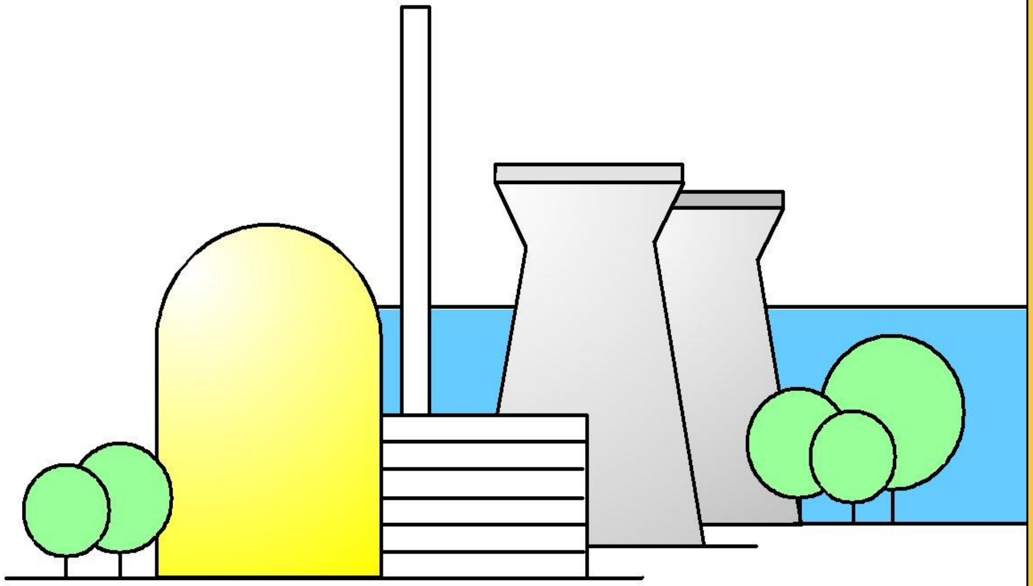
Prevention from Accelerated Plant Ageing

Design and Construction

- Material Selection
- Design Features

Operation

- Weak Point Analysis
- ISI
- Monitoring of relevant Parameters
- Operational Modes
- Rest Lifetime Evaluation



Examples

- ***Material Concept and Design of Components***

- Reactor Pressure Vessel and Irradiadion Behavior
- Inconel 600
- Reactor Pressure Vessel Penetrations
- Steam Generator Tubing
- BWR Austenitic Stainless Steel Piping
- Hard Facing Material

Potential Ageing Mechanisms and Resulting Effects on Components

Aging Mechanisms / Effect on Components	Irradiation	Thermal Aging	Creep	Fatigue (HCF, LCF)	Corrosion							Wear
					Corrosion Fatigue	Stress Corrosion Cracking	Strain Induced Corrosion Cracking	Intergranular Attack	Errosion Corrosion	Local Corrosion Attack	General Corrosion	
Change of Material Properties	●	●	●	●								
Cracking			●	●	●	●	●	●				●
Change of Dimensions	●		●									
Wall Thinning									●		●	●
Denting											●	
Pitting										●		

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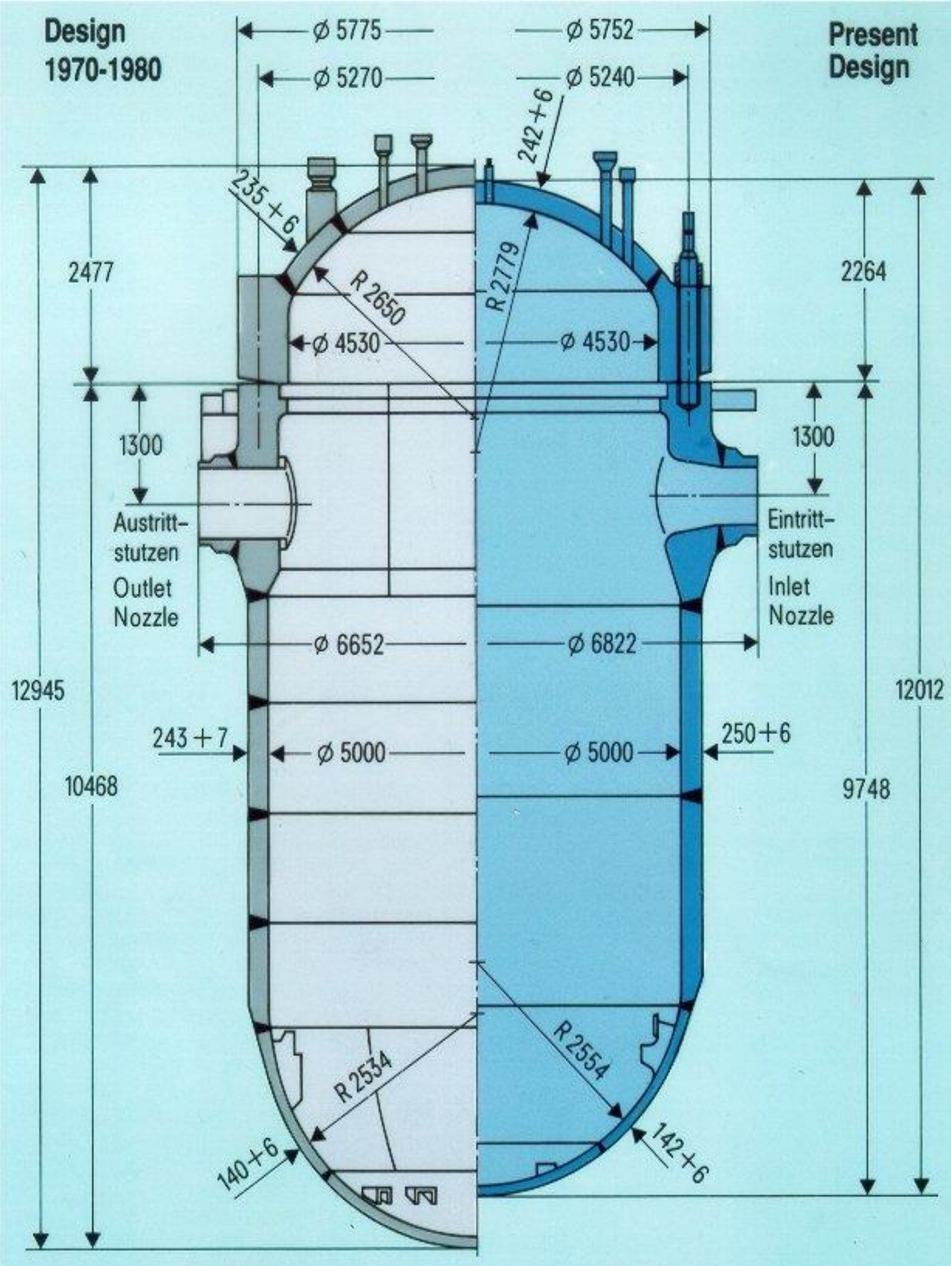
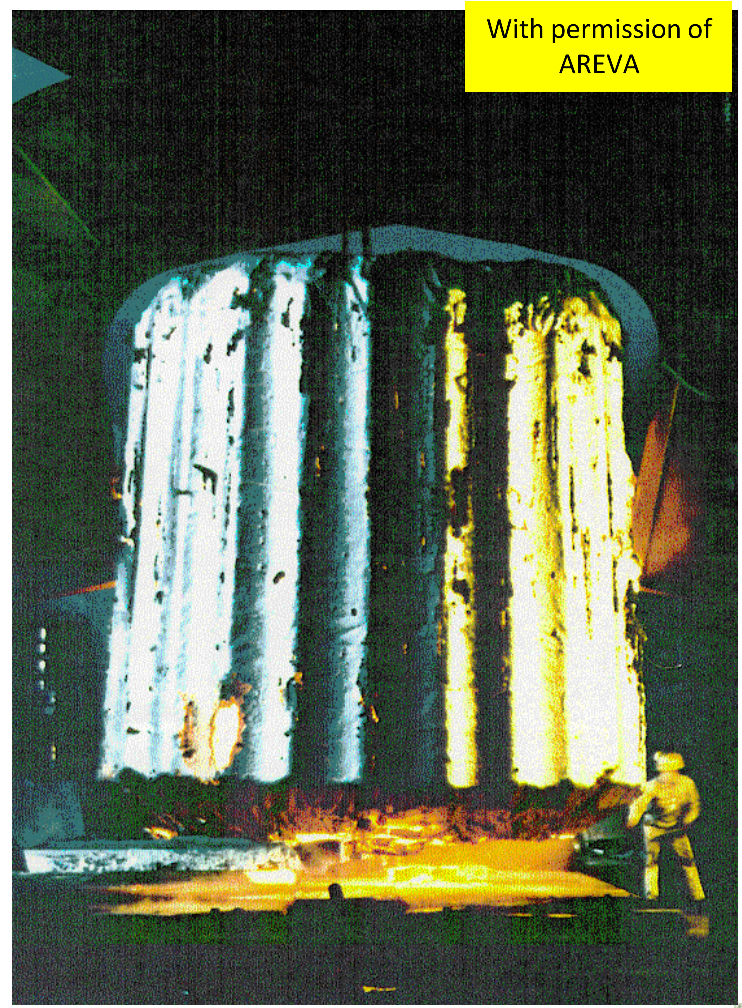
Quality Criteria for PWR Components and Systems

Component or System / Quality Criteria	Reactor pressure vessel	Other parts of reactor coolant system	Reactor pressure vessel internals	Nuclear auxiliary and ancillary systems	Steam generator tubes	Contain-ment	Water/ steam cycle	Wear resistant parts and facings	Fuel assemblies, control assemblies
Thoughness, strength	●	●	●	●	●	●	●	●	●
Amenability to quenching and tempering (large parts)	●	●							
Weldability	●	●	●	●	●	●	●	●	●
Corrosion resistance	●	●	●	●	●		●	●	●
Irradiation behaviour	●		●						●
Special requirements for nuclear applications								●	●
Examples of materials	20 MnMoNi 55 22 NiMoCr 37 Austenitic-cladding		X 6 CrNiNb 18 10 G-X 5 CrNiNb 18 9		Incoloy 800	15 MnNi63 19MnAl 6 V	WStE255/355 C22.8 St35.8 15Mo3 GS-C25	Stellite Co-free-alternatives	Zircaloy 4 AgIn 15Cd5

Reactor Pressure Vessel 1300 Mwe

Development in Material Layout (Design 1970 and Present Design) using large ingots (up to 570 t)





Examples

- Material Concept and Design of Components and Component Parts
- ***Reactor Pressure Vessel and Irradiation Behavior***
- Inconel 600
  - Reactor Pressure Vessel Penetrations
  - Steam Generator Tubing
- BWR Austenitic Stainless Steel Piping
- Hard Facing Material

Radiation Damage of Structural Materials

- Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)
- Irradiation creep (<0.45 TM, >10 dpa)
- Volumetric swelling from void formation (0.3-0.6 TM, >10 dpa)

All of these property changes are determined by microstructural evolution during irradiation

NEUTRON RADIATION

causes:

- **Embritttlement (Reactor Vessel)**
- **Swelling**
- **Buildup of Wigner Energy**

Neutron Moderators (Graphite)

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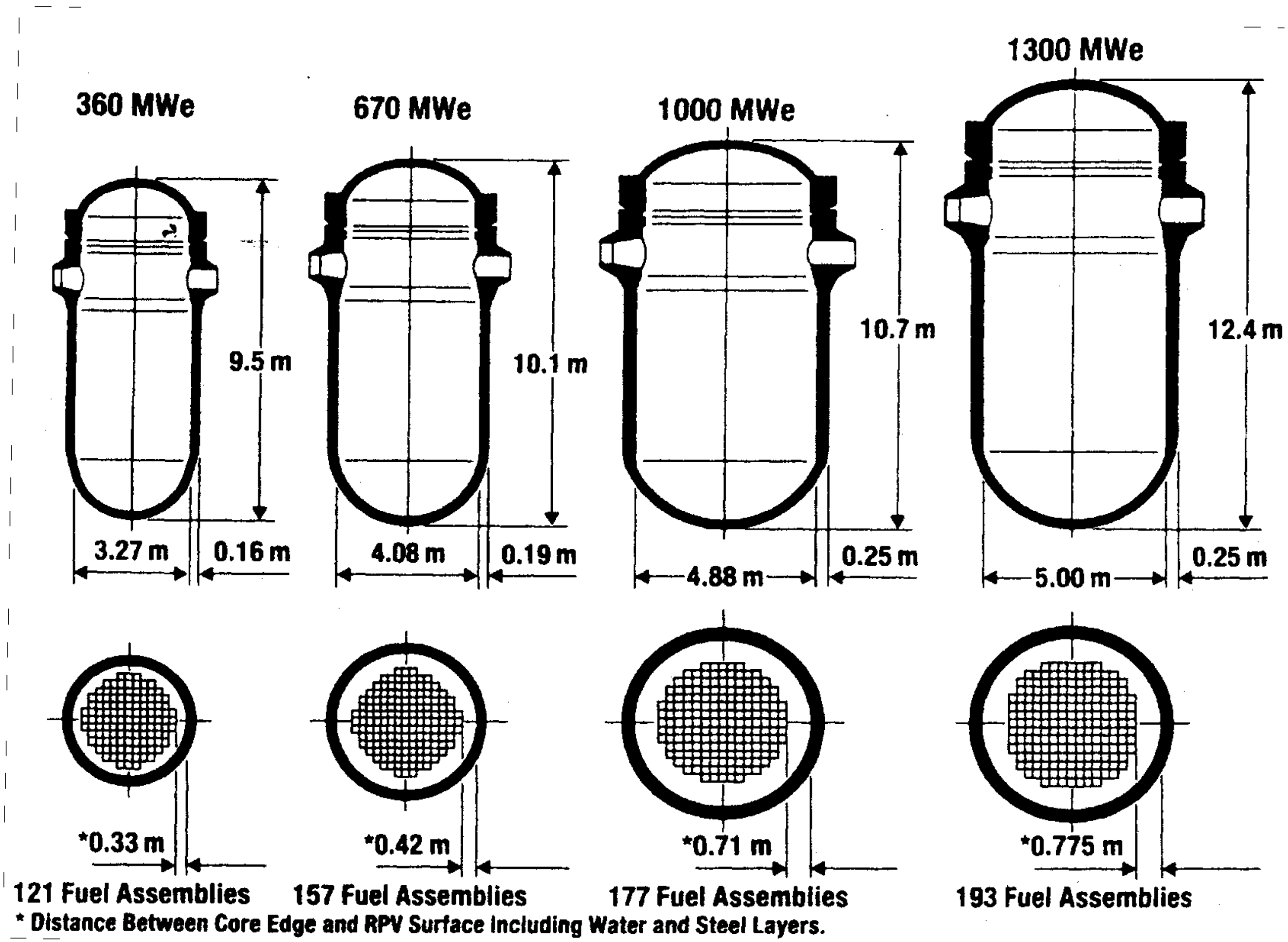
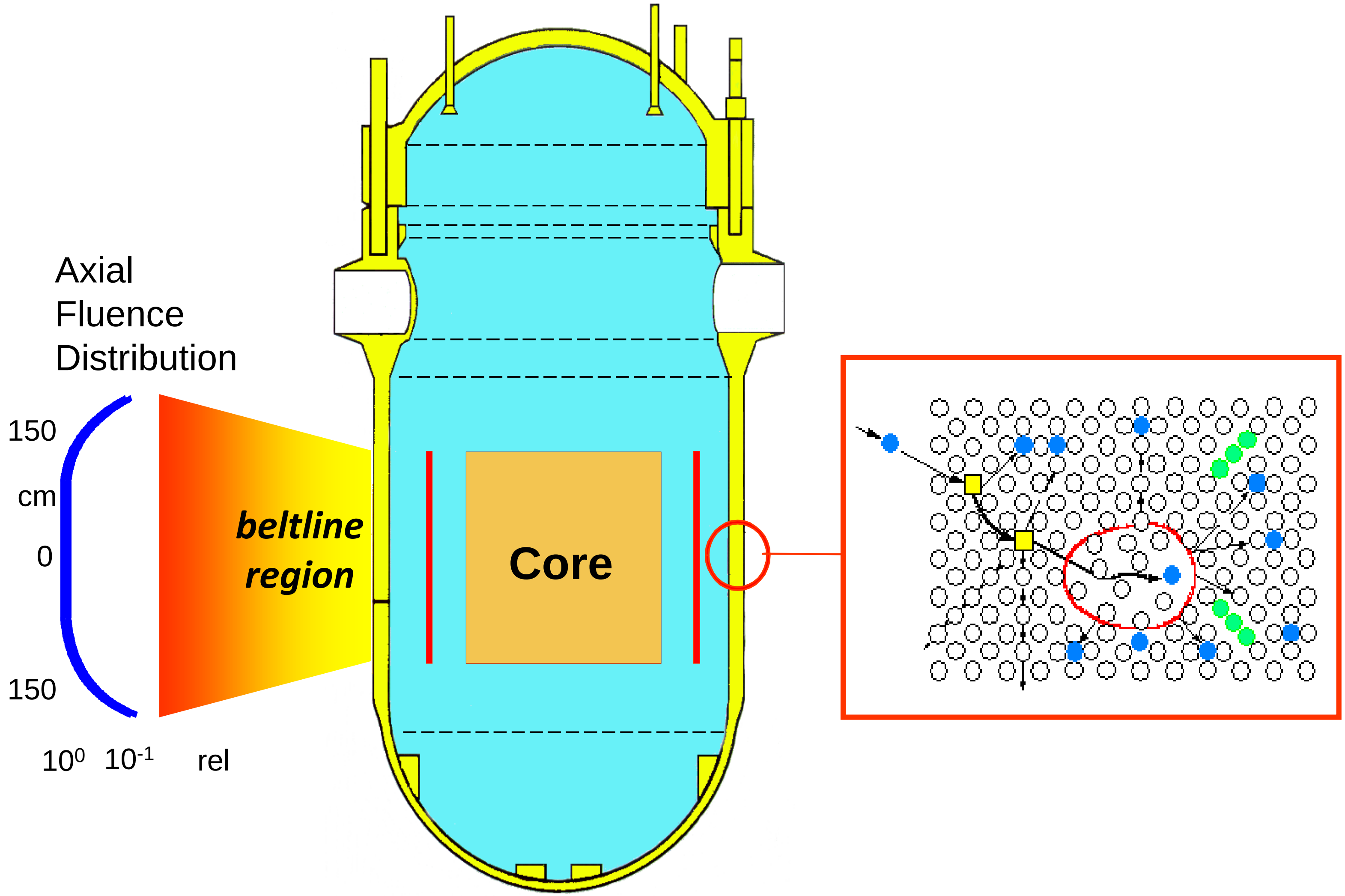
Development of Design and Core Geometries



Irradiation Embrittlement



Neutron Embrittlement

The nuclear vessel is a virtually irreplaceable element

Operating conditions lead to a progressive degradation in time of its constituent steel

The chain fission reactions of U-235 entail the emission of high energy neutrons

Neutron collisions give rise to a complex series of events in the nano and microstructural scale

They modify the mechanical properties of the steel leading to its embrittlement, that is, the decrease in its fracture toughness

Neutron Embrittlement
End of Life (EoL)

In practice, only fast neutrons
(fraction of the energy spectrum
corresponding to a neutron kinetic energy higher than 1 MeV)
is considered to be capable of triggering damage mechanisms
in the vessel steel

Typical design end of life (EOL) neutron fluences (E>1 MeV)

for BWRs: ≈ 10^{18} n/cm2
for PWRs: ≈ 10^{19} n/cm2

PRESSURIZED THERMAL SHOCK

RPV locally embrittled by neutron radiation

An (abnormal) severe transient cause a rapid depressurization in the RPV

Water level drop

Systems provide makeup water much colder than held in the RPV

Impingement of cold water on the hot RPV wall (290°C) produce significant thermal stresses

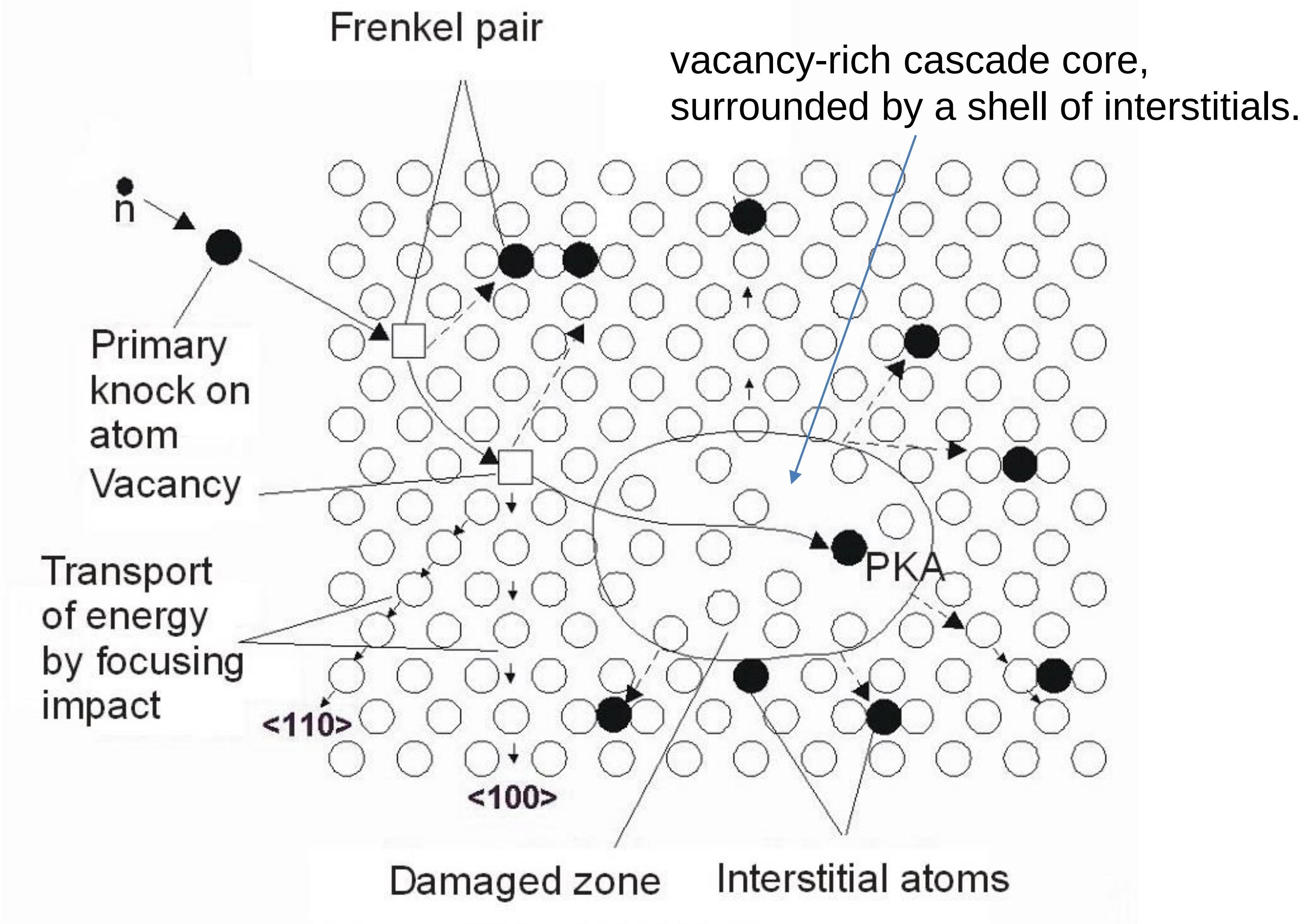
If there is a flaw of critical size and the vessel is repressurized, the combined stresses cause the flaw to propagate rapidly through the vessel wall

Integrity of the RPV is on risk

Main Embrittlement Processes

- **Generation of lattice defects in displacement cascades by high-energy recoil atoms from neutron scattering and reactions. These primary defects are in the form of single and small clusters of vacancies and self-interstitials (Frenkel defects).**
- **Diffusion of primary defects also leading to enhanced solute diffusion; formation of nano-features: nano-scale defect-solute cluster complexes, solute clusters and distinct phases, mainly copper-rich precipitates (CRPs).**
- **As a consequence, this hardening process leads to the shift of the transition temperature, thus facilitating the material fracture through cleavages**

Scheme of neutron damage



Damage Mechanism

Neutrons that collide with the atoms in a crystal structure must have enough energy to displace them from the lattice

Example: a 1 MeV neutron striking graphite
will create 900 displacements;
not all displacements will create defects
because some of the struck atoms will find and fill the vacancies
that were either small pre-existing voids or vacancies
newly formed by the other struck atoms

A high enough temperature allows the displaced graphite structure to realign itself (recombination)

Definitions

Interstitials: *The atoms that do not find a vacancy come to rest in non-ideal locations; that is, not along the symmetrical lines of the lattice. These atoms are referred to as interstitial atoms*

Frenkel Pair: *An interstitial atom and its associated vacancy are known as Frenkel defect.*

Wigner Effect (**decomposition effect)**:
The displacement of atoms in a solid caused by neutron radiation.
Any solid can be affected by the Wigner effect, but the effect is of most concern in neutron moderators (graphite)

What is “dpa”?

displacement per atom (dpa)
corresponds to stable displacement
from their lattice site of all atoms in the material
during irradiation near absolute zero
(no thermally-activated point defect diffusion)

Initial Number of Atoms
knocked off their lattice site during neutron irradiation
is about 100 times the dpa value:
Most of these originally displaced atoms
hop onto another lattice site
during “thermal spike” phase of the displacement cascade
(≈ 1 ps)

Void

3-dimensional vacancy cluster

Cavity

3D vacancy cluster that may contain impurities

EMBRITTLEMENT MODELS
(applied for embrittlement prediction)

Account for:

- **Defect production**
- **Precipitation hardening**

Through understanding of microstructure evolution

→

- **Irradiation temperature**
- **Neutron fluence**
- **Neutron spectrum**
- **Chemical composition**
- **Cu, Ni, P, Mn concentrations**

Microstructure characterization

50nm → 200nm

EMBRITTLEMENT MODELS
(applied for embrittlement prediction)

Microstructural Parameters ⟷ **Material Toughness**

Characterized by both

the critical stress intensity factor, k_{Ic}

&

the microscopic (local) cleavage fracture stress, σ_F^*

FRACTURE MECHANICS

Alan Arnold Griffith and George Rankine Irwin

Structural Material Parameters

Strength:
The strength of a material is its ability
to withstand an applied load without failure

Yield Strength
refers to the point on the engineering stress-strain curve
beyond which the material experiences deformations
that will not be completely reversed
upon removal of the loading

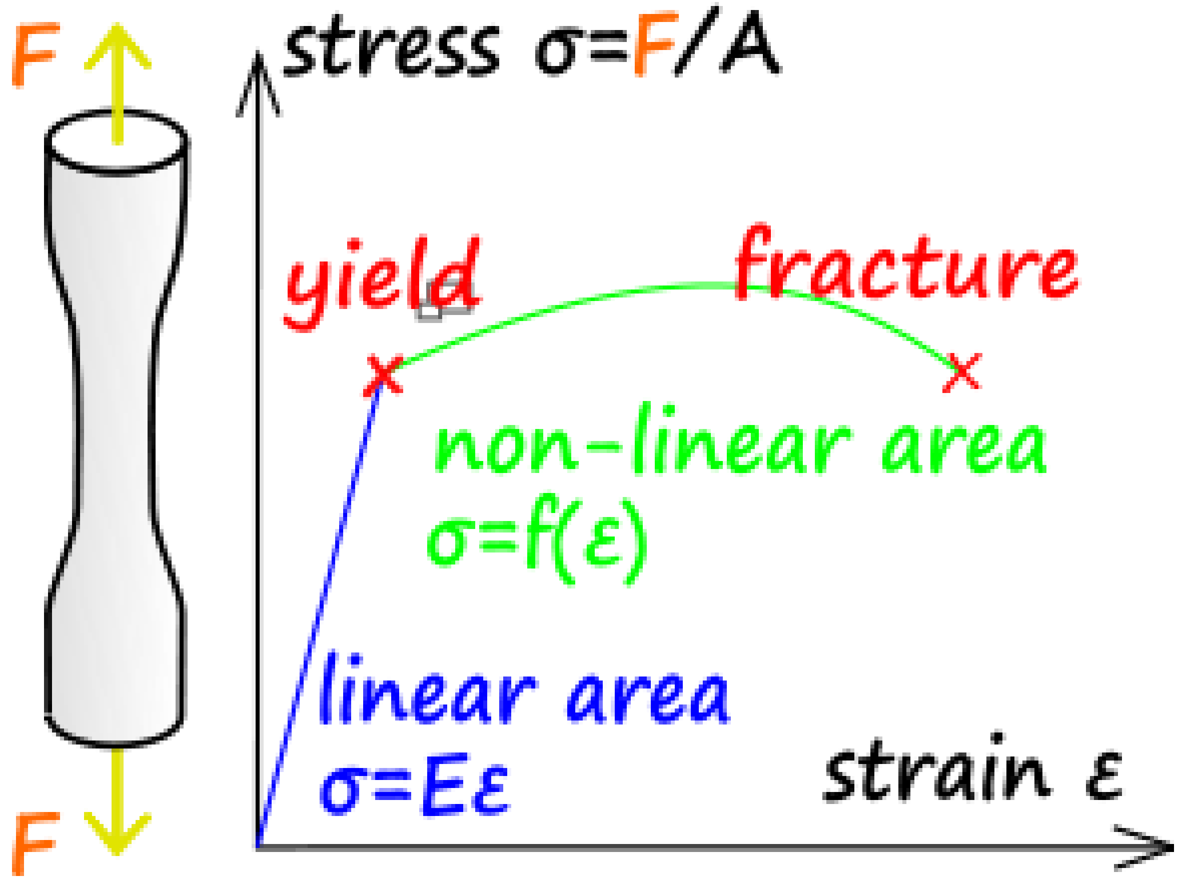
Ultimate Strength
refers to the point on the engineering stress-strain curve
corresponding to the stress that produces fracture.

Structural Material Parameters

Tensile Stress

Compressive Stress

Shear Stress



Basic static response of a specimen under tension

Structural Material Parameters

Static Strength

Impact Strength

is the capability of the material
to withstand a suddenly applied load.
It is expressed in terms of energy,
often measured with the Charpy impact test.

Fatigue Strength

strength of a material under cyclic loading.
It is quoted as stress amplitude or stress range

$$\Delta\sigma = \sigma_{\mathrm{max}} - \sigma_{\mathrm{min}}$$

along with the number of cycles to failure

Structural Material Parameters: *Hardness*

A measure of how resistant solid matter is to various kinds of permanent shape change when a force is applied.

It is dependent on:

ductility, elastic stiffness, plasticity, strain, strength, toughness, viscoelasticity, and viscosity.

Hardness is generally characterized by strong intermolecular bonds, but the behavior of solid materials under force is complex.

It can be measured by indentation tests

(Common indentation hardness scales: Rockwell, Vickers, and Brinell)

Hardness increases with decreasing particle size.

This is known as the Hall-Petch relationship.

Below a critical grain-size, hardness decreases.

This is known as the inverse Hall-Petch effect.

Structural Material Parameters: *Hardness*

Microstructure at the atomic level) controls hardness

There are two types of irregularities at the grain level of the microstructure that are responsible for the hardness of the material:

point defects: irregularities located at a single lattice site inside of the overall three-dimensional lattice of the grain. There are three main point defects

- Vacancy defect (an atom is missing from the array)
- Substitutional defect (a different type of atom at the lattice site)
- Interstitial defect (an atom exists in a site where there should not be)

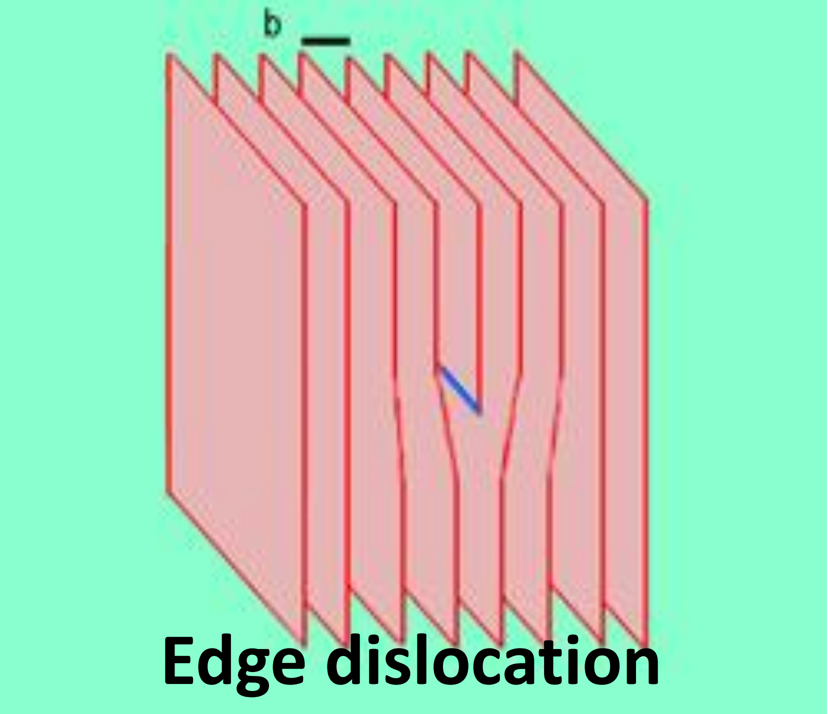
line defects: irregularities on a plane of atoms

- Dislocations are a type of line defect involving the misalignment of these planes.

Structural Material Parameters: *Hardness*

a half plane of atoms is wedged between two planes of atoms.

(In the case of a **screw dislocation**
two planes of atoms are offset
with a helical array running between them)



The way to inhibit the movement of planes of atoms makes the material harder.
It involves the interaction of dislocations with each other and interstitial atoms.
When a dislocation intersects with a second dislocation,
it can no longer traverse through the crystal lattice.
The intersection of dislocations creates an anchor point
and does not allow the planes of atoms to continue to slip over one another.
A dislocation can also be anchored by the interaction with interstitial atoms.

Structural Material Parameters: *Toughness*

Ductility:

a measure of how much something deforms plastically before fracture

Toughness:

the ability of a material to absorb energy and plastically deform without fracturing

Material toughness is the amount of energy per volume that a material can absorb before rupturing;

$$\frac{\text{energy}}{\text{volume}} = \int_0^{\epsilon_f} \sigma \, d\epsilon$$

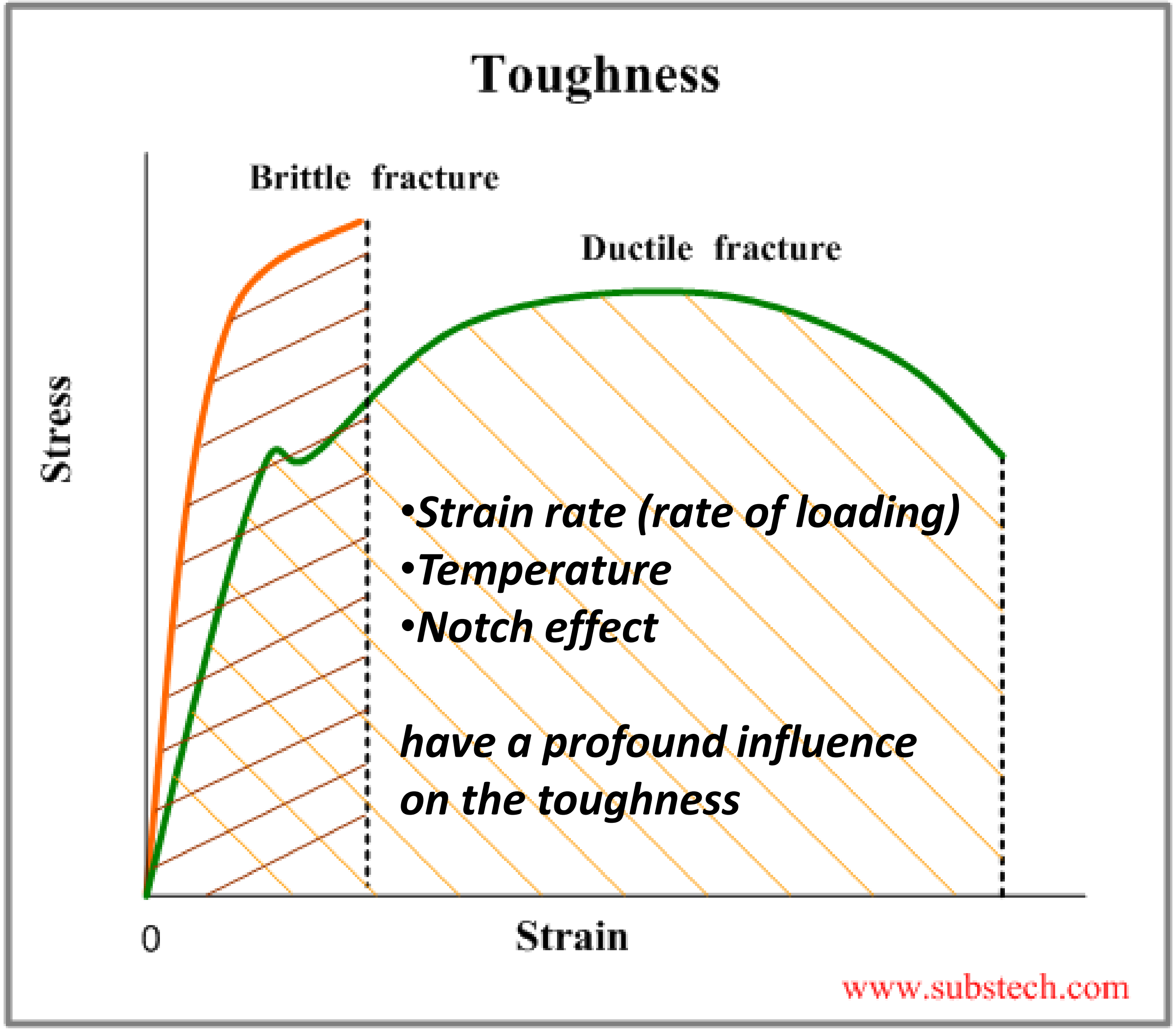
ε: strain; ε_f : strain upon failure

σ: stress

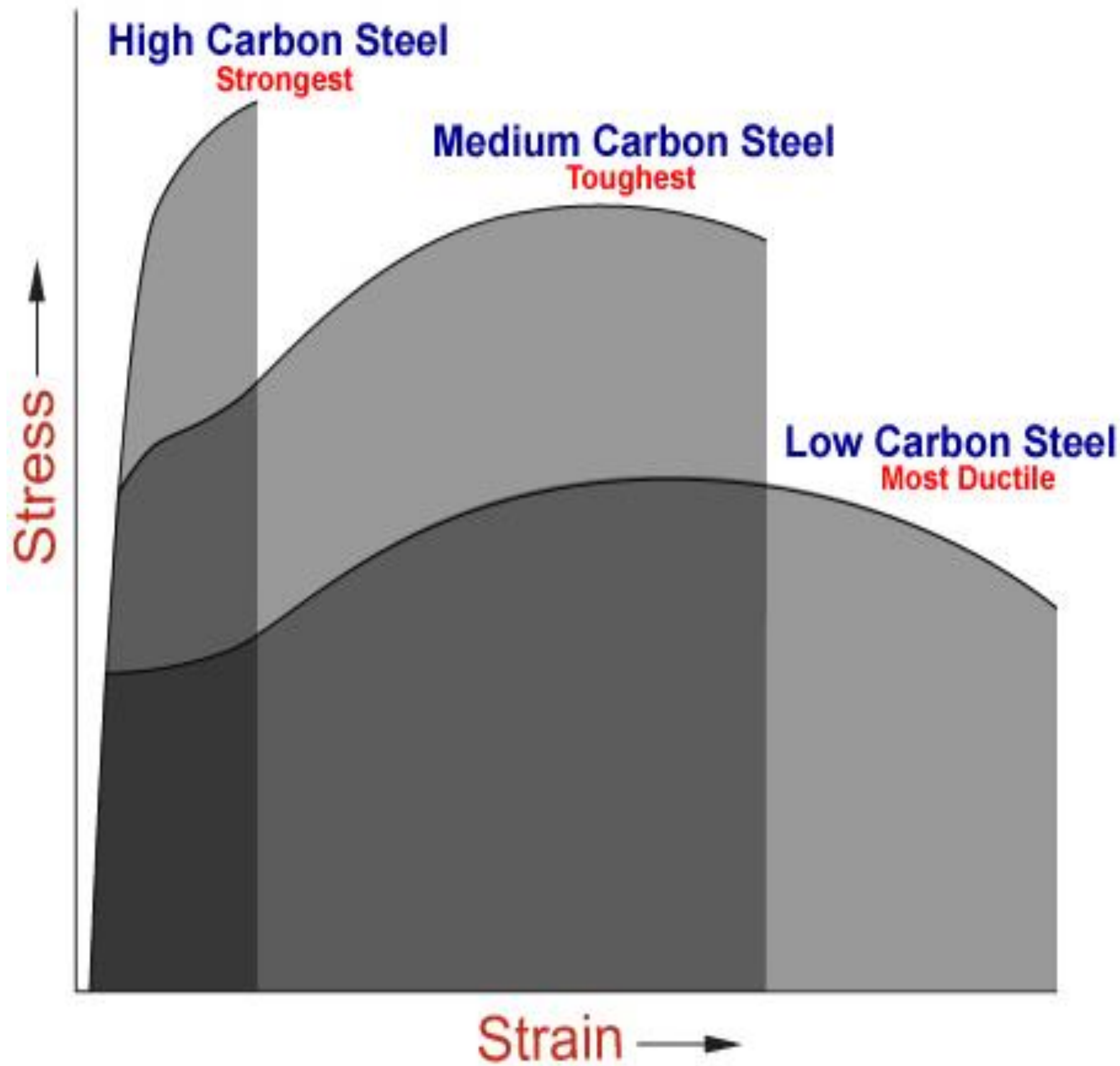
(Toughness is related to the area under the stress-strain curve)

It is also defined as the resistance to fracture of a material when stressed.

Toughness requires a balance of strength and ductility

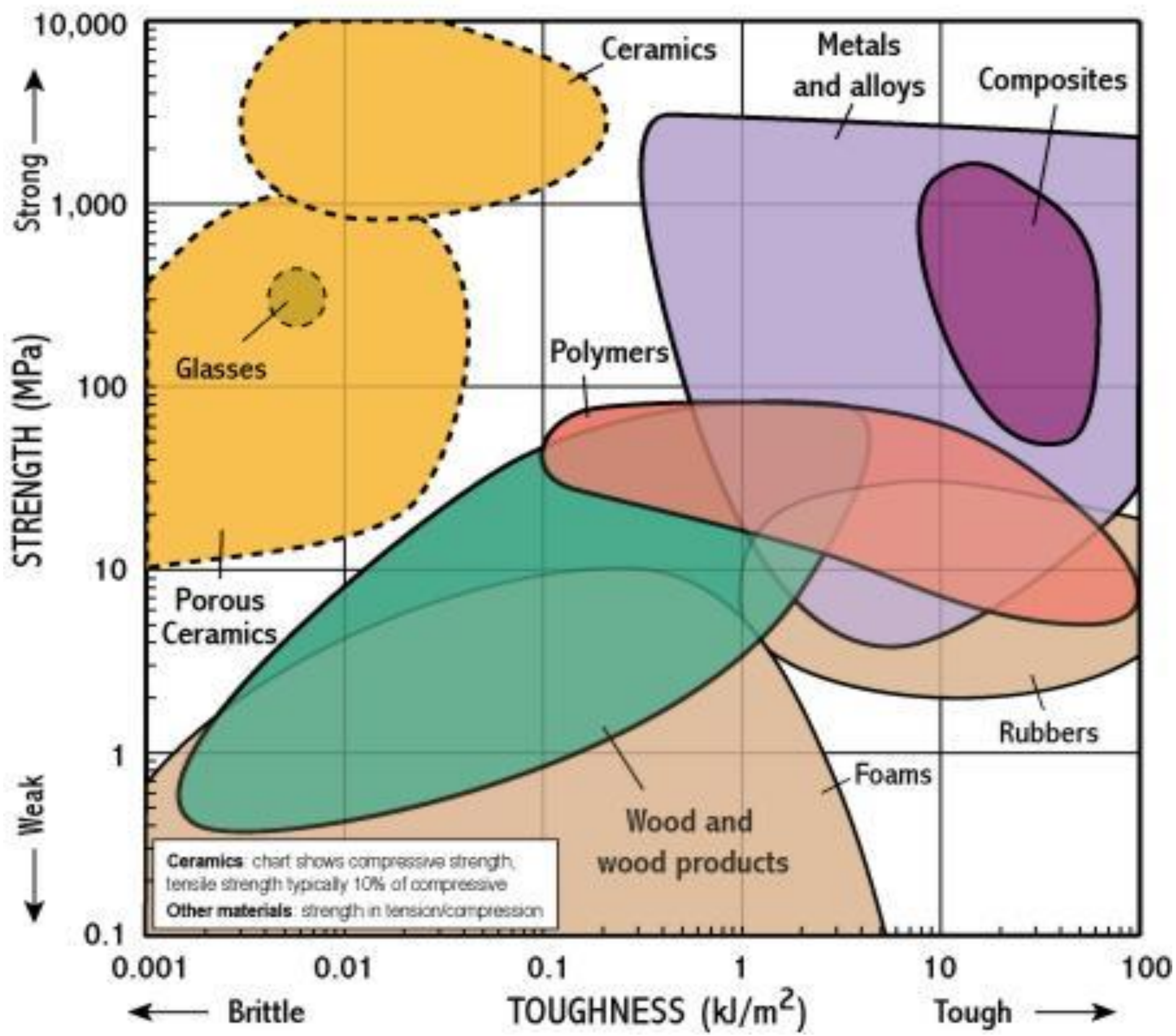

Toughness
Brittle fracture
Ductile fracture
Stress
Strain
0
•Strain rate (rate of loading)
•Temperature
•Notch effect
have a profound influence
on the toughness
www.substech.com

Structural Material Parameters: *Toughness*



Iowa State University
Center for NDE

Structural Material Parameters



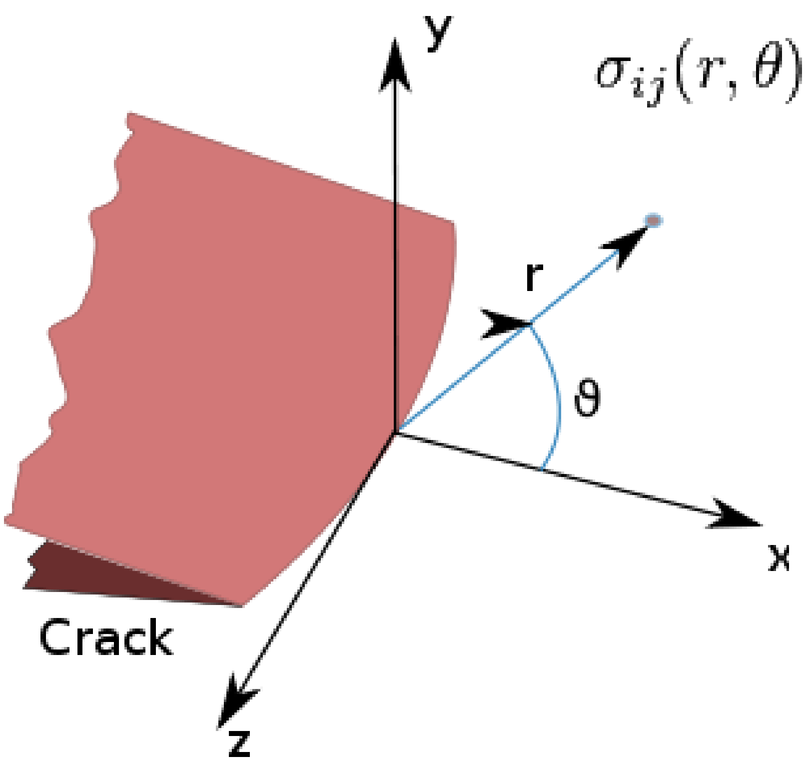
Strength
measures the resistance of a material to failure, given by the applied stress (or load per unit area)

Toughness
measures the energy required to crack a material

Increasing strength usually leads to decreased toughness

Stress Intensity Factor K

The stress intensity factor K is used in fracture mechanics to predict the stress state ("stress intensity") near the tip of a crack caused by a remote load or residual stresses.



$$\sigma_{ij}(r,\theta) = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) + \text{higher order terms}$$

(f_{ij} : dimensionless quantity that depends on the load and geometry)

K depends on

- **sample geometry,**
- **the size and location of the crack,**
- **the magnitude and the modal distribution of loads on the material.**

Stress Intensity Factor K

Take Notice

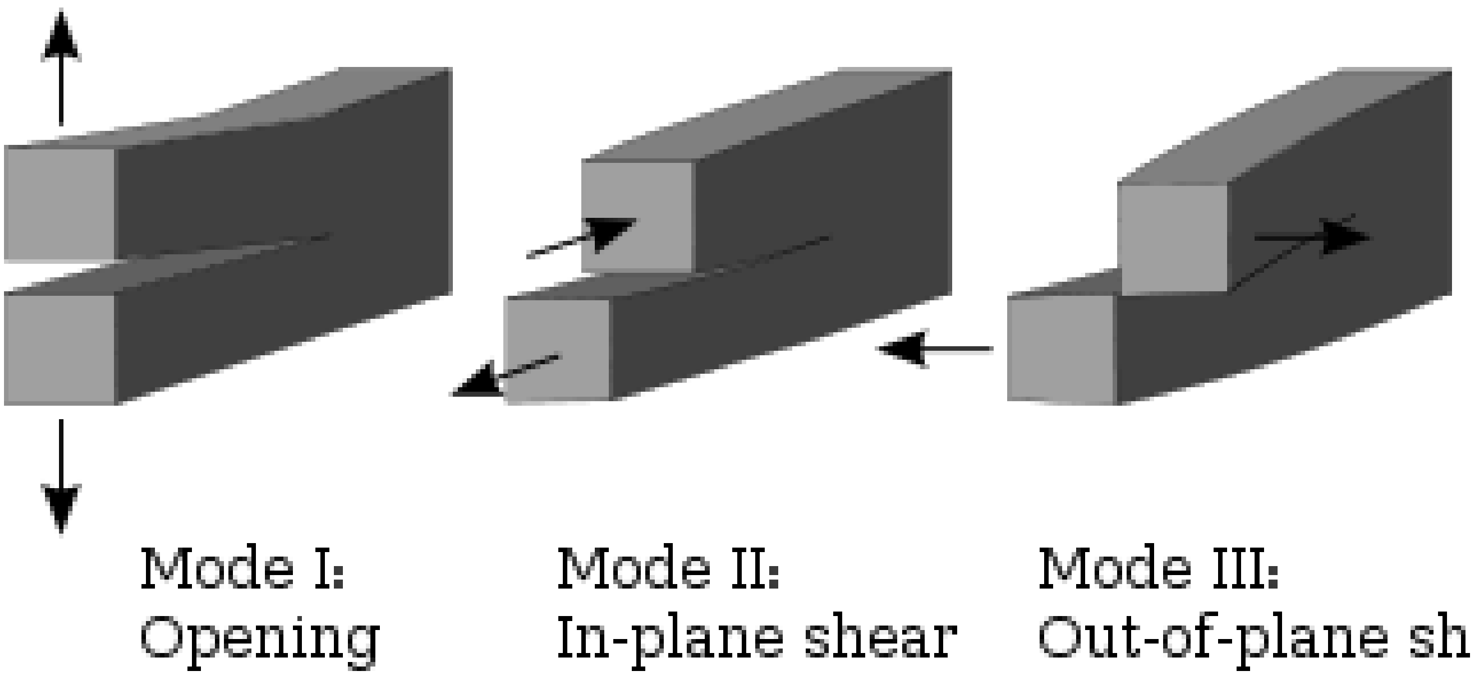
K is a theoretical construct usually applied to
a homogeneous, linear elastic material.
It is useful for providing a failure criterion
for brittle materials

K is usually applied to
a homogeneous, linear elastic material.
It is useful for providing a failure criterion
for brittle materials.

The concept can also be applied to materials
that exhibit *small-scale yielding* at a crack tip.

Plane-Strain Fracture Toughness

K_{IC} – plane strain critical stress-intensity factor relating to the fracture modes in which the loading direction is normal to the crack plane (Mode I)



Plane-Strain Fracture Toughness

K_{IC} is used for estimation critical stress applied to a specimen with a given crack length:

$$\sigma_C \leq K_{IC} / (Y(\pi a)^{1/2})$$

Where

K_{IC} – stress-intensity factor, measured in MPa*m½;

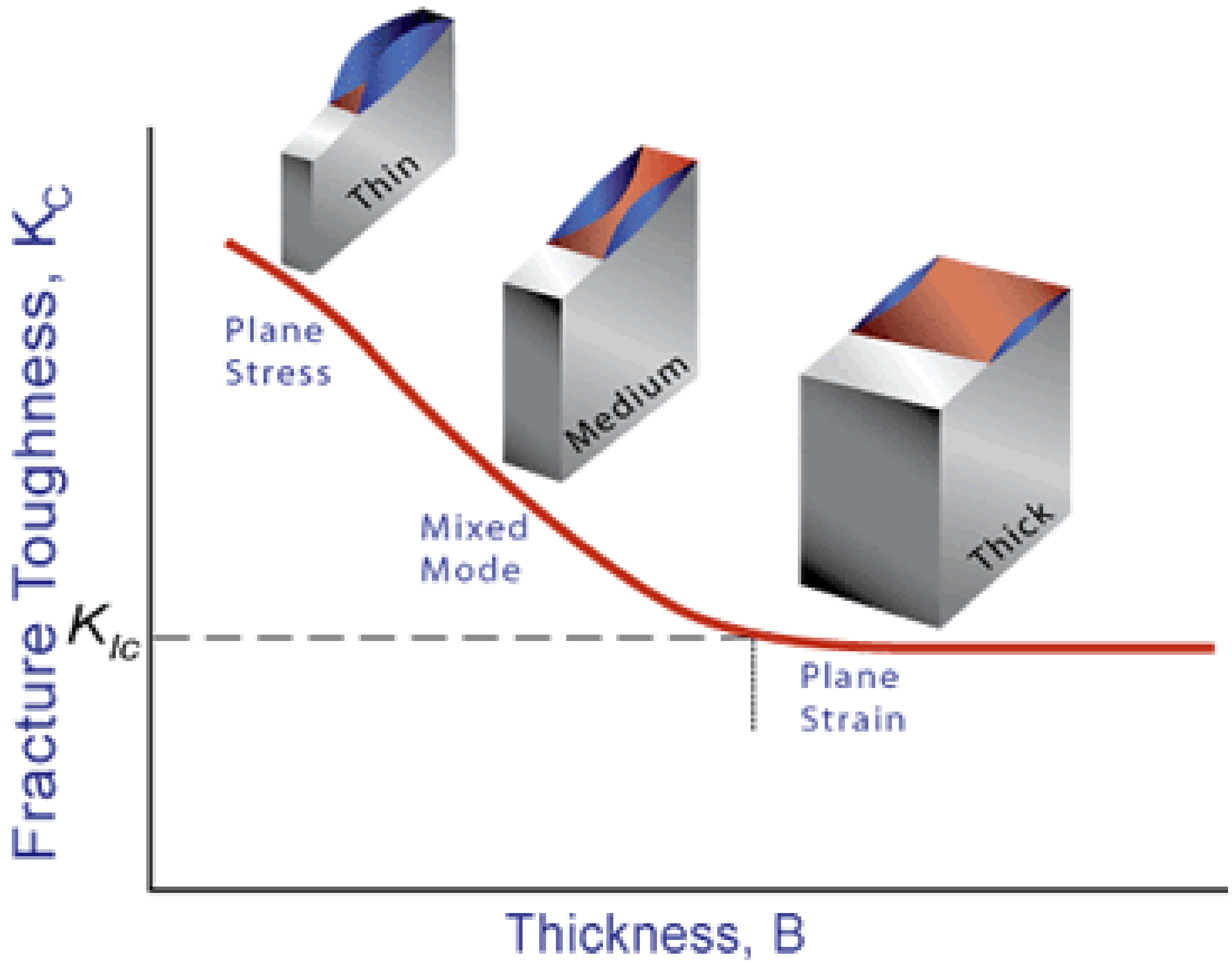
σ_C – the critical stress applied to the specimen;

a – the crack length for edge crack or half crack length for internal crack;

Y – geometry factor

Plane-Strain Fracture Toughness

Geometry



Uses of Plane-Strain Fracture Toughness

K_{IC} values are used

- to determine the critical crack length when a given stress is applied to a component.

$$a_c = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma Y}\right)^2$$

- to calculate the critical stress value when a crack of a given length is found in a component.

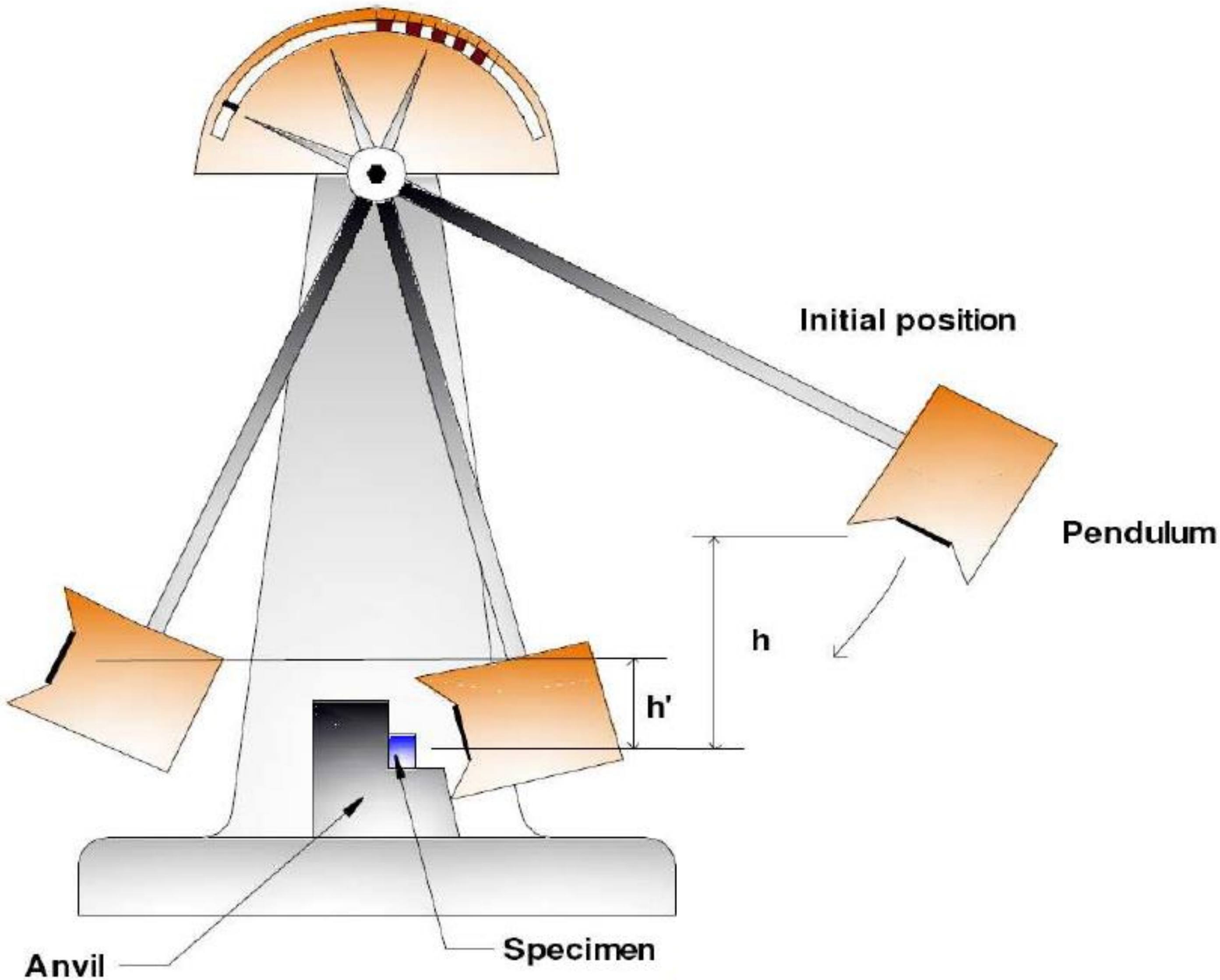
$$\sigma_C \leq \frac{K_{IC}}{Y\sqrt{\pi a}}$$

Y: Geometry Factor

a: Crack Length

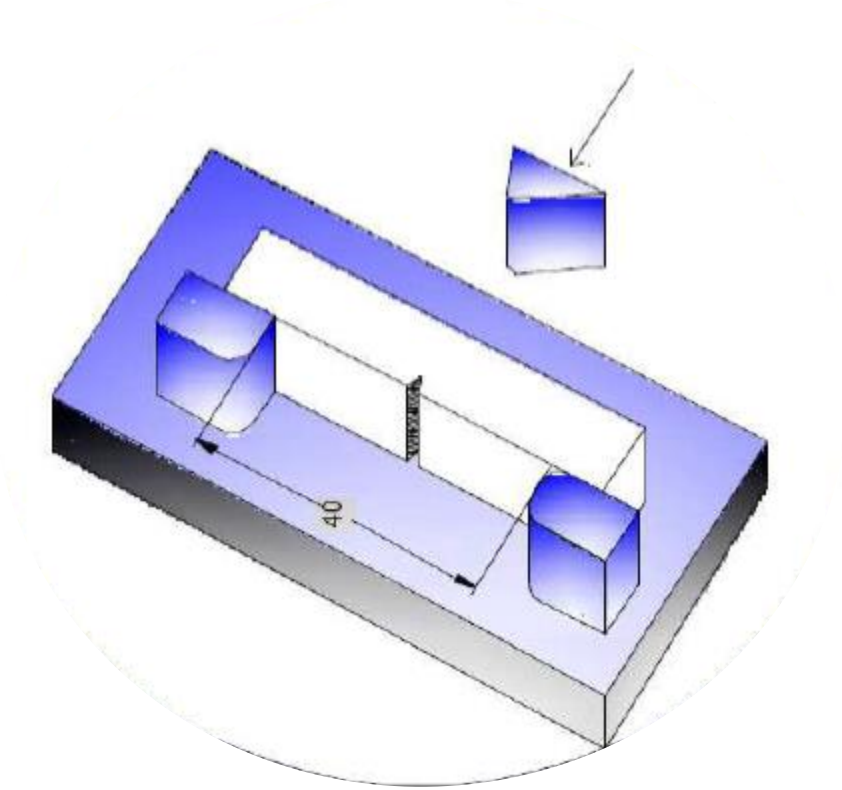
From 2

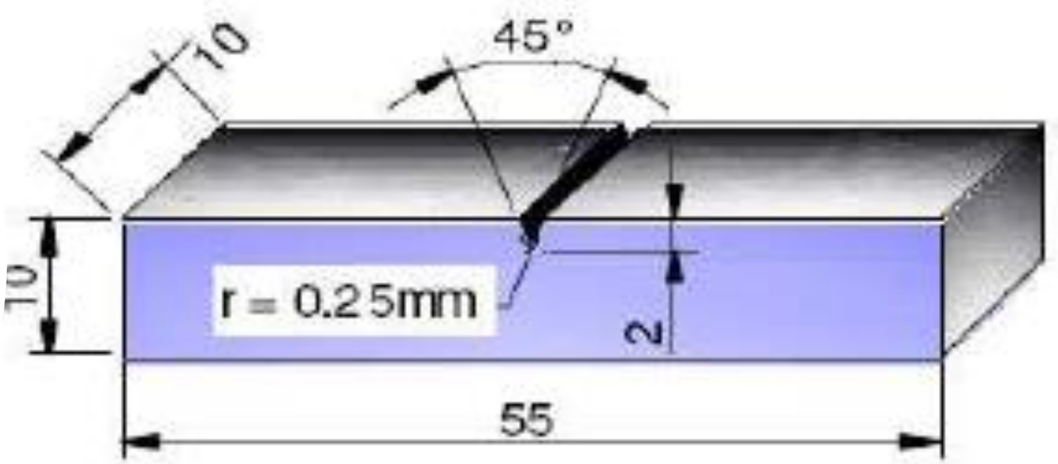
1905



Sketch of the Charpy pendulum

From 2



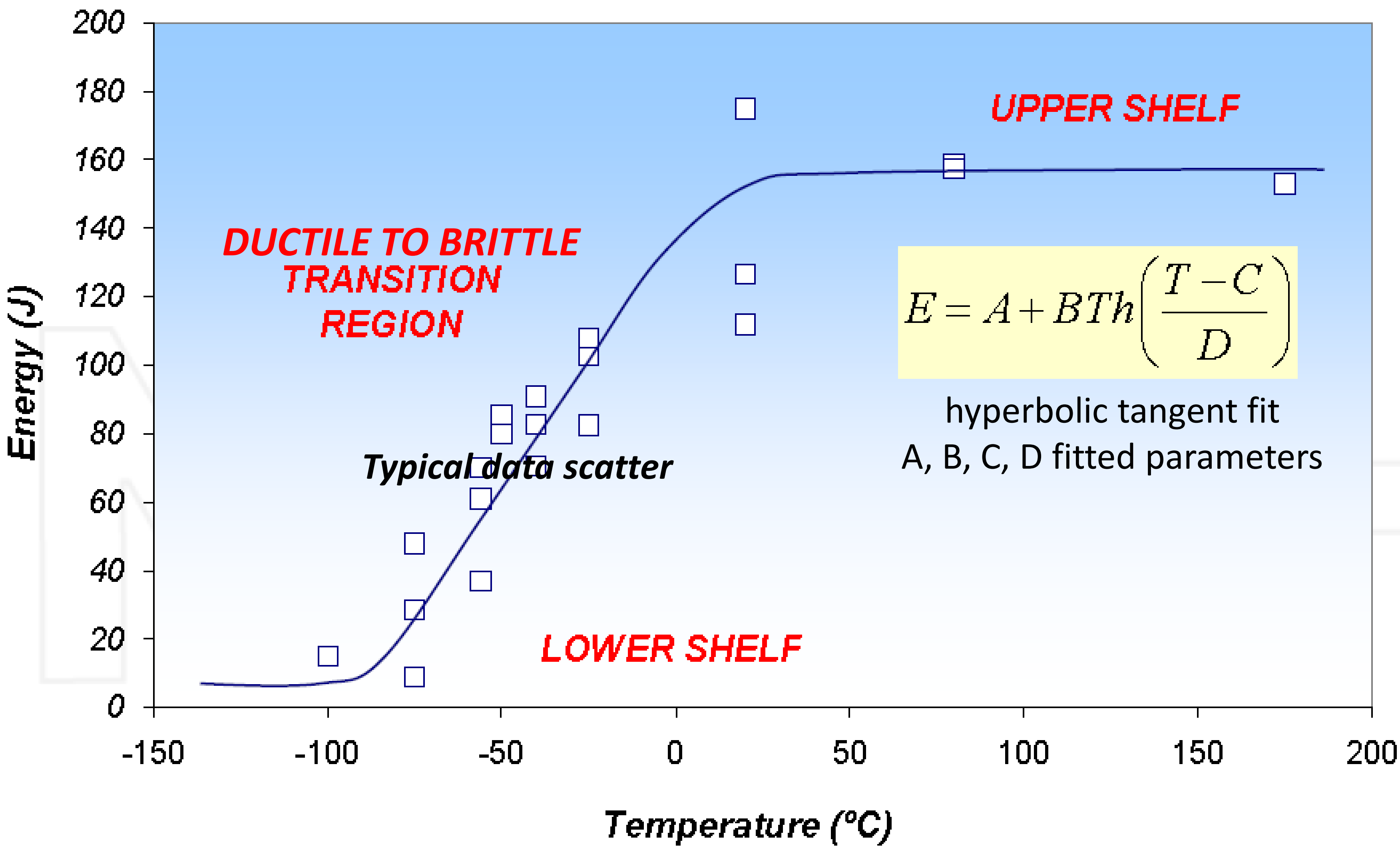


Dimensions in mm

Standard Charpy specimen

From 2

CHARPY CURVE



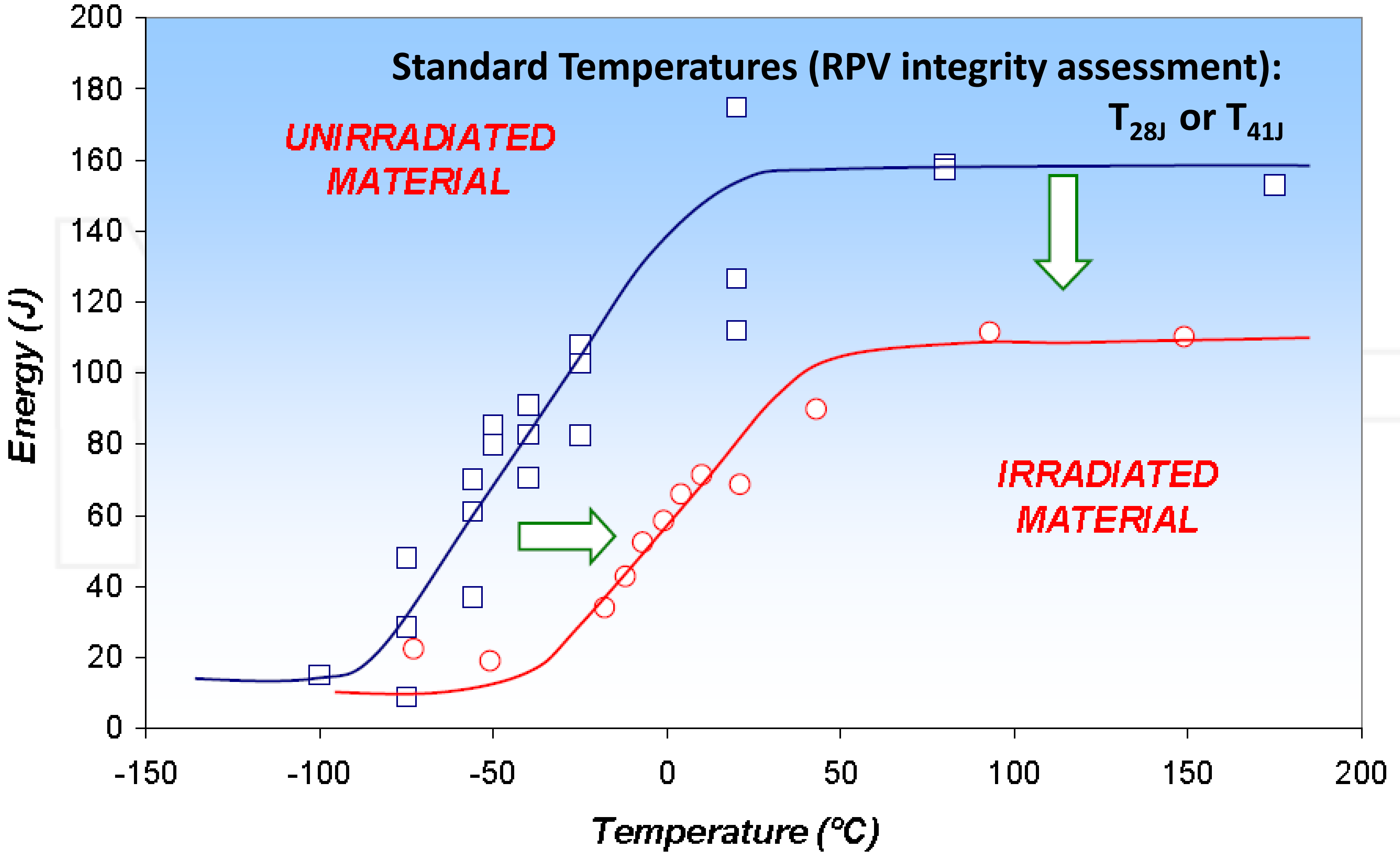
$$E = A + B\,Th\left(\frac{T - C}{D}\right)$$

hyperbolic tangent fit

A, B, C, D fitted parameters

From 2

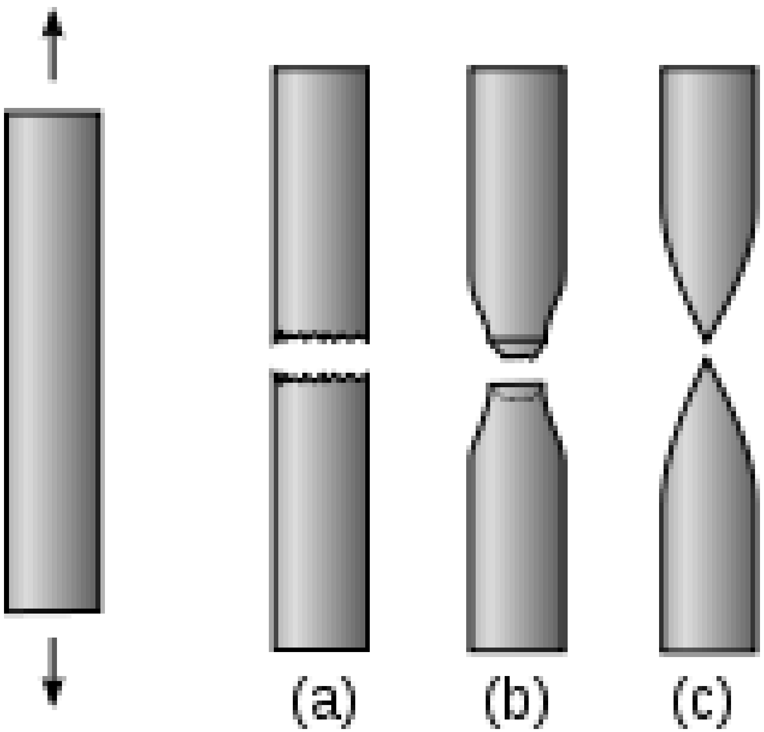
Effect of Irradiation on Charpy Curves



Reference Temperature RT_{NDT}

The ductile–brittle transition temperature (DBTT), nil ductility temperature (NDT), or nil ductility transition temperature

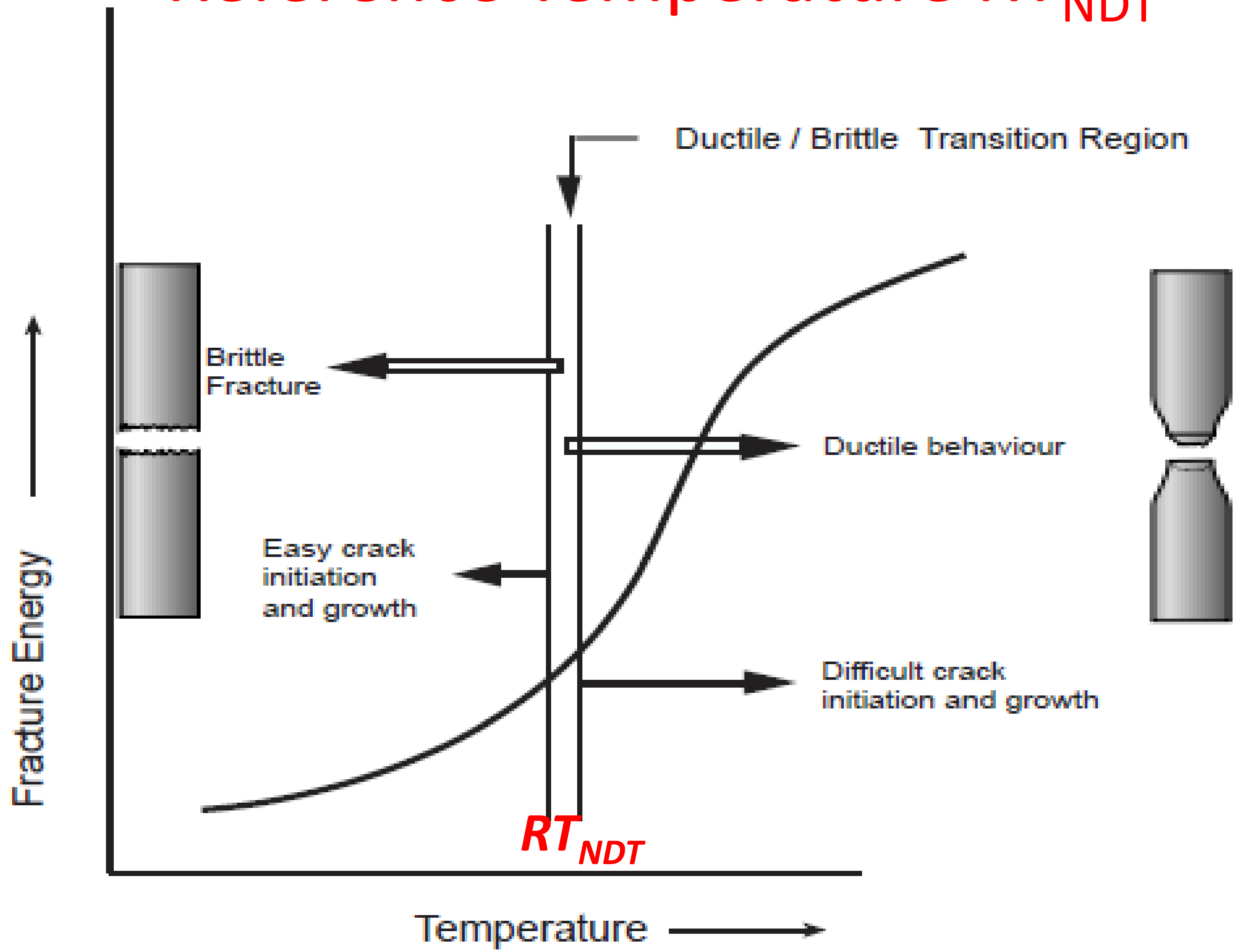
represents the point
at which the fracture energy passes
below a pre-determined point
(for steels typically 40 J
for a standard Charpy impact test.



Schematic appearance of round metal bars after tensile testing:
(a) Brittle fracture
(b) Ductile fracture
(c) Completely ductile fracture

From 2

Reference Temperature RT_{NDT}

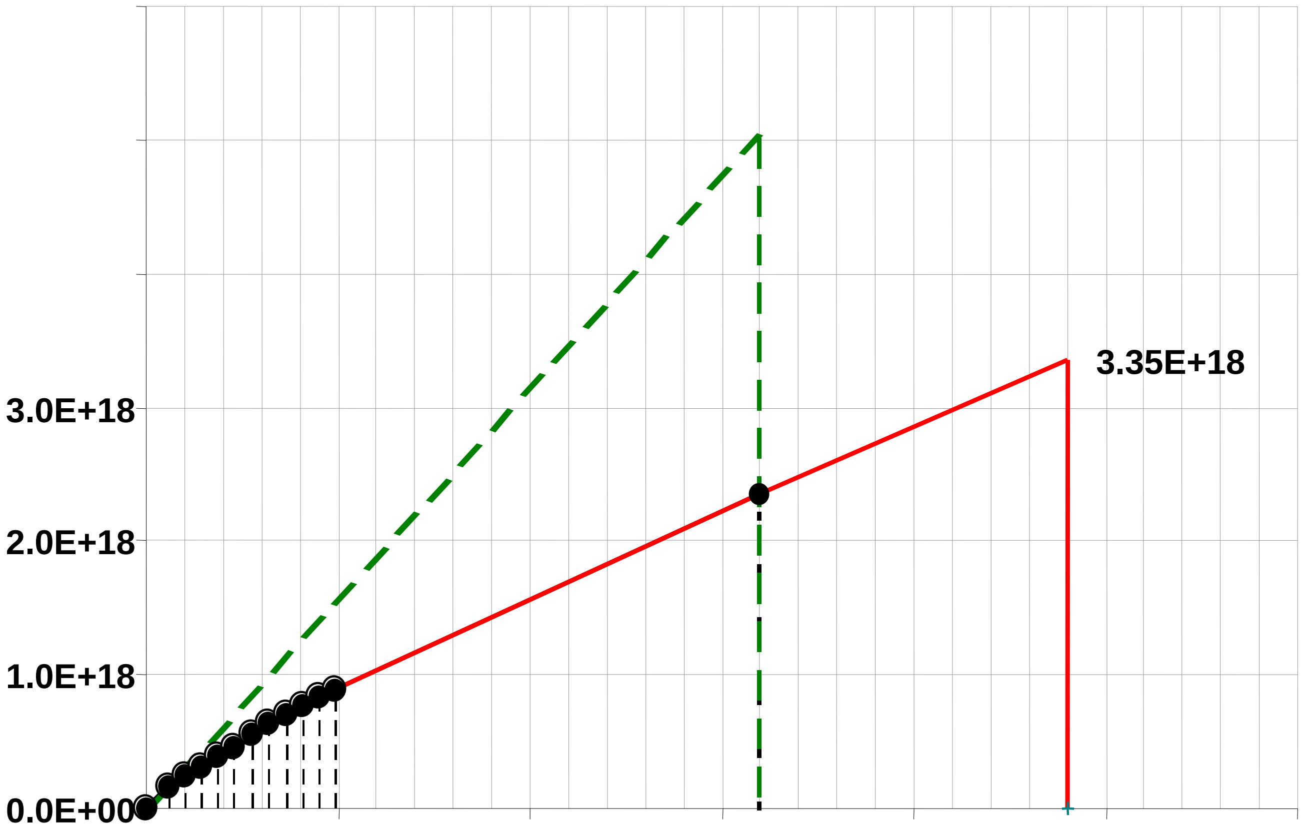


From 2

Irradiation Behaviour of RPV in German NPP, KTA Requirements

Operating Time (Years of Full Power)	40	60
Specified RT_{NDT} (°C) at BoL	-12	-12
Neutron Fuence (cm^{-2} für E > 1MeV) at EoL	5×10^{18}	$7{,}5 \times 10^{18}$
RT_{Limit}	< 40°C	< 40°C

From 2



Fluence versus Full Power Years of Operation for a Konvoi Plant

From 2

Konvoi Nuclear Power Station
Fluence and RT_{NDTj} During Operation

Operating Time (Years)	40	60
RT_{NDT} (°C) (Determined at BoL)	-42	-42
Neutron Fluence cm^{-2} for (E > 1MeV) at EoL	2.36×10^{18}	3.35×10^{18}
RT_{Limit}	< 40°C	< 40°C
Adjusted RT_{NDT} (°C) (Determined by Surveillance Programme)	-30°C	-29°C

Irradiation behavior of RPV is not limiting plant life!

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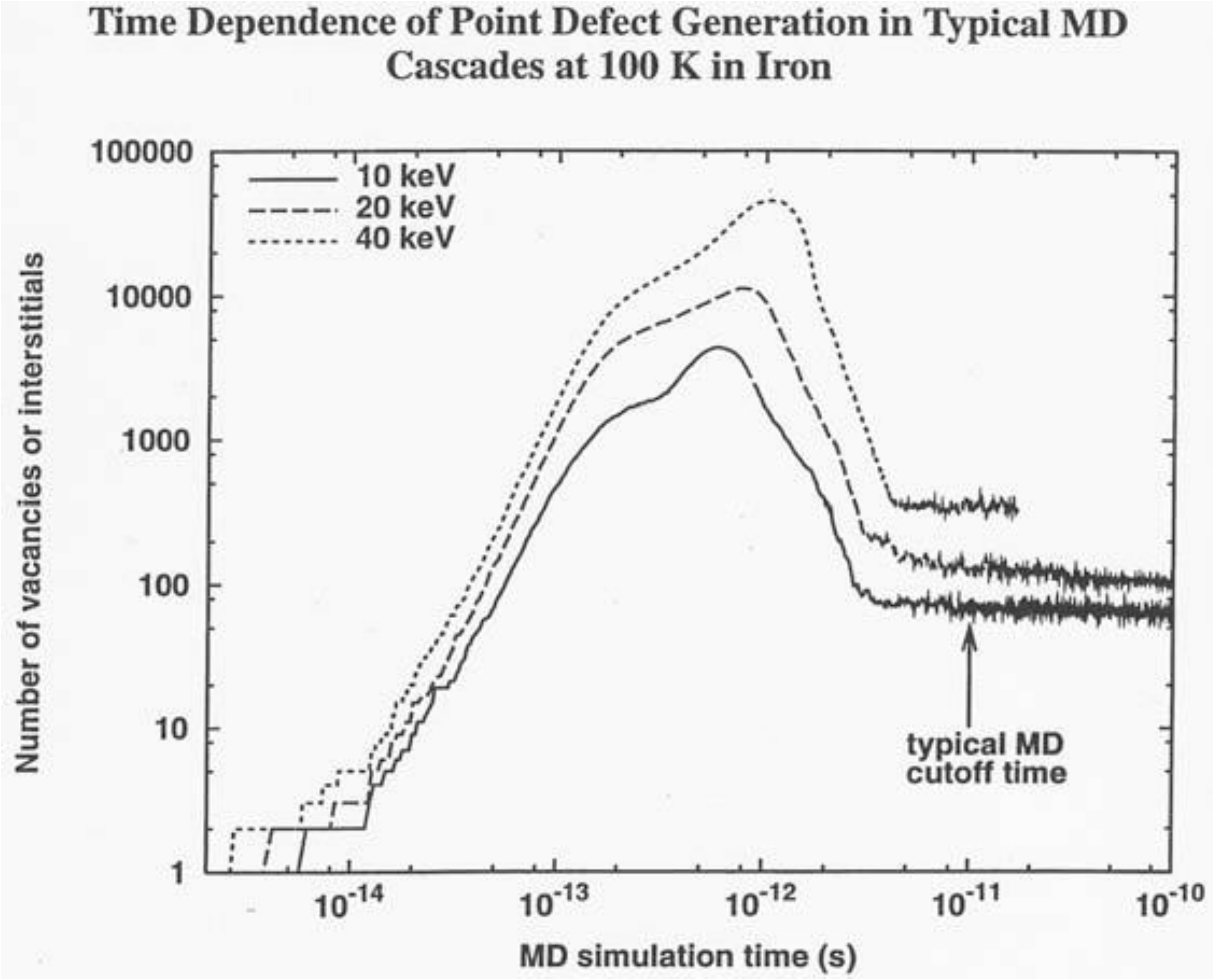
Time Dependence of Point Defect Generation in Typical MD Cascades at 100 K in Iron
Number of vacancies or interstitials
100000
10000
1000
100
10
1
10 keV
20 keV
40 keV
10^-14
10^-13
10^-12
10^-11
10^-10
MD simulation time (s)
typical MD cutoff time

INSPECTION WITH CAUSE

Primary Water Stress Corrosion Cracking - PWSCC