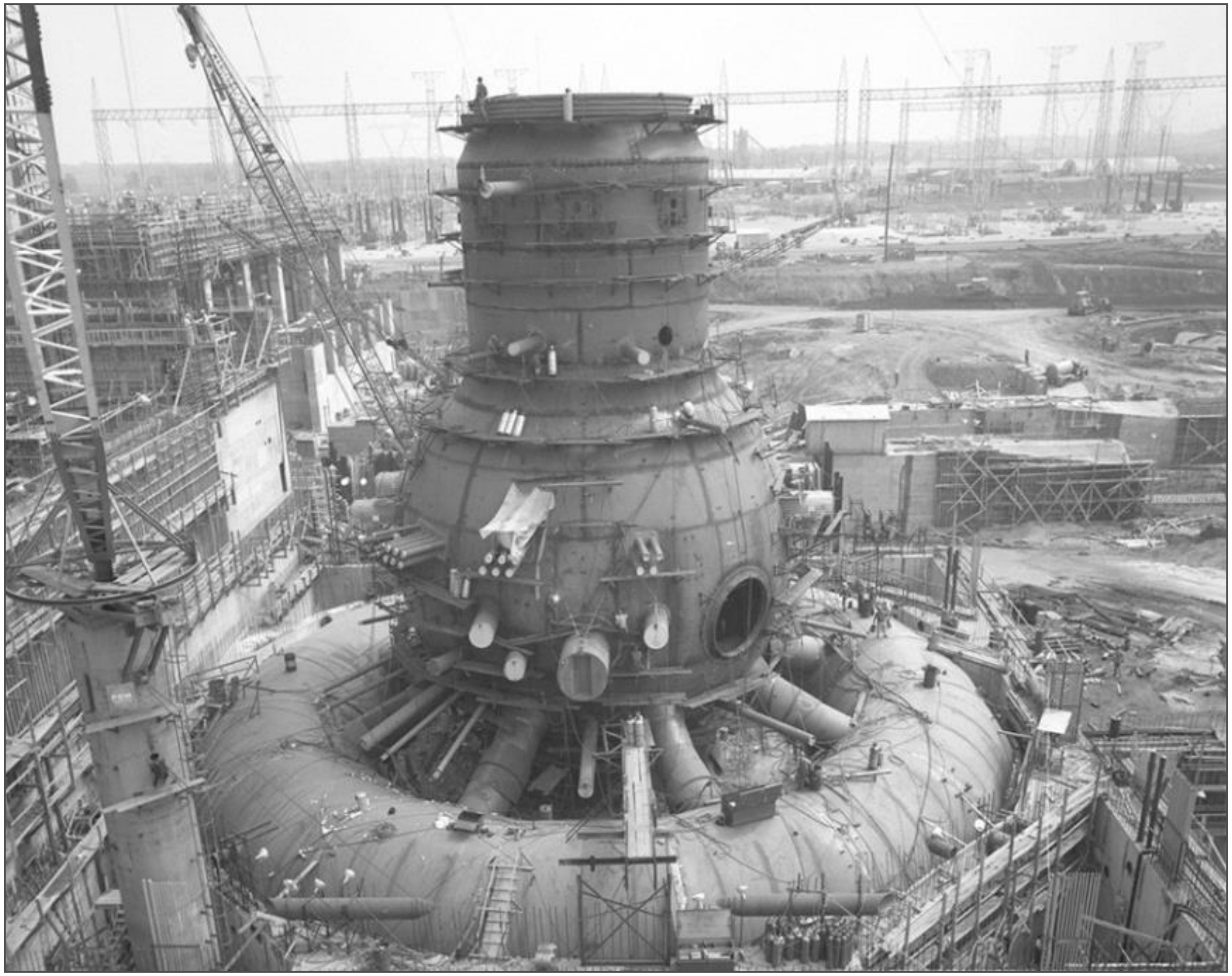
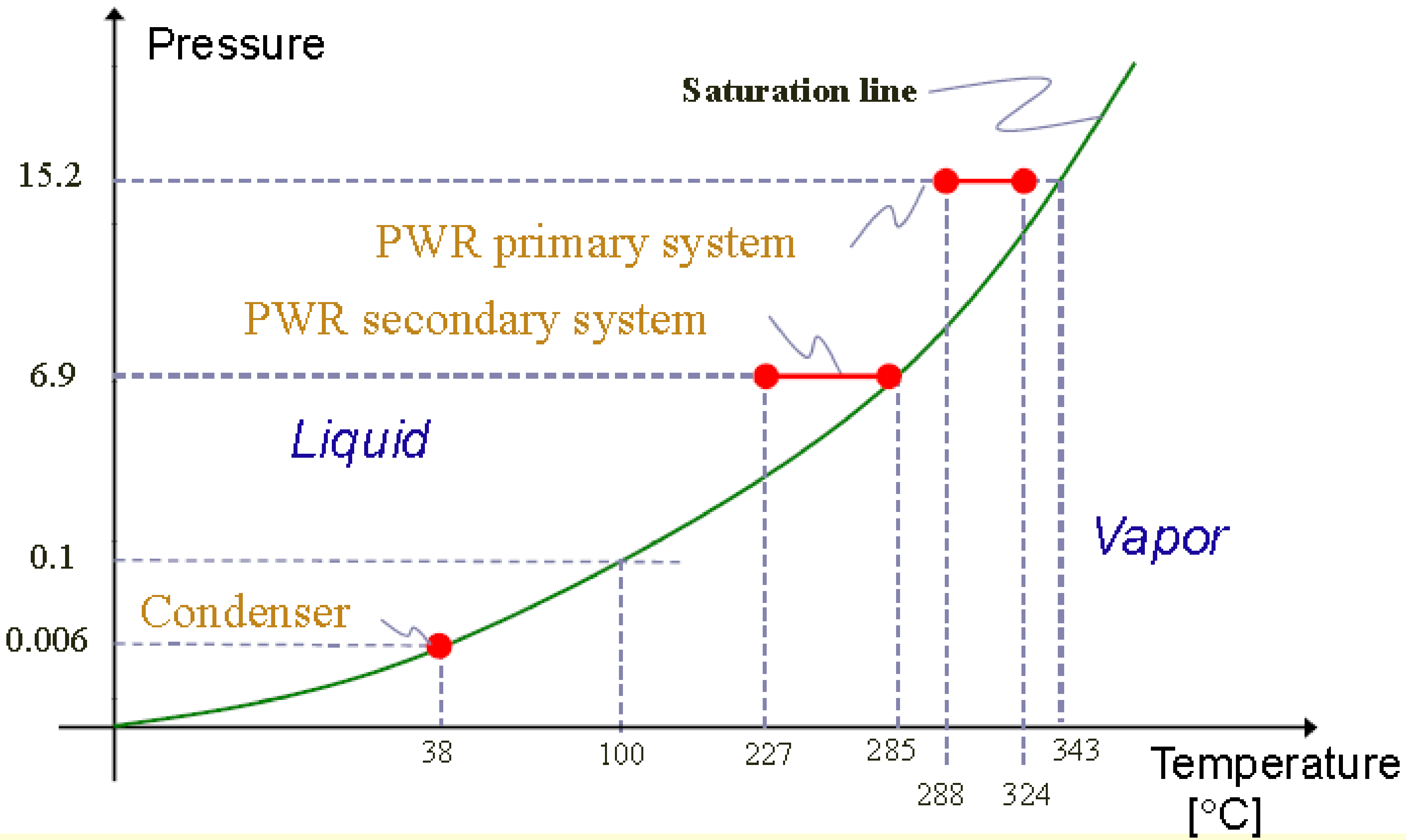
# Pressurized Components of Nuclear Power Plants

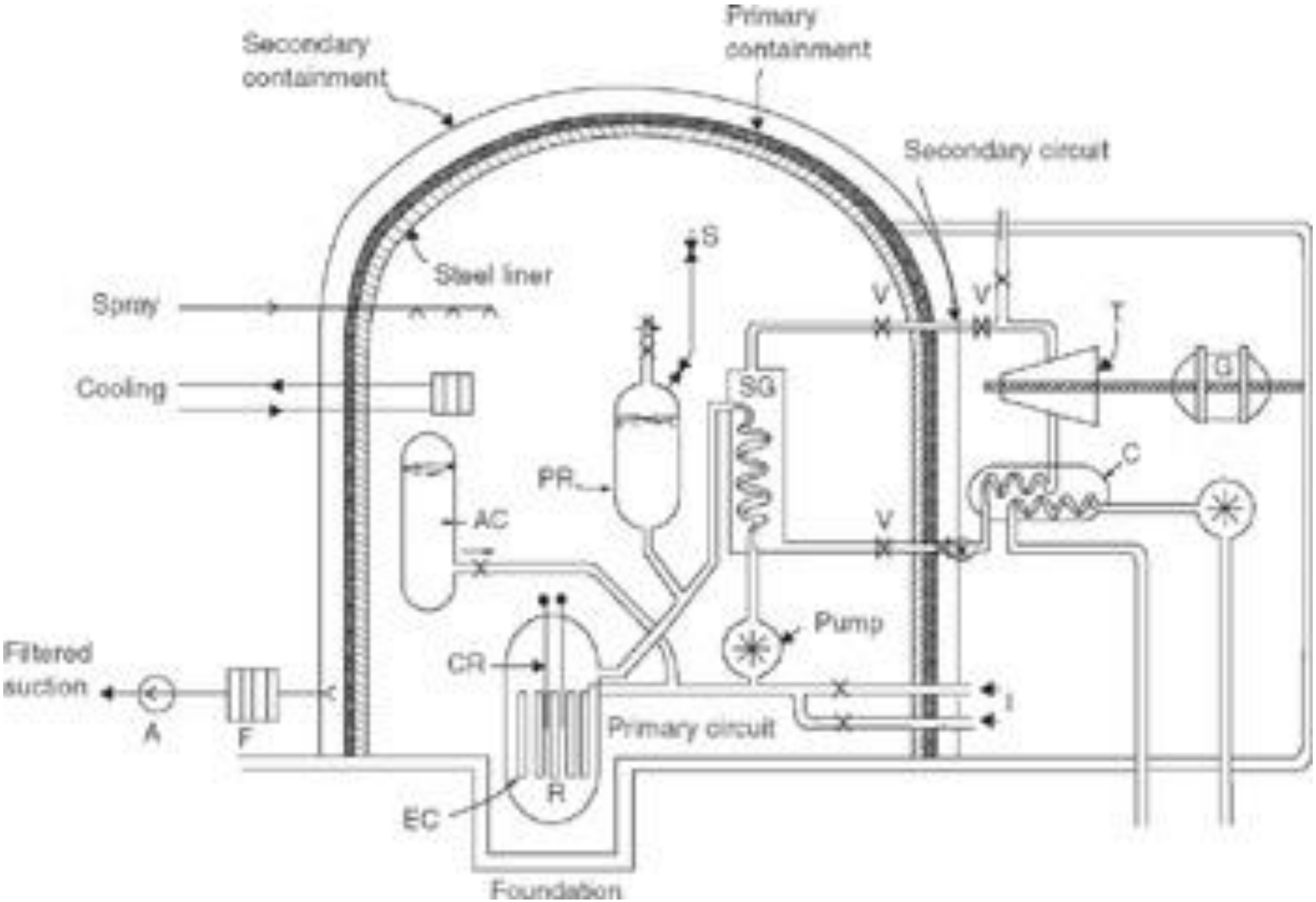


MARK I Containment

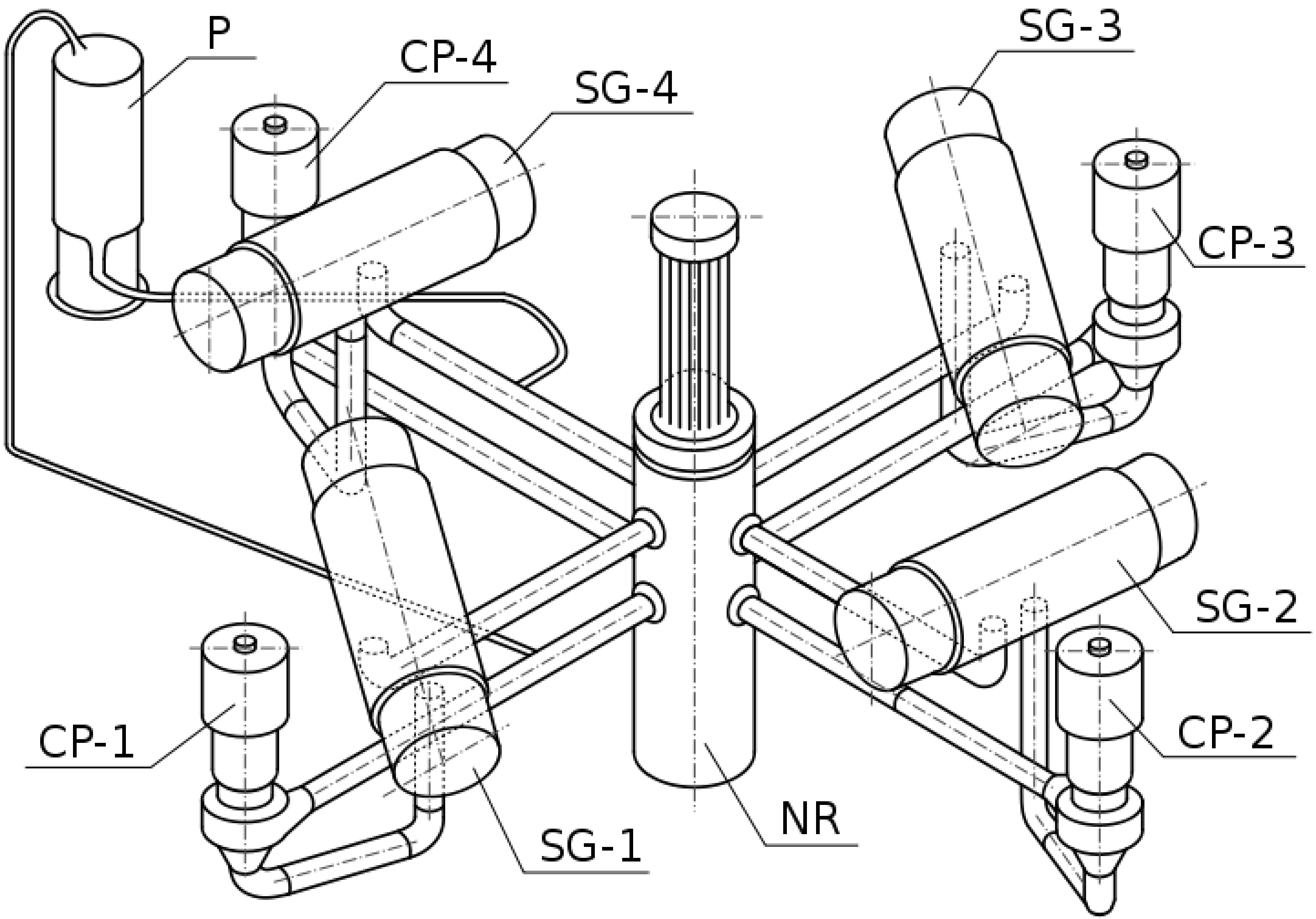
# Phase Diagram of Water



# Pressurized Components of Nuclear Power Plants



# 4 Loop Pressurized Water Reactor (VVER 1000)




VVER-1000-Stereometric.svg

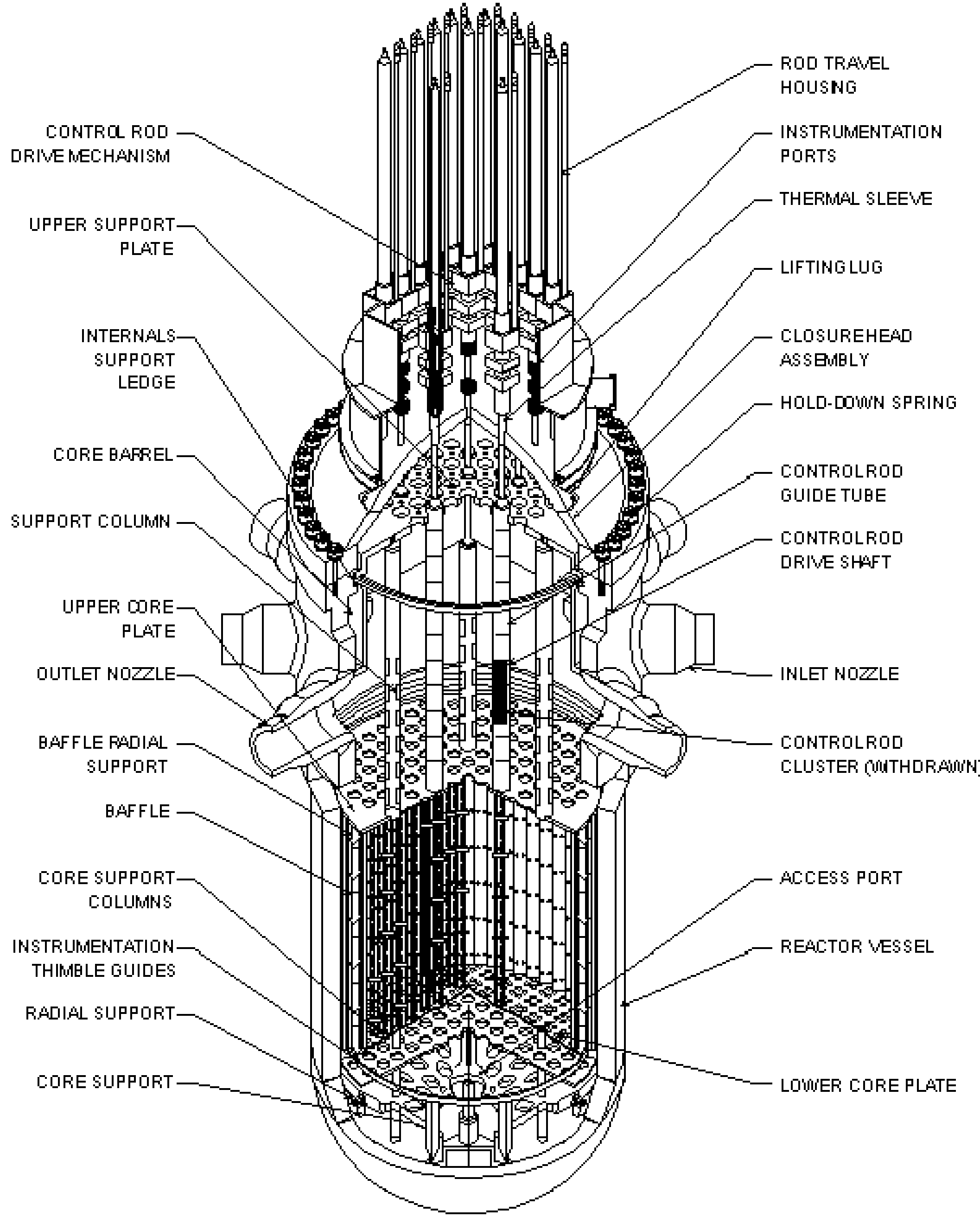
# Typical 4 Loop Parameters

| | |
|---|---|
| Total heat output | ~3250-3411 MWt |
| Heat generated in fuel | 97.4% |
| Nominal system pressure | 15.6 MPa |
| Total coolant flow rate | ~1.74 x $10^4$ kg/s |
| Coolant temperature | |
| *Nominal inlet* | 291.9°C |
| *Average rise in vessel* | 33.9°C |
| *Outlet from vessel* | 325.8°C |
| Equivalent core diameter | 3.37 m |
| Core length, between fuel ends | 3.66 m |
| Fuel weight, uranium (first core) | 86,270 kg |
| Number of fuel assemblies | 193 |

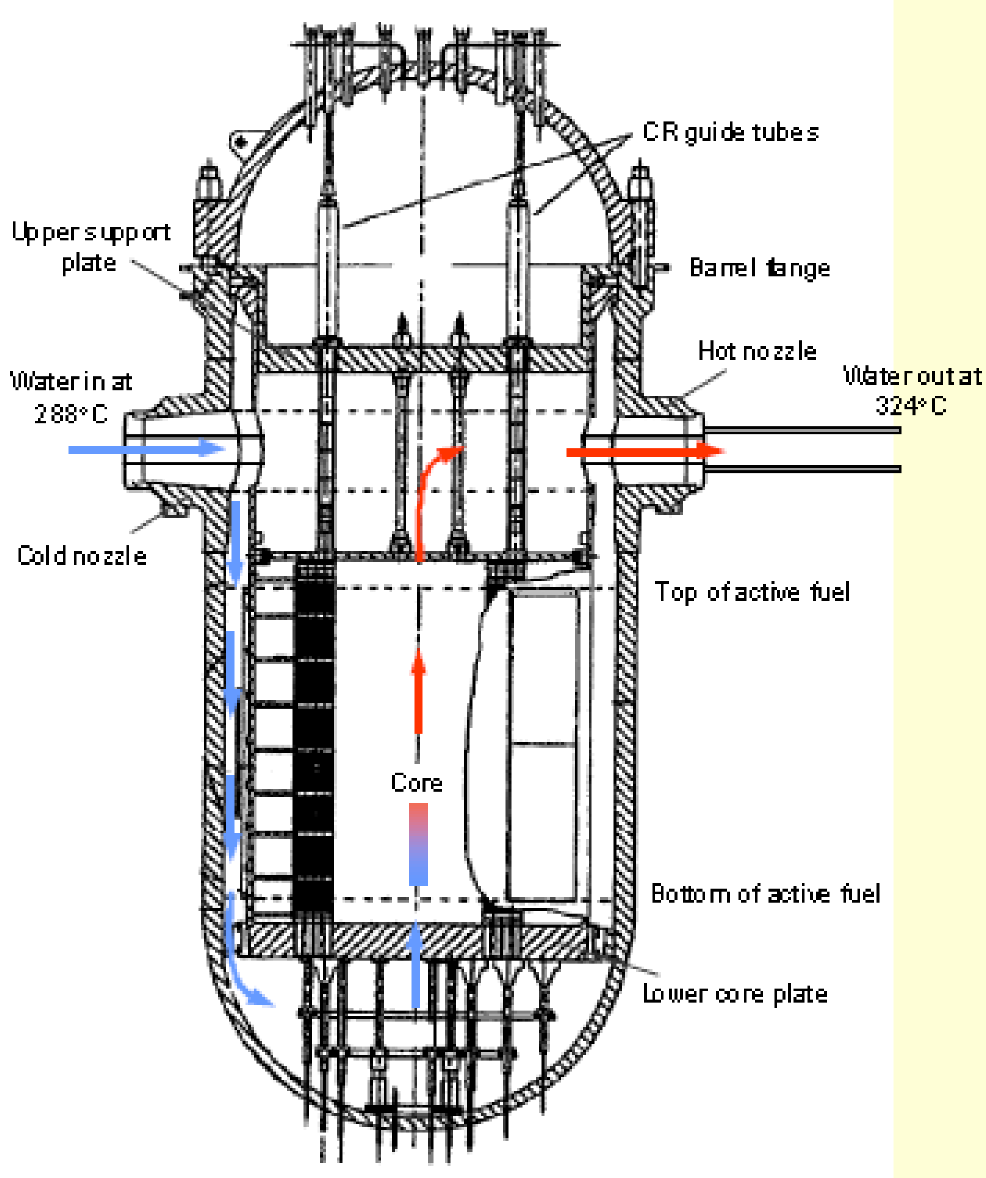
# TYPICAL 4-LOOP REACTOR VESSEL PARAMETERS

| | |
|---|---|
| Overall length of assembled vessel, closure head, and nozzles | 13.36 m |
| Inside diameter of shell | 4.39 m |
| Radius from center of vessel to nozzle face | |
| Inlet | 3.33 m |
| Outlet | 3.12 m |
| Nominal cladding thickness | 5.56 mm |
| Minimum cladding thickness | 3.18 mm |
| Coolant volume with core and internals in place | 134.2 $m^3$ |
| Operating pressure | 15.51 MPa |
| Design pressure | 17.24 MPa |
| Design temperature | 343.3°C |
| Vessel material | Carbon steel |
| Cladding material | Stainless steel |
| Number of vessel material surveillance capsules, total | 8 |

# Reactor Vessel and Internals



# Flow Path within Reactor Vessel



# Central Ring with Outlet and Inlet Nozzles

# Closure Head with Control Rod and Instrumentation Nozzles

# Core Plate

# Geometry of the fuel

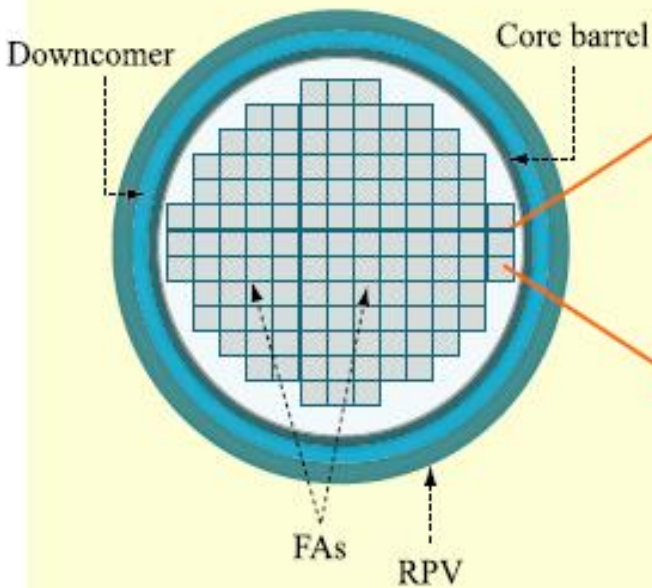



Image by MIT OpenCourseWare.

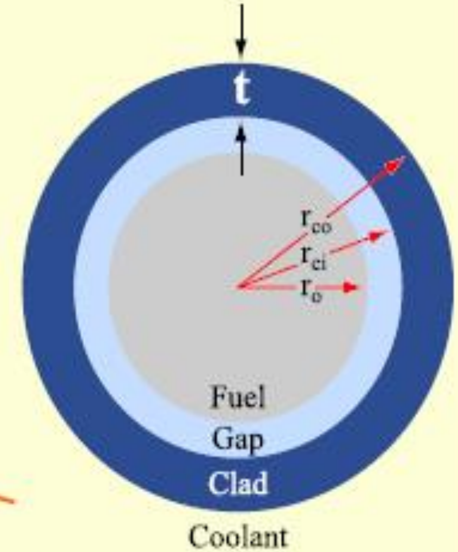


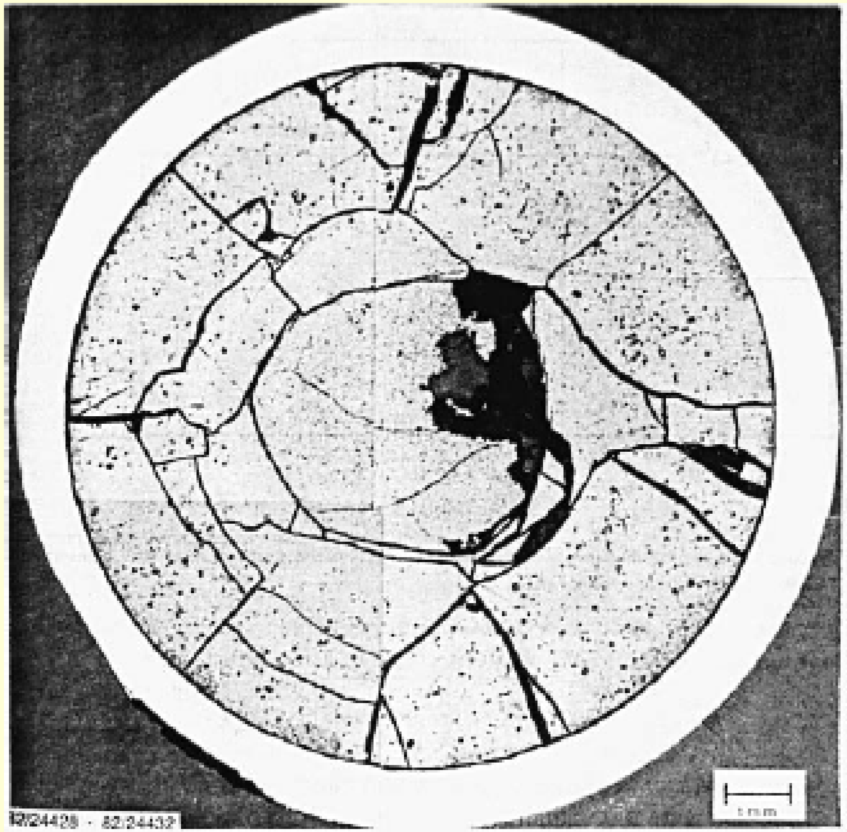

Image by MIT OpenCourseWare.

Cross Section of a Representative Fuel Pin (not drawn to scale)

| mm (in.) | BWR | PWR |
|---|---|---|
| $2r_o$ | 10.40 (0.409) | 8.20 (0.323) |
| $2r_{co}$ | 12.27 (0.483) | 9.50 (0.374) |
| t | 0.813 (0.032) | 0.57 (0.023) |

# Why the fuel/clad gap?

- Provides clearance for fuel pellet insertion during fabrication
- Accommodates fuel swelling without breaking the clad
- Filled with helium gas




**Example of a Cracked Fuel Cross Section**

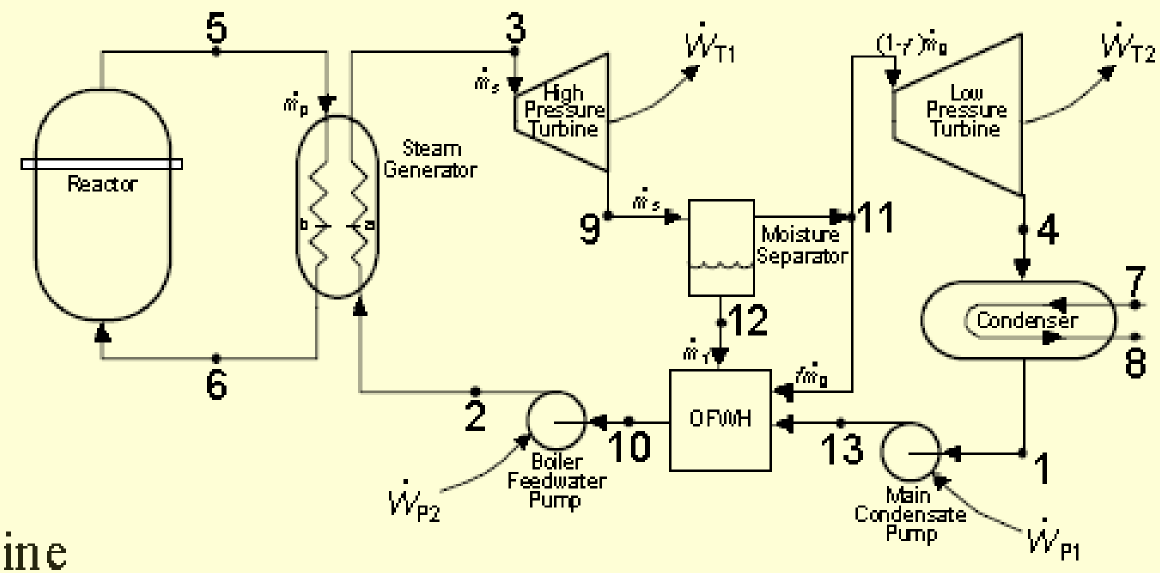
Source: Todreas & Kazimi, Vol. I, p. 333

# PWR STEAM GENERATORS

Primary side, Hot ($T_{in} = 324^{\circ}C$, $T_{out} = 288^{\circ}C$): High Pressure Liquid
Secondary side, Cold ($T_{sat} = 285^{\circ}C$): Lower Pressure Steam and Liquid

- Water Boils on Shell Side of Heat Exchanger
- Steam Passes through Liquid Separators, Steam Dryers
- Liquid Water Naturally Recirculates via Downcomer
- Level Controlled via Steam and Feedwater Flowrates

# PWR Power Cycle (Secondary System)




Turbine

Low Steam Pressure Requires:

Large turbine

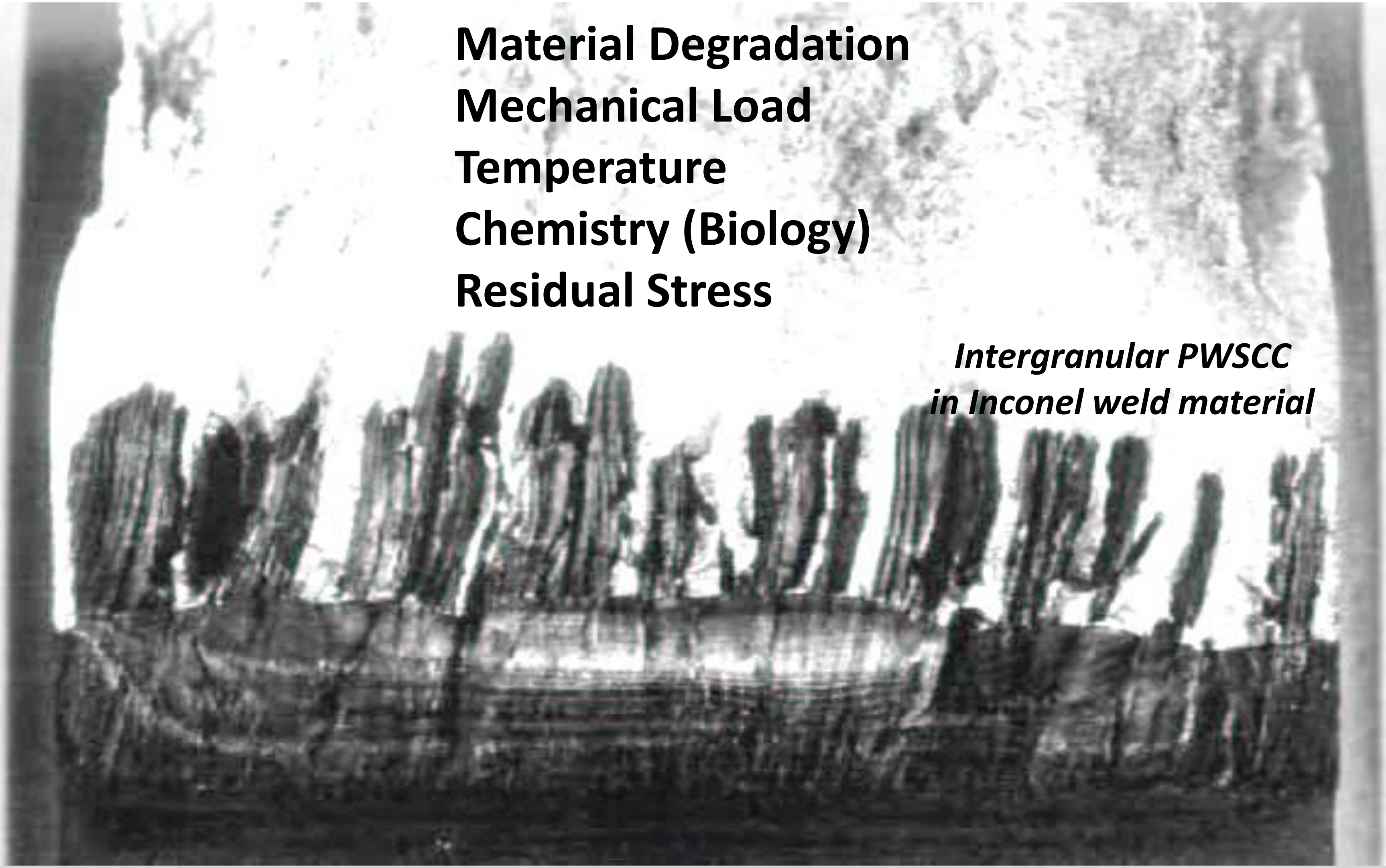
Lower rotational speed (1800 RPM)

Condenser

Steam Side at Low Pressure

Cooling water from sea, river or cooling tower

# Degradation of nuclear structures during operation



**Material Degradation**
**Mechanical Load**
**Temperature**
**Chemistry (Biology)**
**Residual Stress**

***Intergranular PWSCC in Inconel weld material***

# 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)

# 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

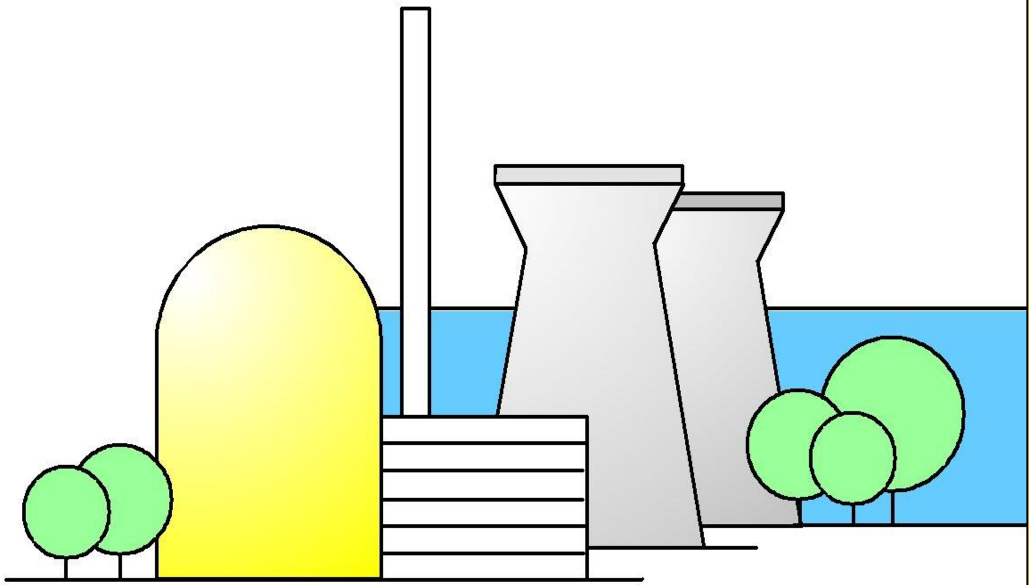
# Prevention from Accelerated Plant Ageing

## 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

With permission of AREVA

# Potential Ageing Mechanisms and Resulting Effects on Components

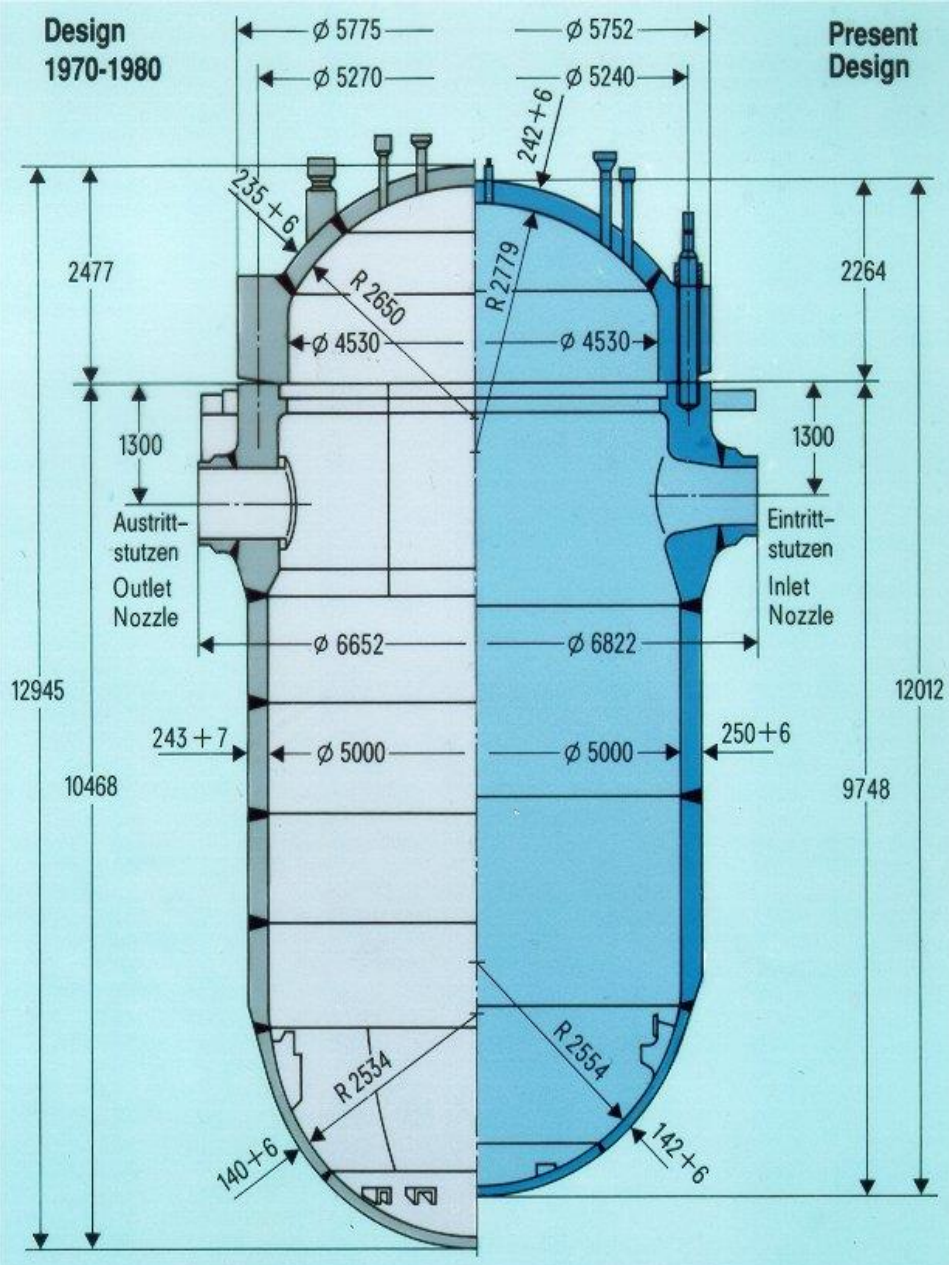
| Aging Mechanisms / Effect on Components | Irradiation | Thermal Aging | Creep | Fatigue (HCF, LCF) | Corrosion | | | | | | | Wear |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Corrosion Fatigue | Stress Corrosion Cracking | Strain Induced Corrosion Cracking | Intergranular Attack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

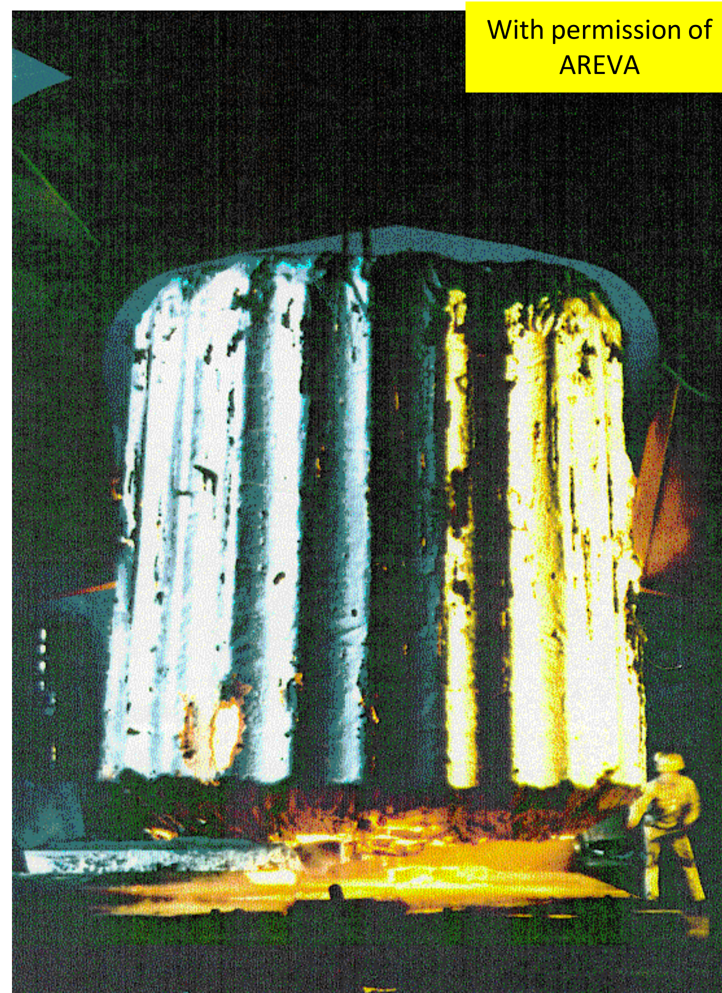
# Quality Criteria for PWR Components and Systems

| Quality Criteria \ Component or System | 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<br>22 NiMoCr 37<br>Austenitic-cladding | | X 6 CrNiNb 18 10<br>G-X 5 CrNiNb 18 9 | | Incoloy 800 | 15 MnNi63<br>19MnAl 6 V | WStE255/355<br>C22.8<br>St35.8<br>15Mo3<br>GS-C25 | Stellite<br>Co-free-alternatives | Zircaloy 4<br>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
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- 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

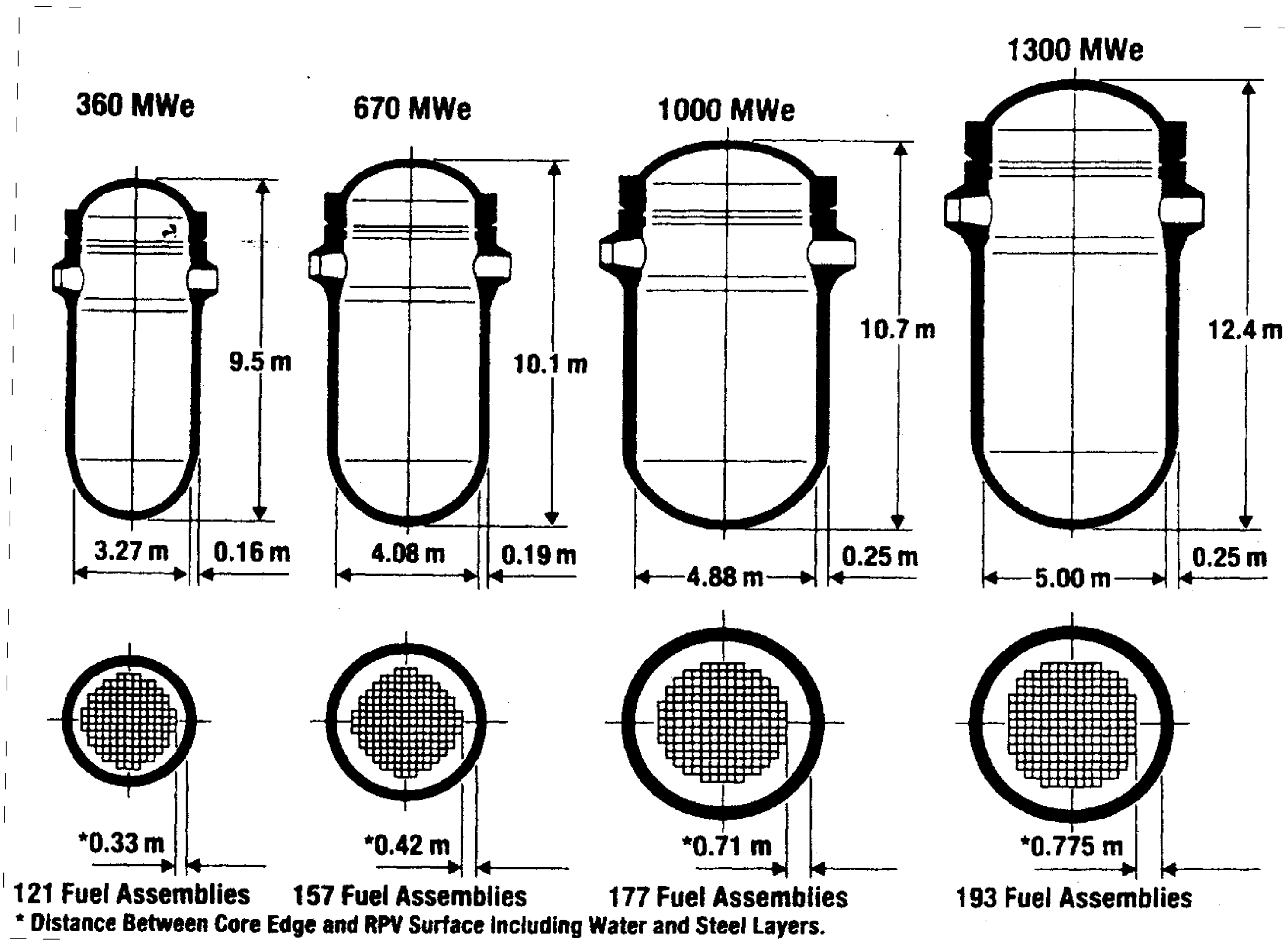
**causes:**

- **Embritttlement (Reactor Vessel)**

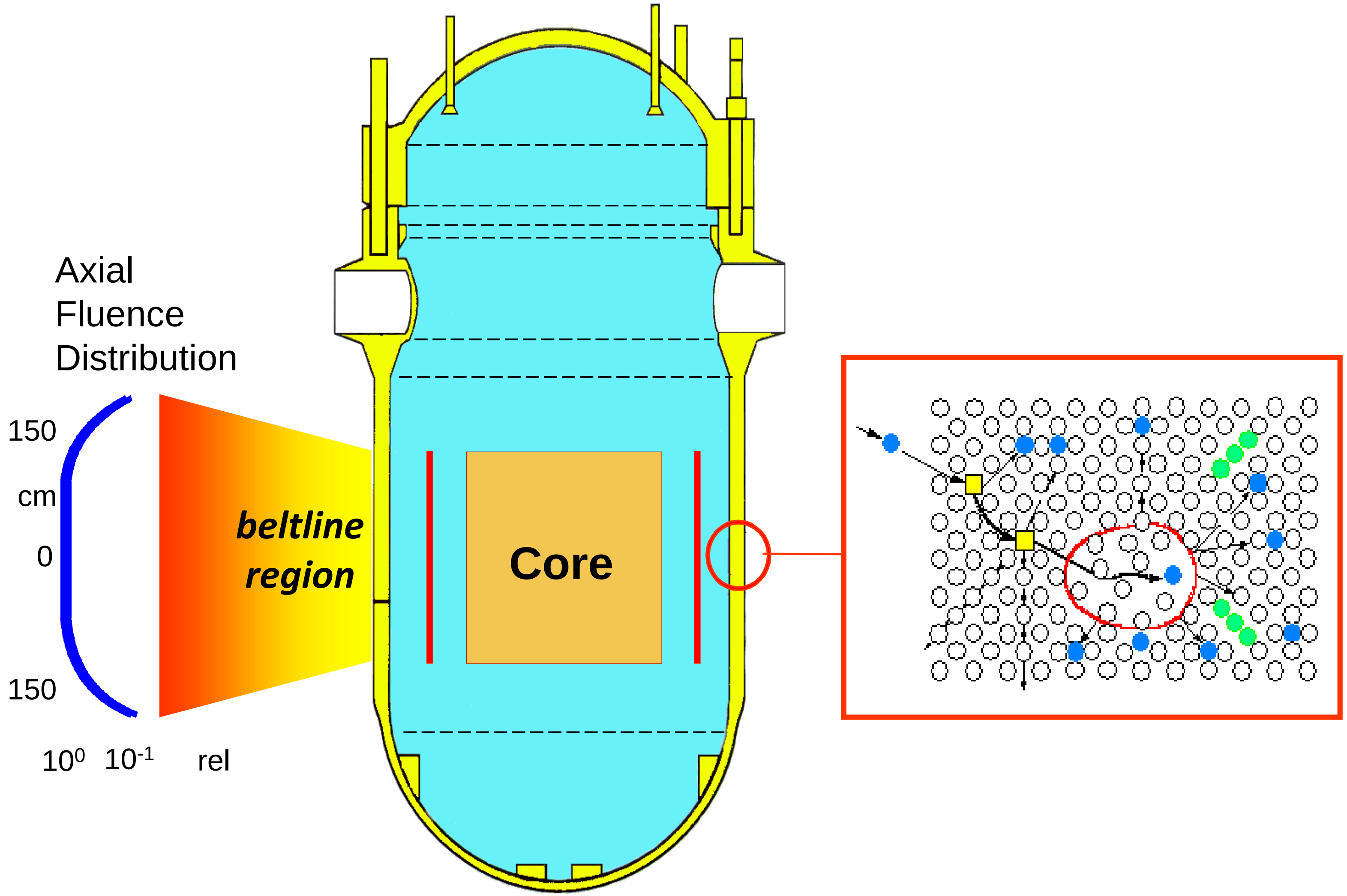
- **Swelling**
- **Buildup of Wigner Energy**

**Neutron Moderators (Graphite)**

# 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**

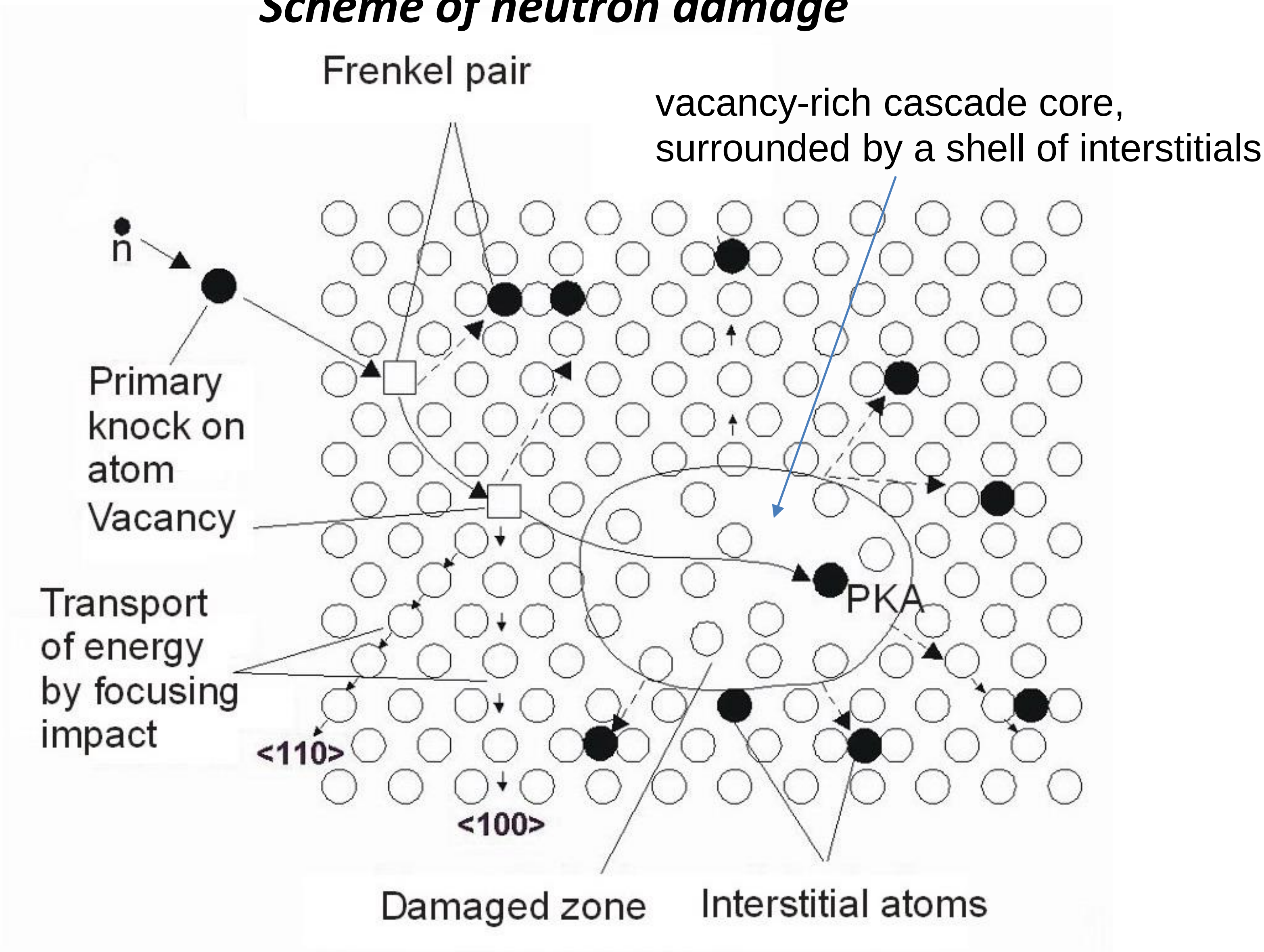
**If there is a flaw of critical size and the vessel is repressurized, the combined stresses cause the flaw to propagate rapidly through the vessel wall**

**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
($\approx$1 ps)

# 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, $\sigma_F^*$**

***FRACTURE MECHANICS***

Alan Arnold Griffith and George Rankine Irwin

# Structural Material Parameters

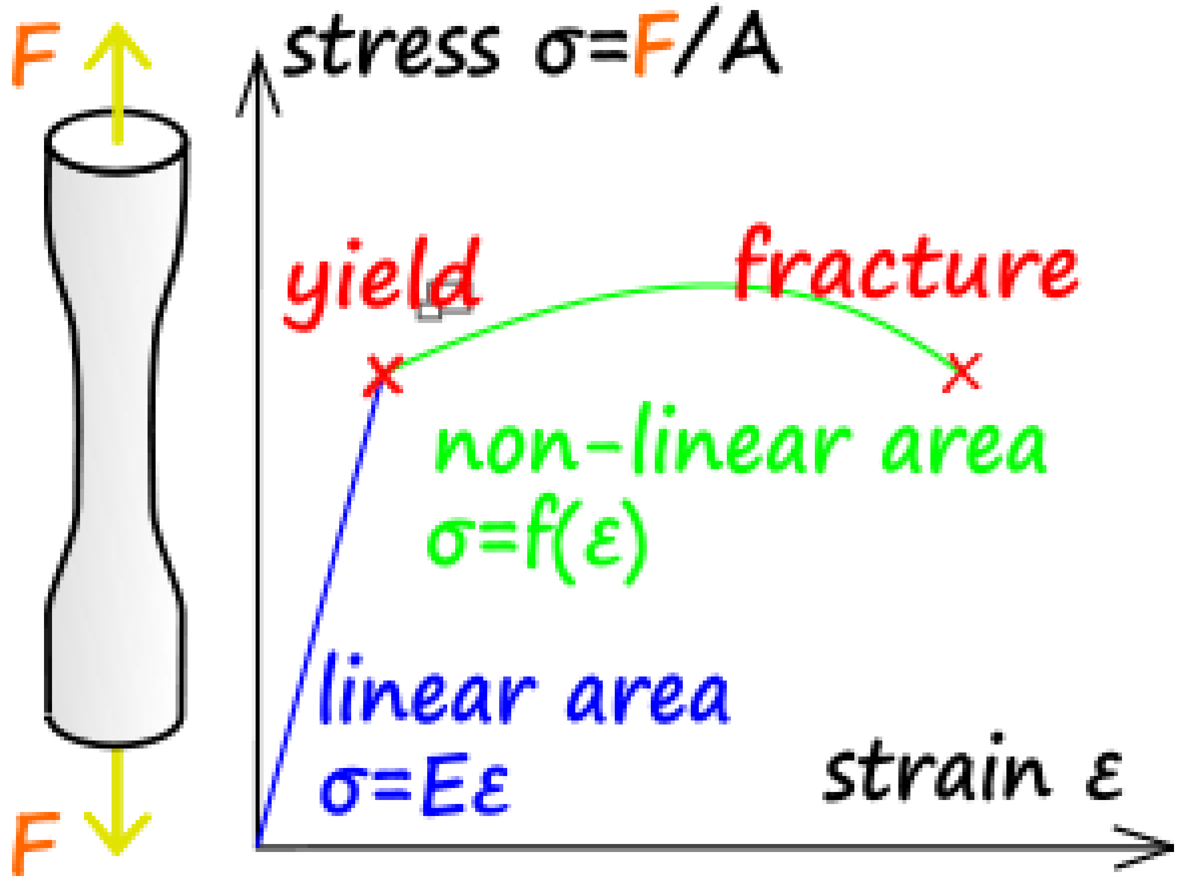
***Strength:***
The strength of a material is its ability
to withstand an applied load without failure
***Yield Strength***
refers to the point on the engineering stress-strain curve
beyond which the material experiences deformations
that will not be completely reversed
upon removal of the loading
***Ultimate 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)

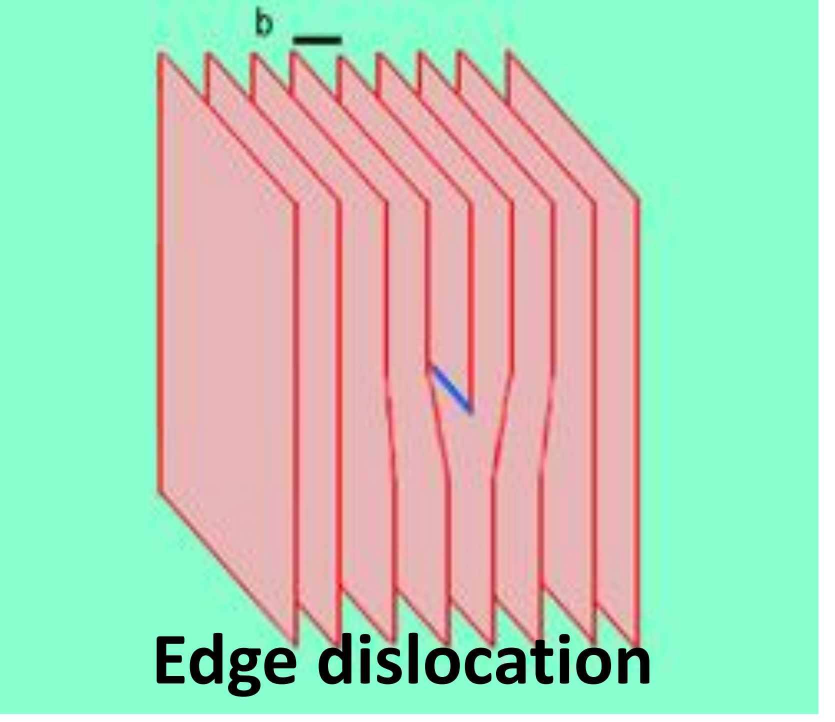
**line defects:** irregularities on a plane of atoms

- 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;

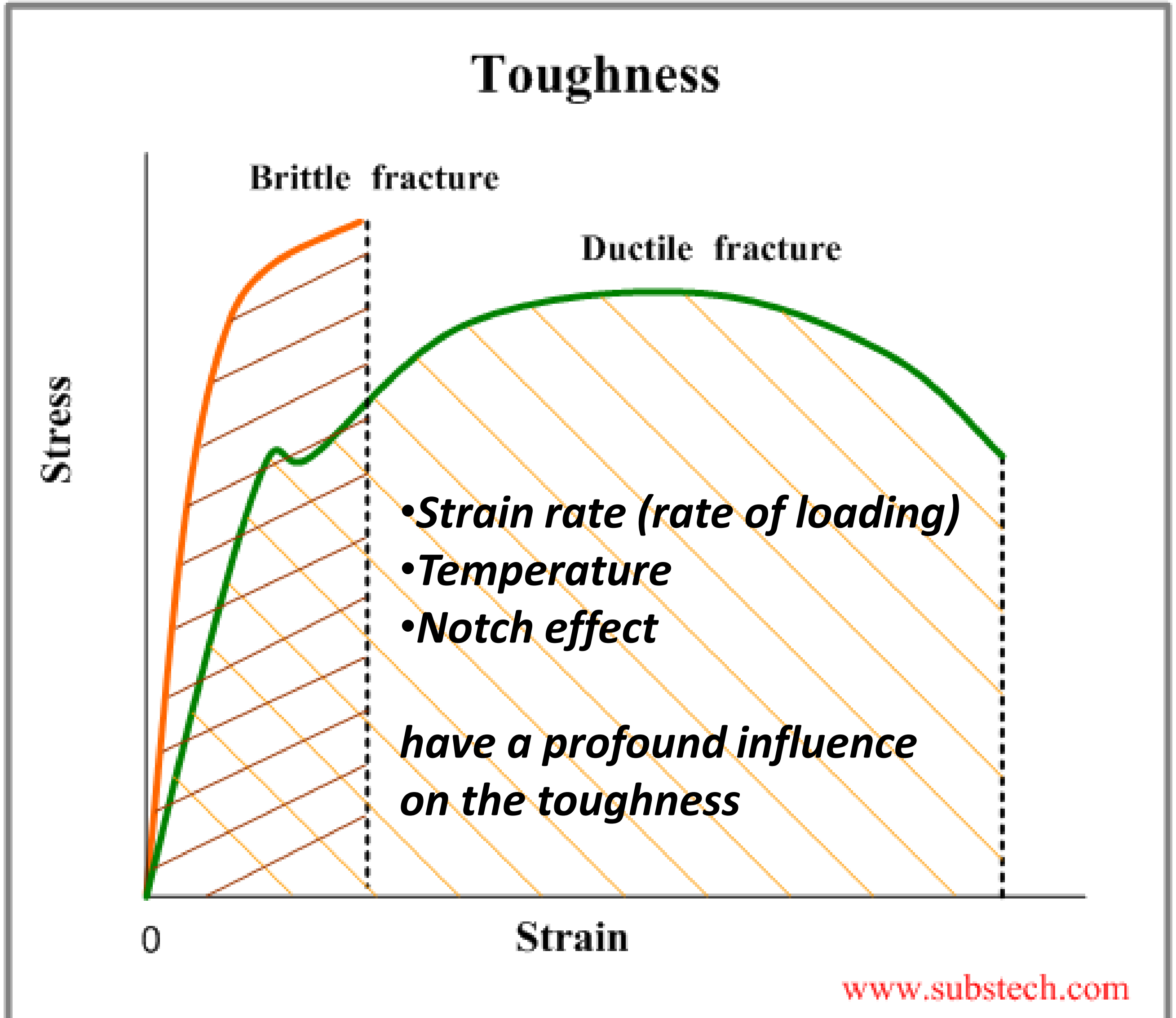
$$\frac{\text{energy}}{\text{volume}} = \int_0^{\epsilon_f} \sigma \, d\epsilon$$

$\varepsilon$: strain; $\varepsilon_f$ : strain upon failure
$\sigma$: stress

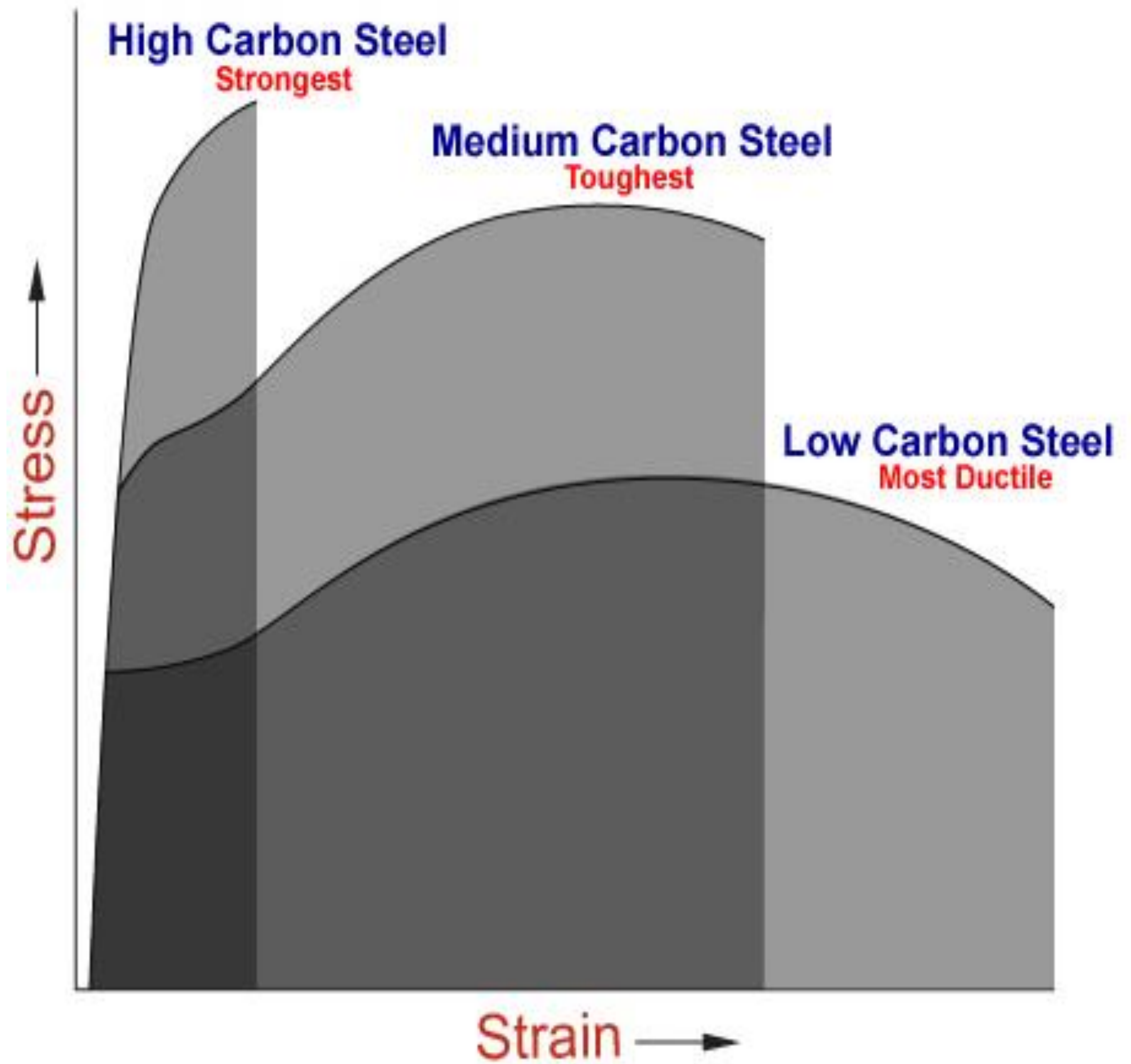
(Toughness is related to the area under the stress-strain curve)

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

**Toughness requires a balance of strength and ductility**

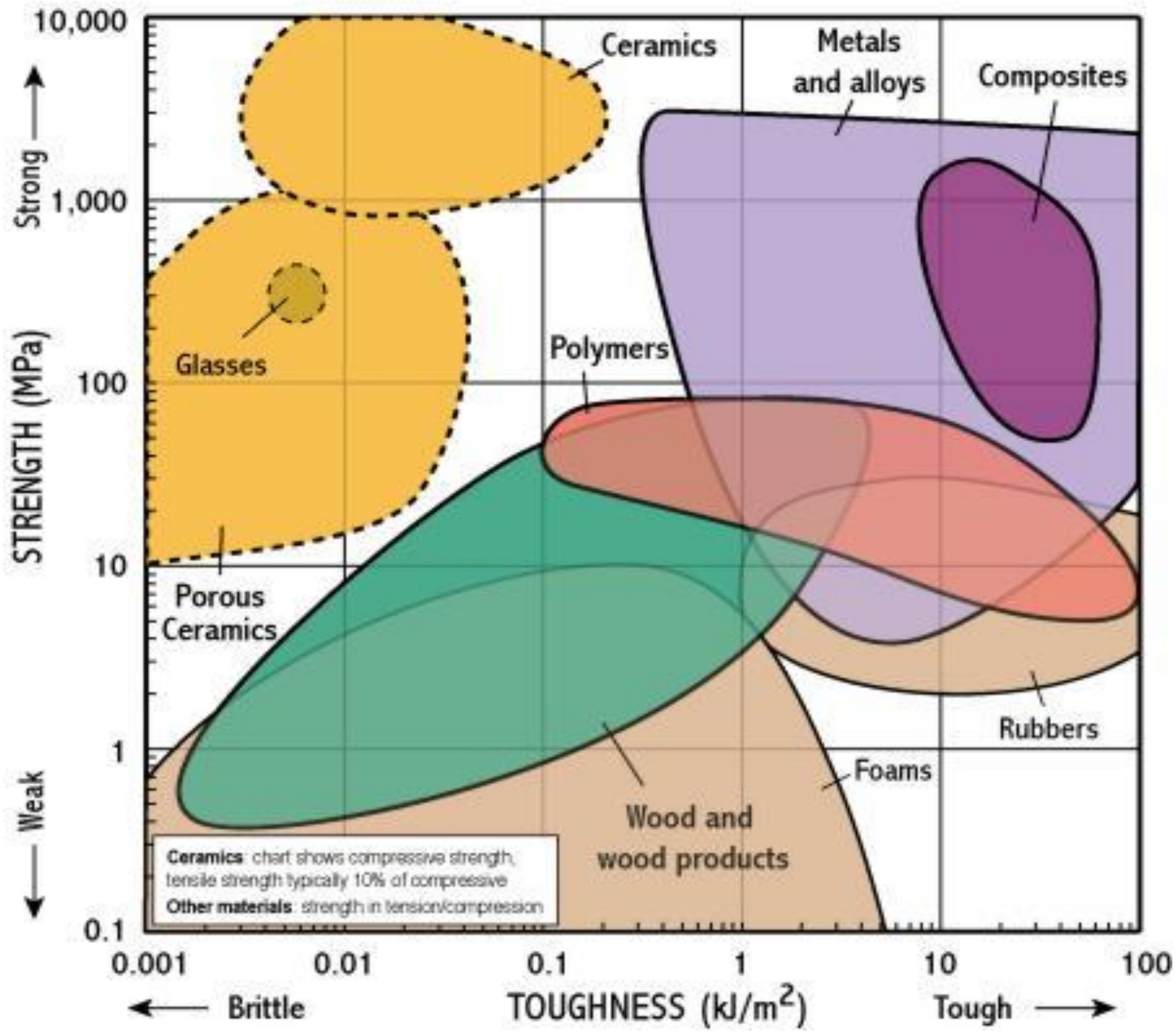

Toughness
Brittle fracture
Ductile fracture
Stress
Strain
0
•Strain rate (rate of loading)
•Temperature
•Notch effect
have a profound influence
on the toughness
www.substech.com

# Structural Material Parameters: *Toughness*




Iowa State University
Center for NDE

# Structural Material Parameters



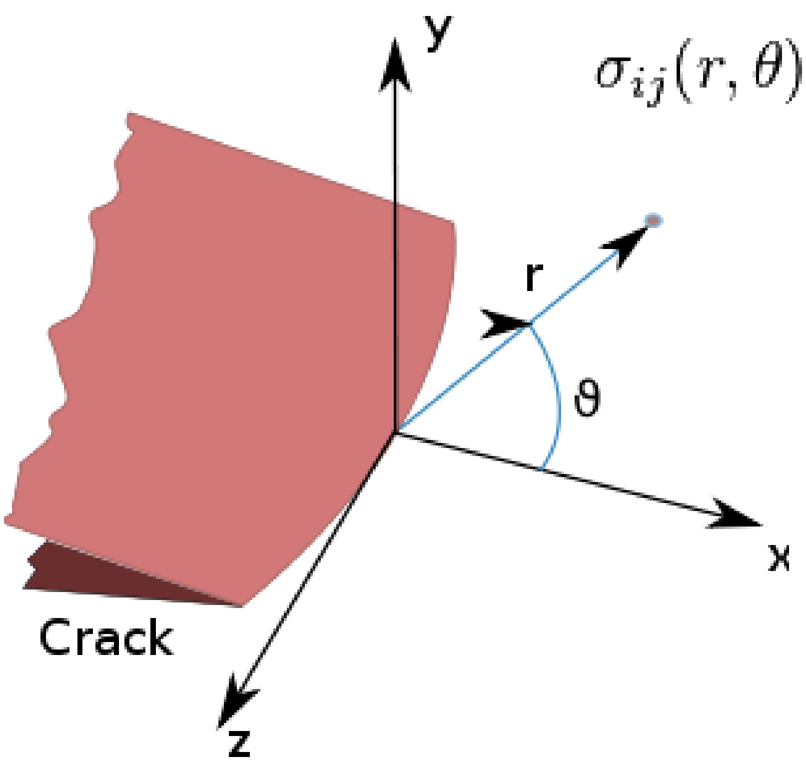

**Strength**
measures the resistance of a material to failure, given by the applied stress (or load per unit area)

**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

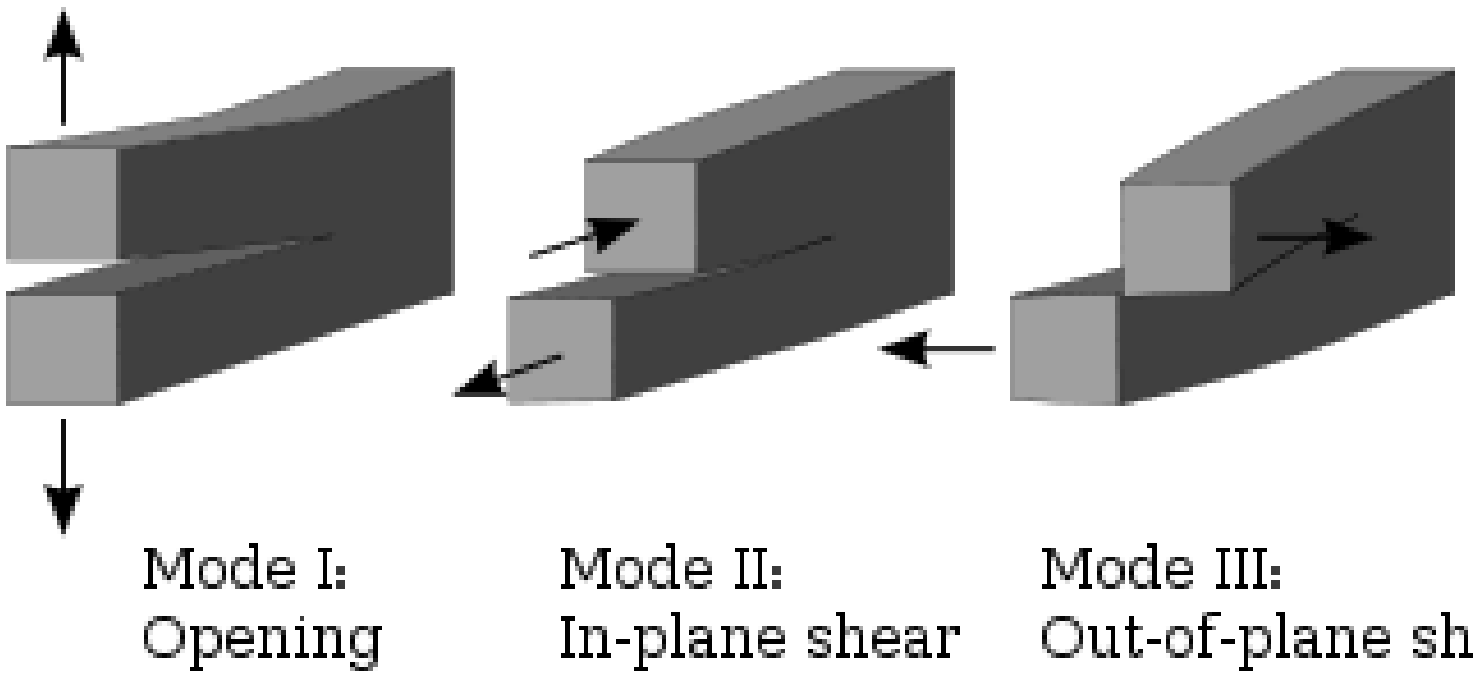
**K is a theoretical construct usually applied to**
**a homogeneous, linear elastic material.**
**It is useful for providing a failure criterion**
**for brittle materials**

**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

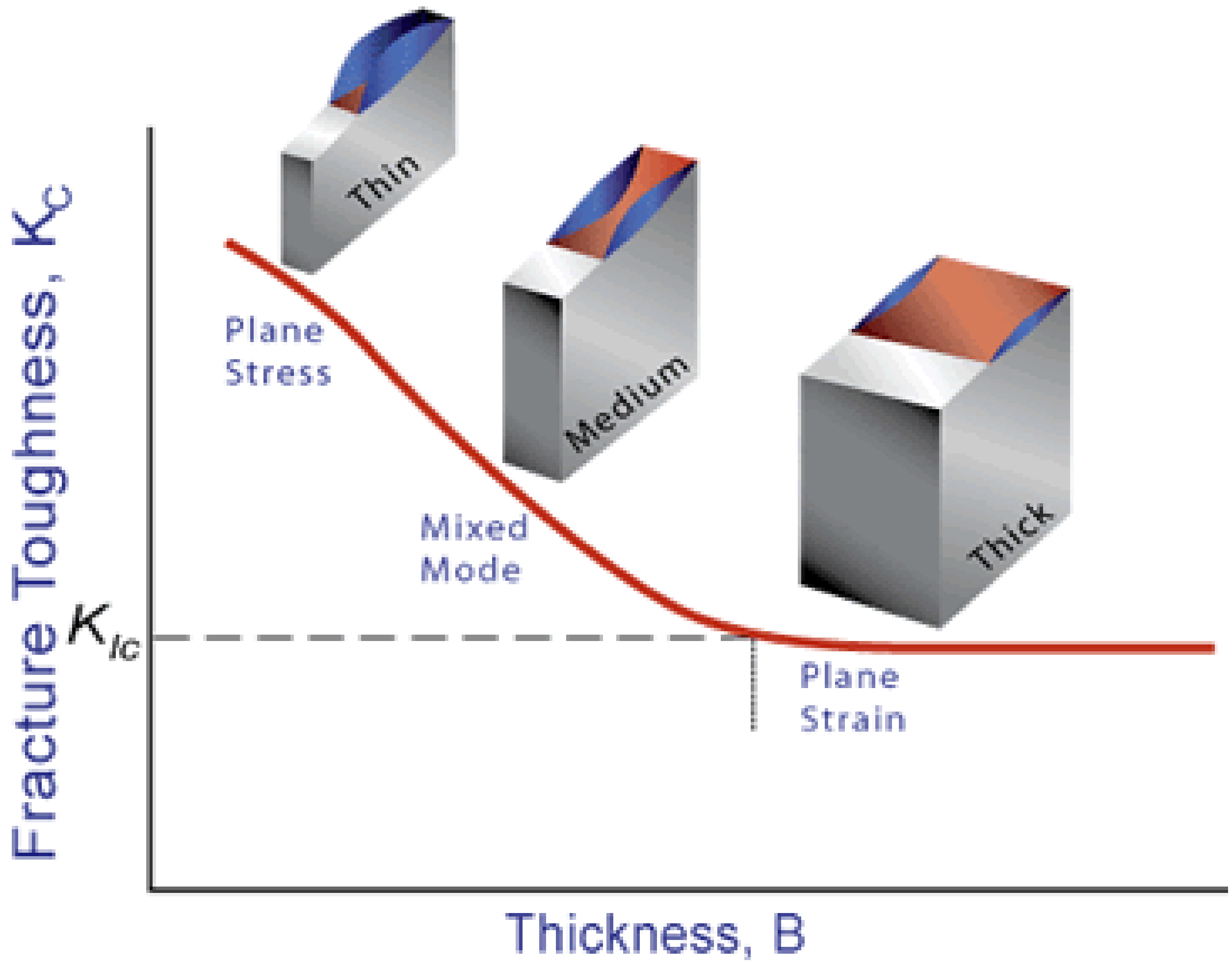
**$K_{IC}$ is used for estimation critical stress applied to a specimen with a given crack length:**

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

***Where***
***$K_{IC}$ – stress-intensity factor, measured in MPa*m½;***
***$\sigma_C$ – 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.

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

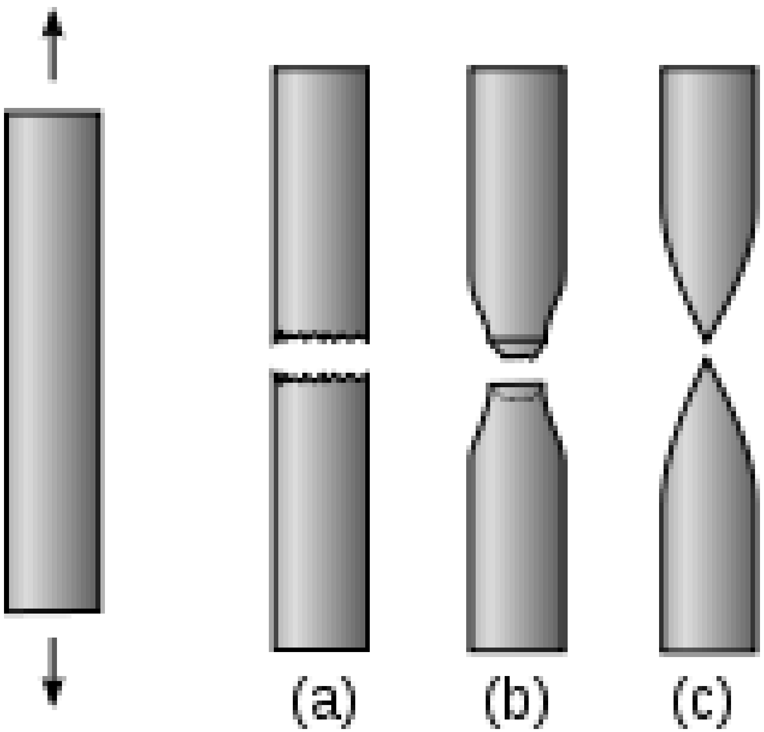
***Y: Geometry Factor***

***a: Crack Length***

# Reference Temperature $RT_{NDT}$

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

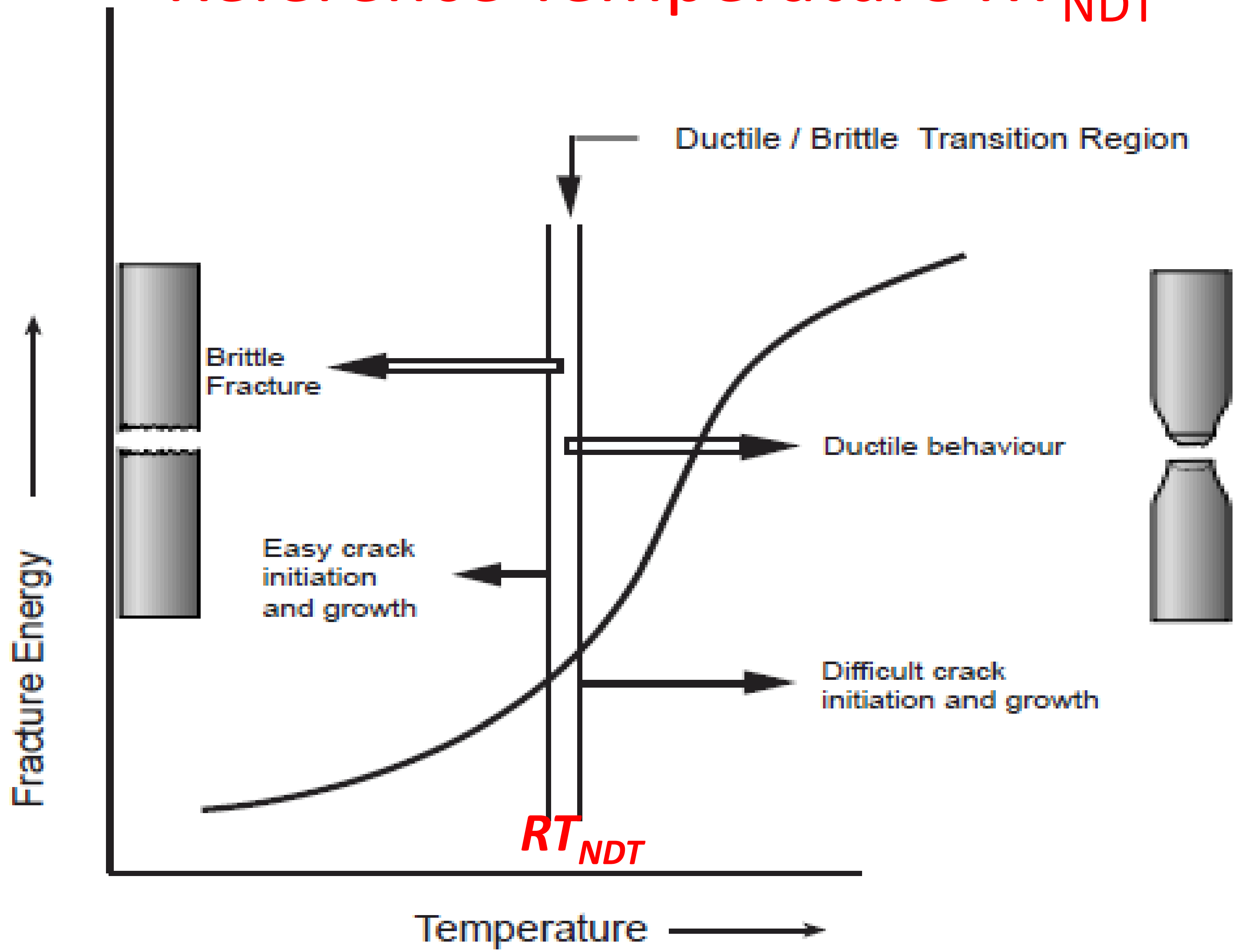
***represents the point***
***at which the fracture energy passes***
***below a pre-determined point***
***(for steels typically 40 J***
***for a standard Charpy impact test.***




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 | $5 \times 10^{18}$ | $7{,}5 \times 10^{18}$ |
| $RT_{Limit}$ | < 40°C | < 40°C |