MATERIAL ENGINEERING

Follow Up Training on Reactor Engineering and Safety)

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BIODATA

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Education

Saitama University | 1995

Mechanical Engineering, Bachelor Degree

Saitama University | 1997

Mechanical Engineering, Master Degree

Saitama University | 2001

Production Science, Doctor Degree

Field of Research

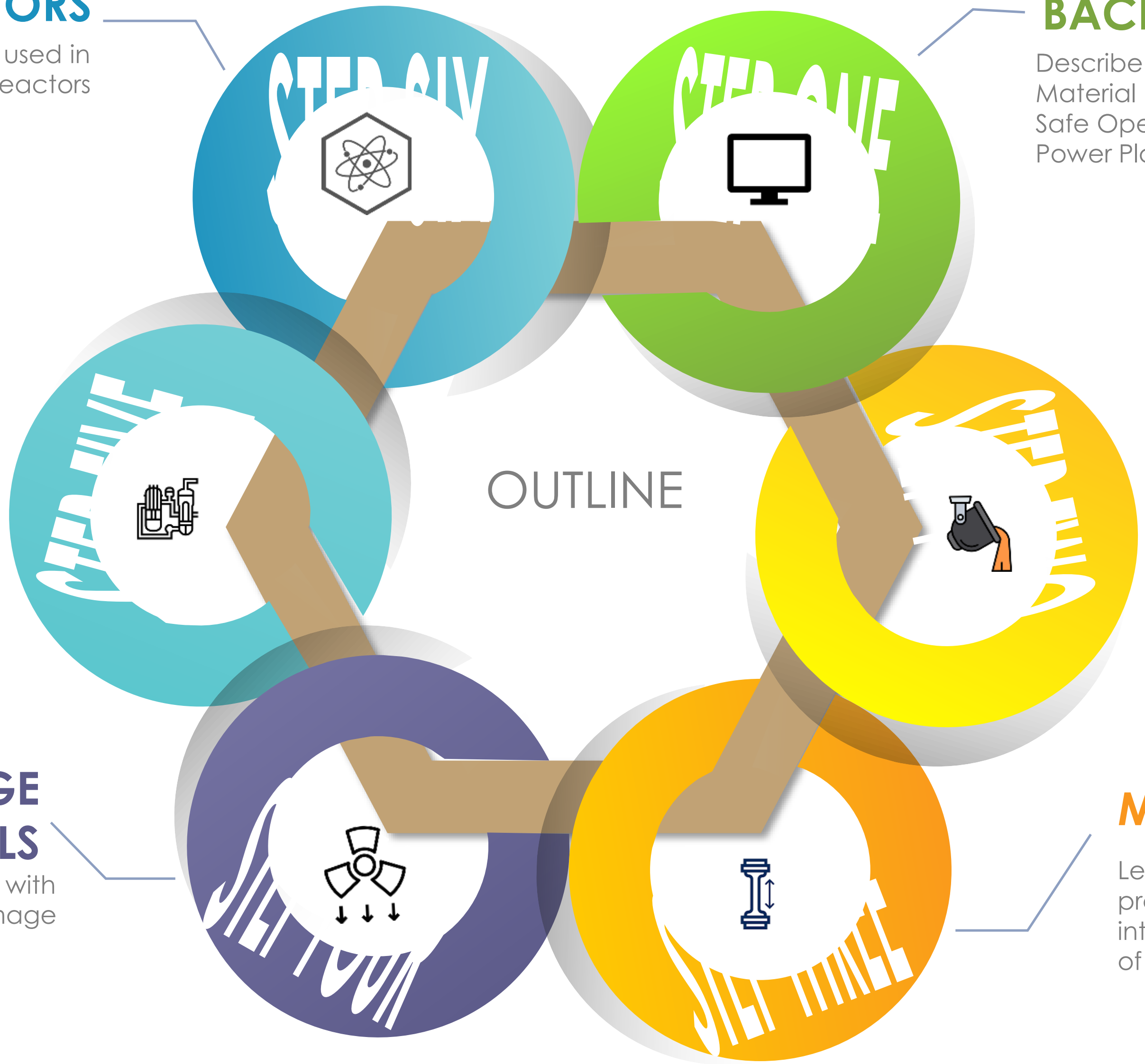
- Strength of Material
- Stress Analysis
- Non-destructive Testing (Ultrasonic Testing and Radiography Testing

Profesional

1. Professional Engineer in Nuclear Engineering
1. Ultrasonic Testing Level II
1. Ultrasonic Phased Array

Experiences

1. BATAN – JAEA Joint Research Program in the Field of Nuclear Safety
2. Feasibility Study for Development of Nuclear Reactor
3. Design Analysis of Nuclear Reactor
4. Lecturer on Mechanical Structure of NPP, Material Engineering, and Non-destructive Testing
5. Various Training of Trainer



BACKGROUND

Describe the importance of Material Engineering to Ensure Safe Operation of Nuclear Power Plant

BASIC MATERIAL/METALLURGY

Describe a basic of Material Science or Metallurgy Engineering

MECHANICAL PROPERTIES

Learning basics mechanical properties importance for integrity of mechanical structure of Nuclear Reactor

BASIC IRRADIATION DAMAGE in MATERIALS

Learning how irradiation interacts with material and resulting damage

MATERIAL for LWR

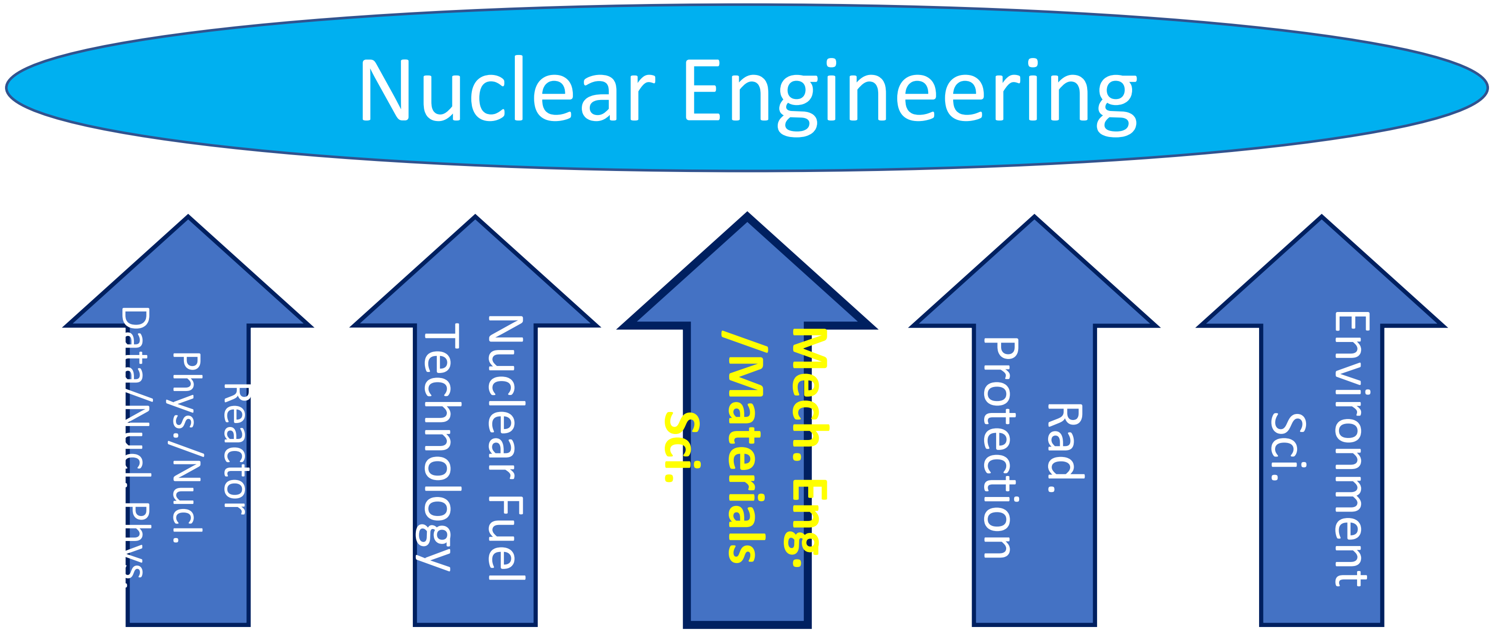
Describe types of material used in Light Water Reactor

MATERIAL for Gen-IV REACTORS

Introducing materials used in Gen-IV Reactors

I. Background

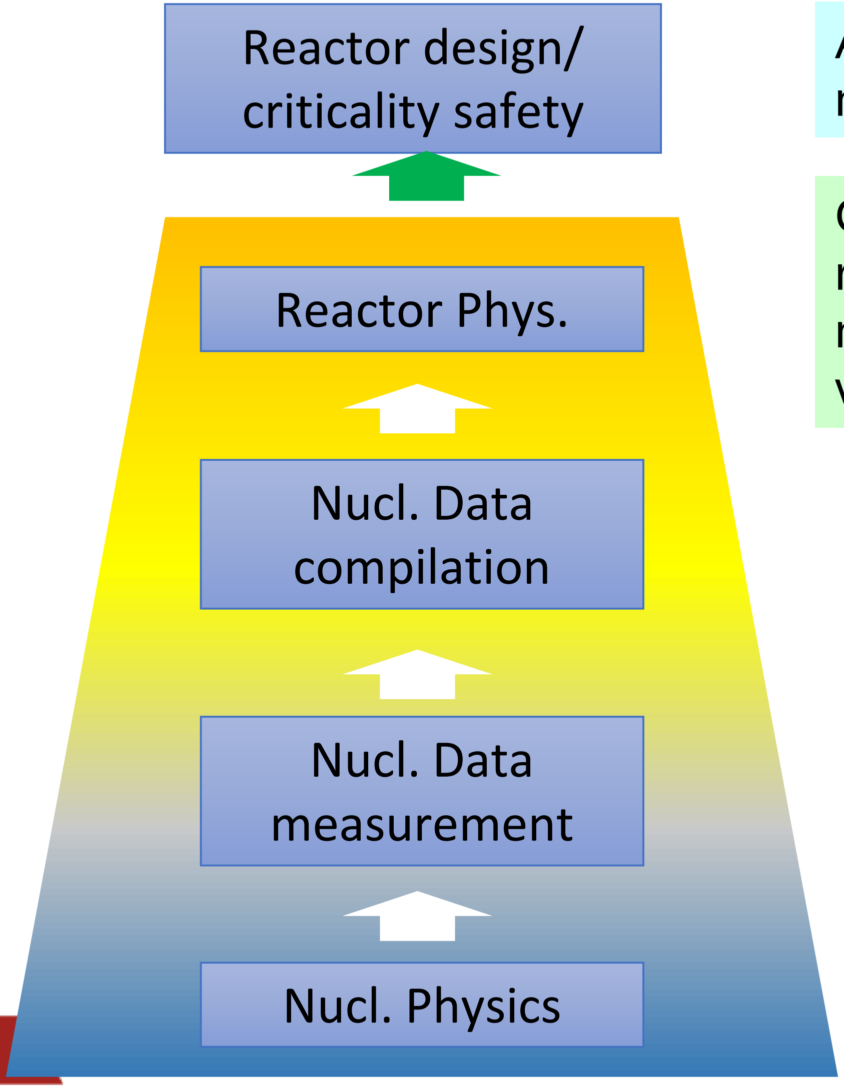
Integrated Engineering



Nuclear Engineering is supported by many fields of basic science and technology. This is relatively well-known.

Each field has a layered structure, from basic science to application engineering.

Layered structure in Nucl. Phys.



A typical layered-structure is seen in nuclear physics-reactor design field.

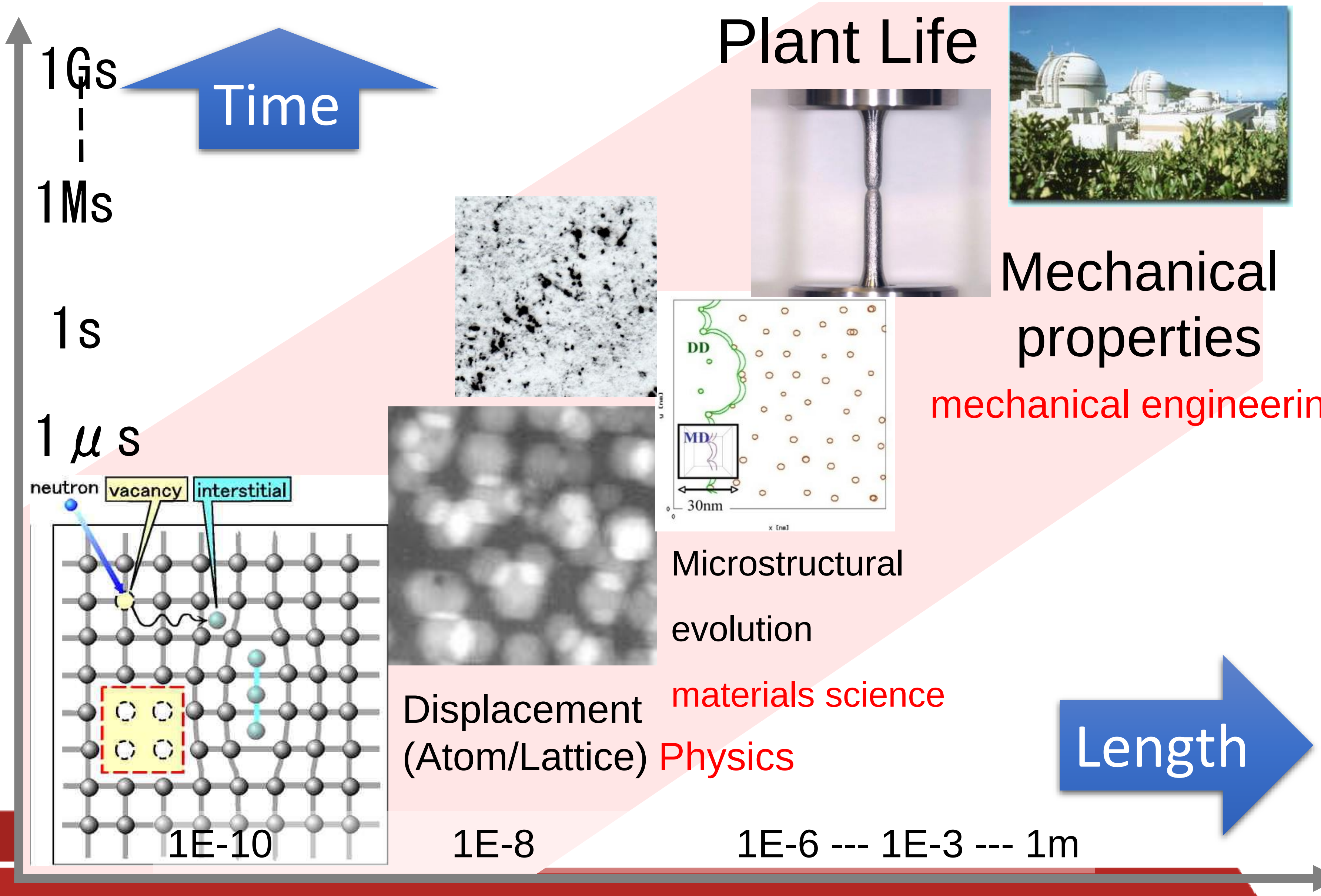
Computer codes which can evaluate chain reactions in a reactor core assembly, based on nuclear data sets and neutron transportation calculations. Experiments to verify these calculations are also included.

Measured nuclear data are insufficient in accuracy and quantity. Evaluated nuclear data sets, such as JENDL, are generated according to use requirements.

Nuclear data are engineering data and experimentally measured using reactors and accelerators.

Nuclear physics is a science which gives us a new understanding on nuclei.

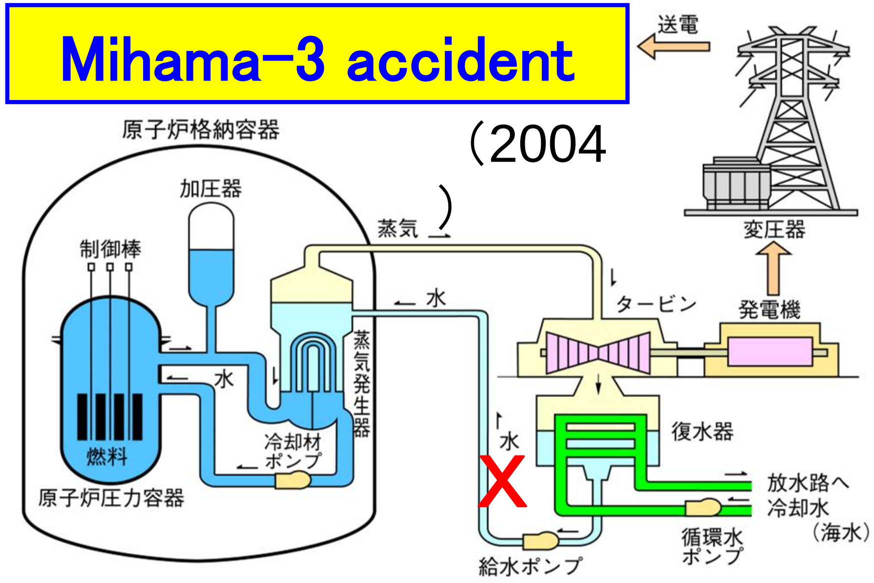
Multi-scale Modeling in nuclear materials



Accidents due to material failure

Mihama-3 accident

(2004)



The worst nuclear power plant accident before Fukushima in Japan

Rupture of a hot-water pipe in the secondary system killed five workers. The wall thickness of the pipe made of carbon steel was very thin at the time due to corrosion for 28 years service without check or replacement.

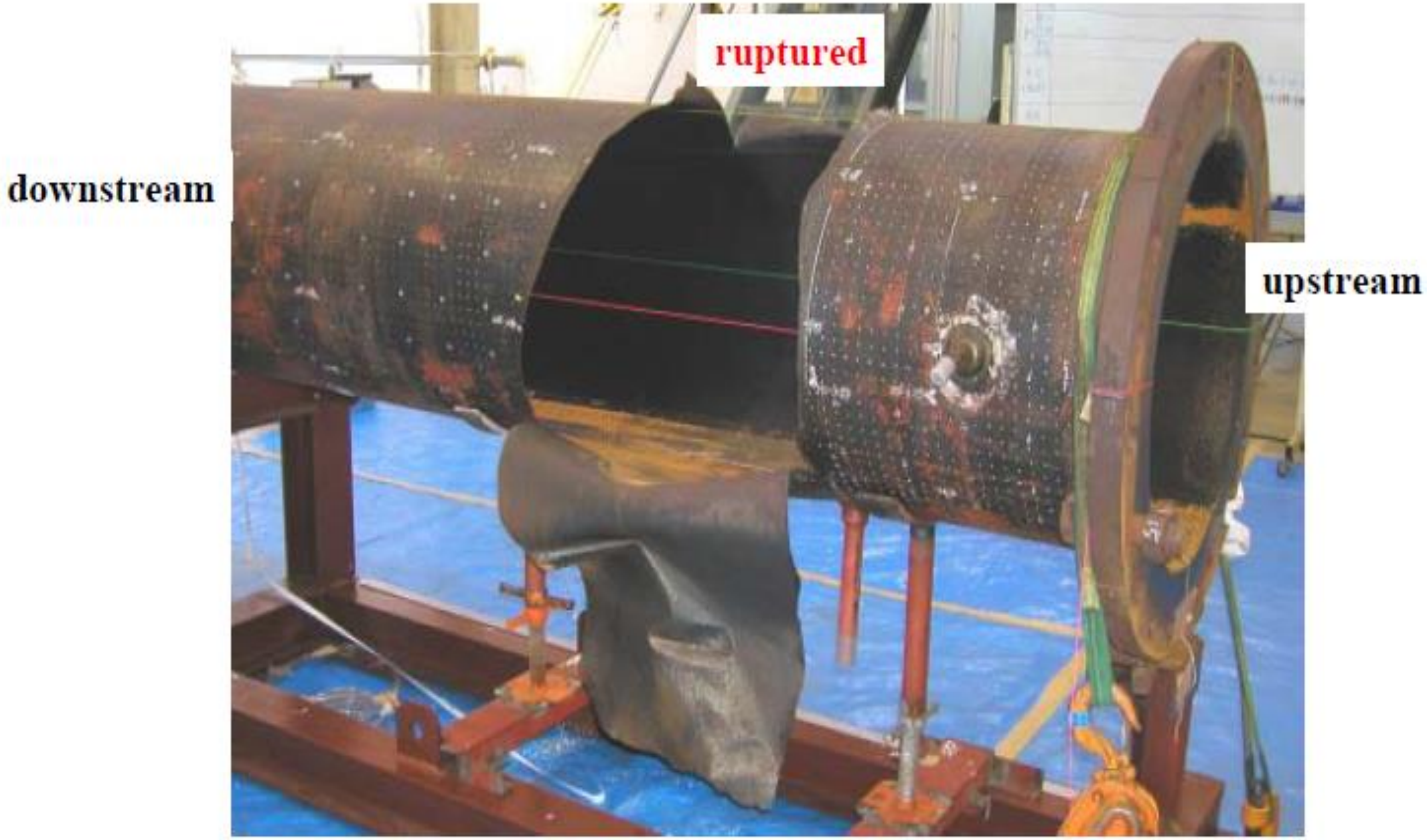
B-747 crash at Mt. Osutaka (1985)

Incorrect repair of cabin pressure wall caused fatigue fracture, resulting 520 casualities.

The secondary system of a PWR or cabin pressure wall in a airplane may not be considered as an important one, but it would cause a severe accident.

Accidents due to material failure

A photo of ruptured piping of Mihama-3



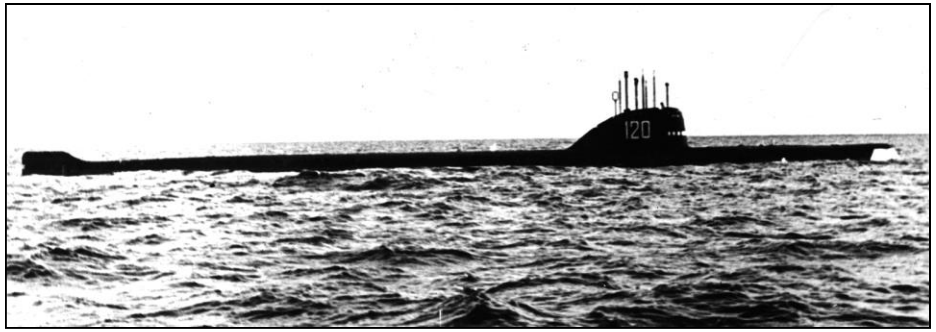
Accidents due to material failure

Critical Issues

Compatibility of cladding and structural materials with lead alloy and the inhibition of channel plugging caused by the precipitation of solid lead oxide (PbO) and precipitation of dissolved metals such as iron.

Solutions

- **High corrosion resistant materials**
- **Control of oxygen concentrations in lead alloy**



K-27 – first submarine with Pb-Bi cooled reactor

1963 – Commissioning

1968 – Accident

P.N. Martynov, et.al., The 1st COE-INES-1, Tokyo (2004)

Slag deposits in The vessel

Slag on pipeline

Slag deposits in The Heat Exchanger

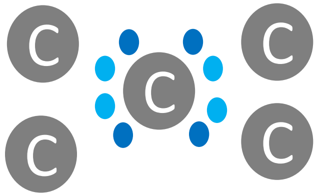
Slag deposits in recuperator tube

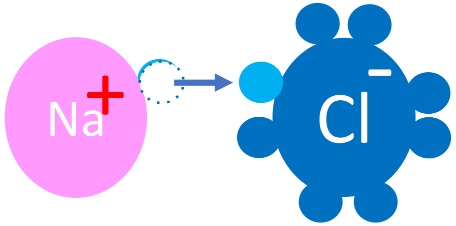
II. Basic Materials/Metallurgy

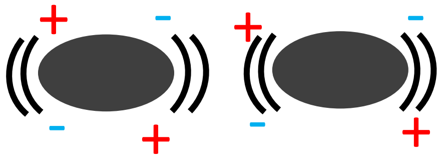
What is "metal" ?

Solid with metallic bonding

covelent bond	DIAMOND. Four valence electrons of a carbon atom forms pairs with electrons of other carbon atoms and make closed shell structure.
ionic bond	SALT (NaCl). A Na atom releases one electron and a Cl atom accepts it, making closed shell in both atoms. Na ions with + charge and Cl ions with – charge make an ionic crystal.
van der Waals bond	GRAPHITE(between layers). Fluctuating polarizations of neutral particles causes attractive force
metallic bonding	GOLD. Many atoms releasing their electrons share these electrons, forming lower energy state. Energy states of these electrons have some width (band structure).



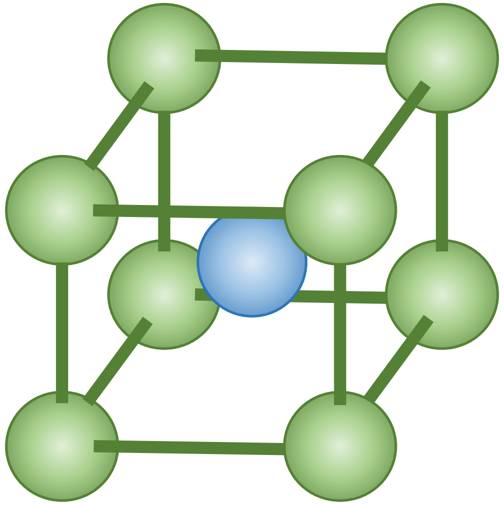




Energy state of these electrons is free , then ..

They can move in the crystal freely, and metals are electrically conductive.

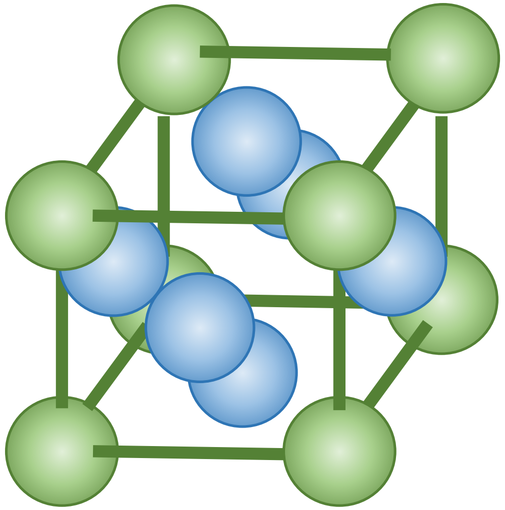
Typical crystal structure of metals



BCC

(body centered Cubic)

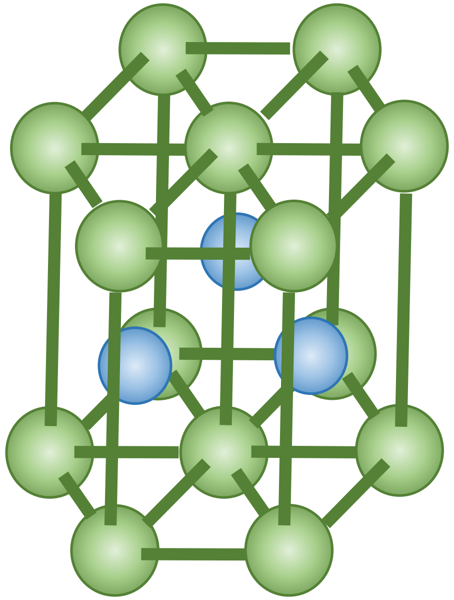
Fe(at room temperature), W, Mo, Na, K



FCC

(face centered Cubic)

Au, Ag, Cu, Ni, Al
Fe (at high temperature)
Austenitic stainless steel



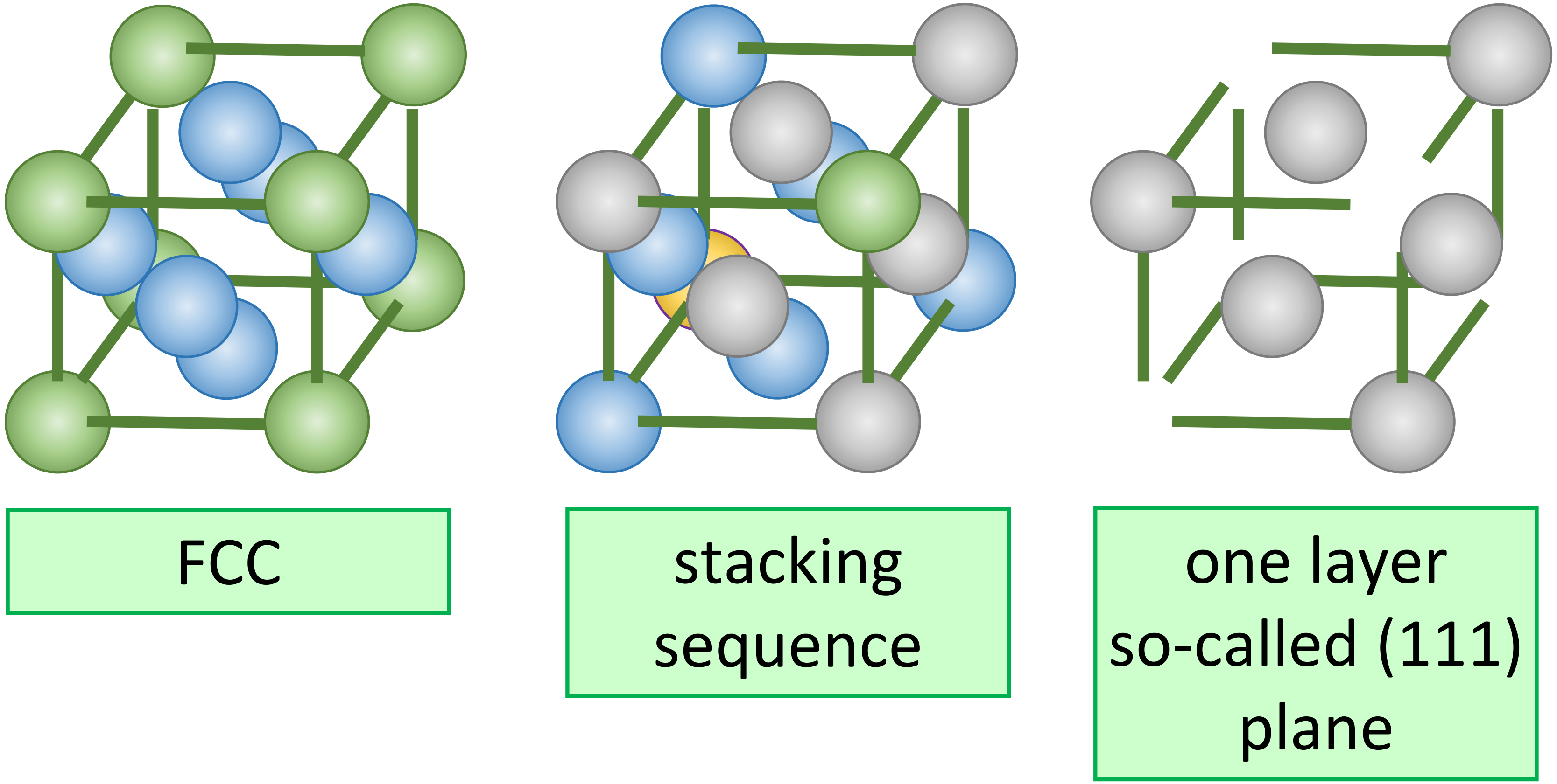
HCP

(hexagonal close packed)

Zn, Mg, Be

Note: Difference in color is just for explanation.

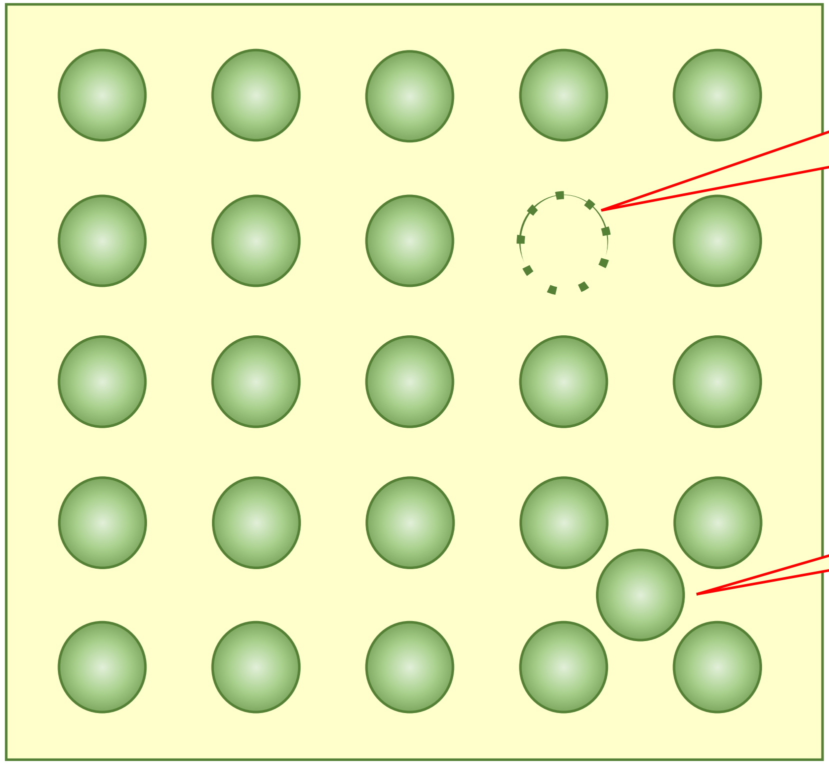
FCC: Combination of triangle makes...



Basic structure of FCC is a tetrahedron, or triangles. Their combination makes a cubic.

Crystalline defects : point defect

This is a perfect crystal.



A lattice site without the atom is called as a vacancy.

An extra atom locating among other atoms in normal lattice site is called an interstitial atom.

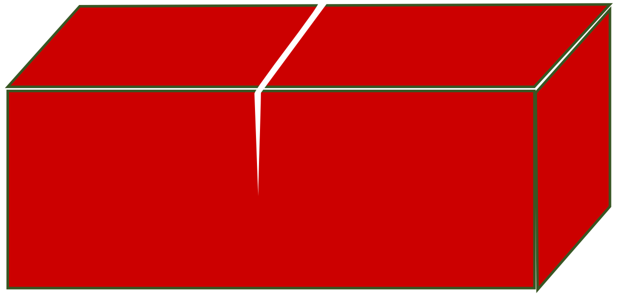
This is not a perfect crystal, including crystalline defects.

Vacancies and interstitial atoms are called point defects.

Line defect : dislocation 1: edge type

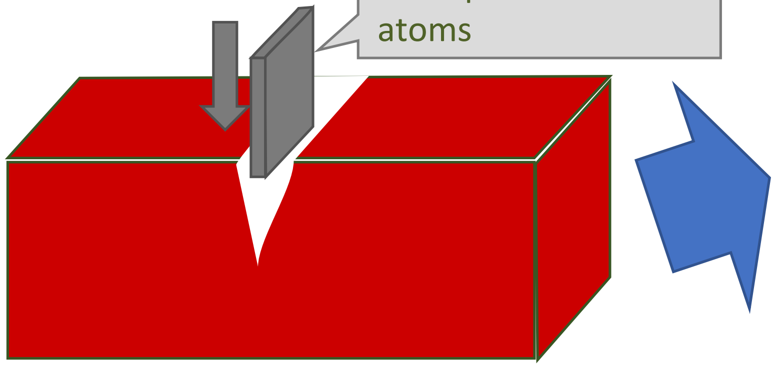
Imagine that ....

A cheese bar



with a slit

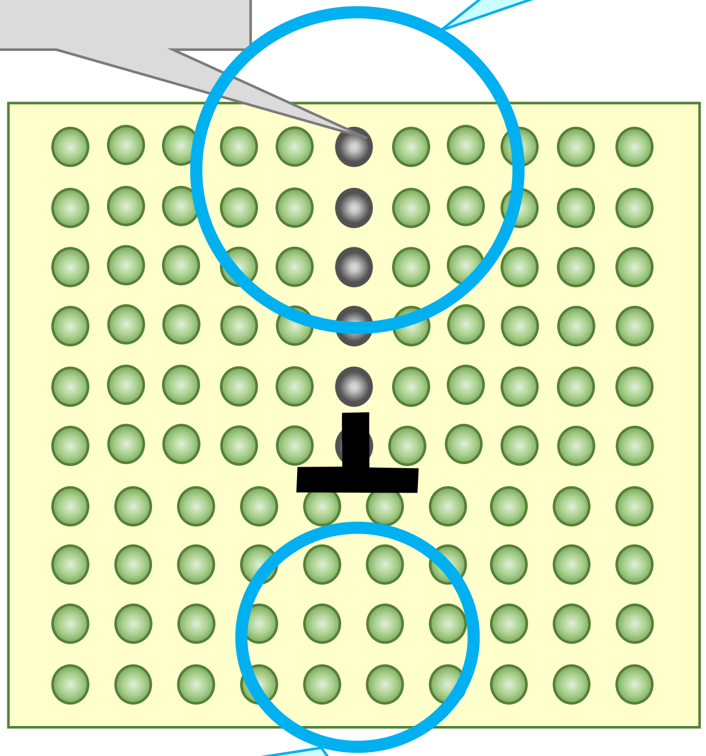
extra plane of same atoms



insertion of another cheese slice into the slit.

Difference in color is just for explanation. Orange and green atoms are of same element.

This area is also perfect crystal.

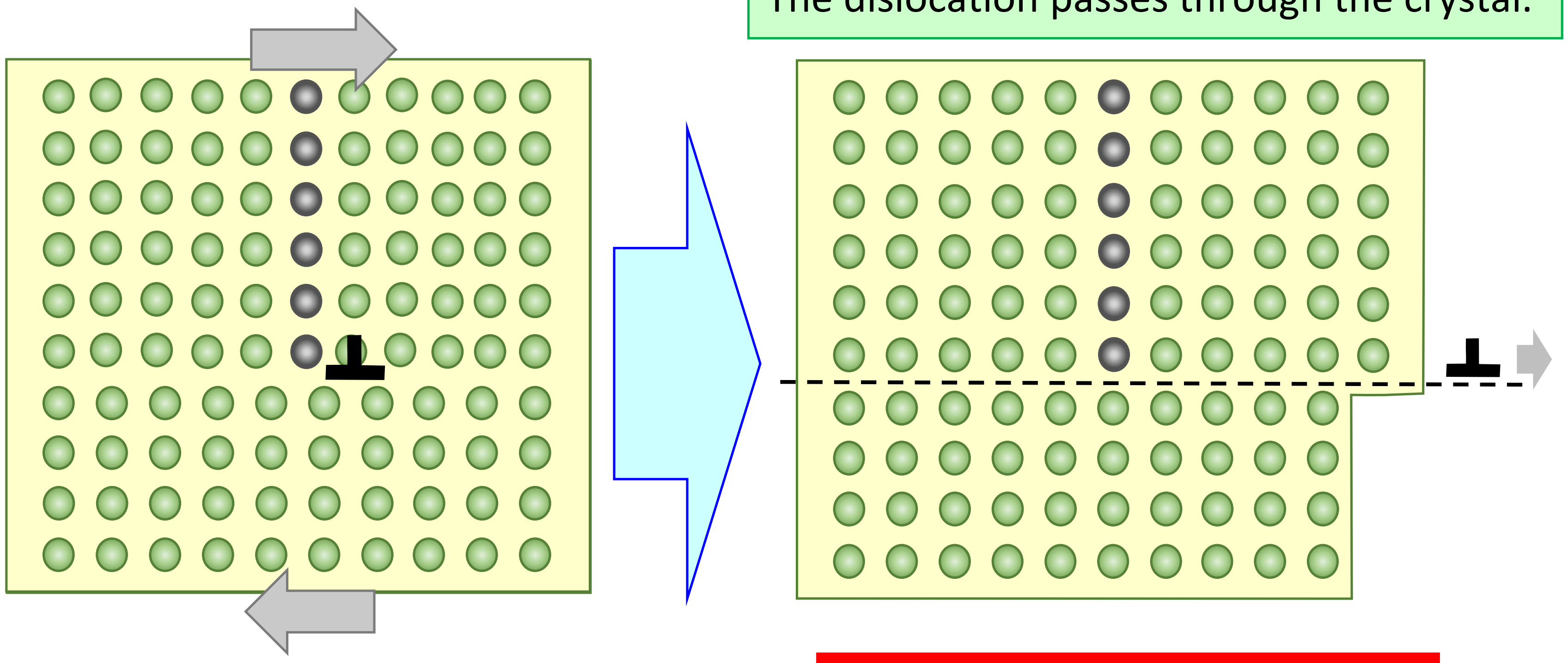


This area is perfect crystal

Cross-section of the crystal including edge dislocation.

Micro deformation due to dislocation glide

The dislocation passes through the crystal.



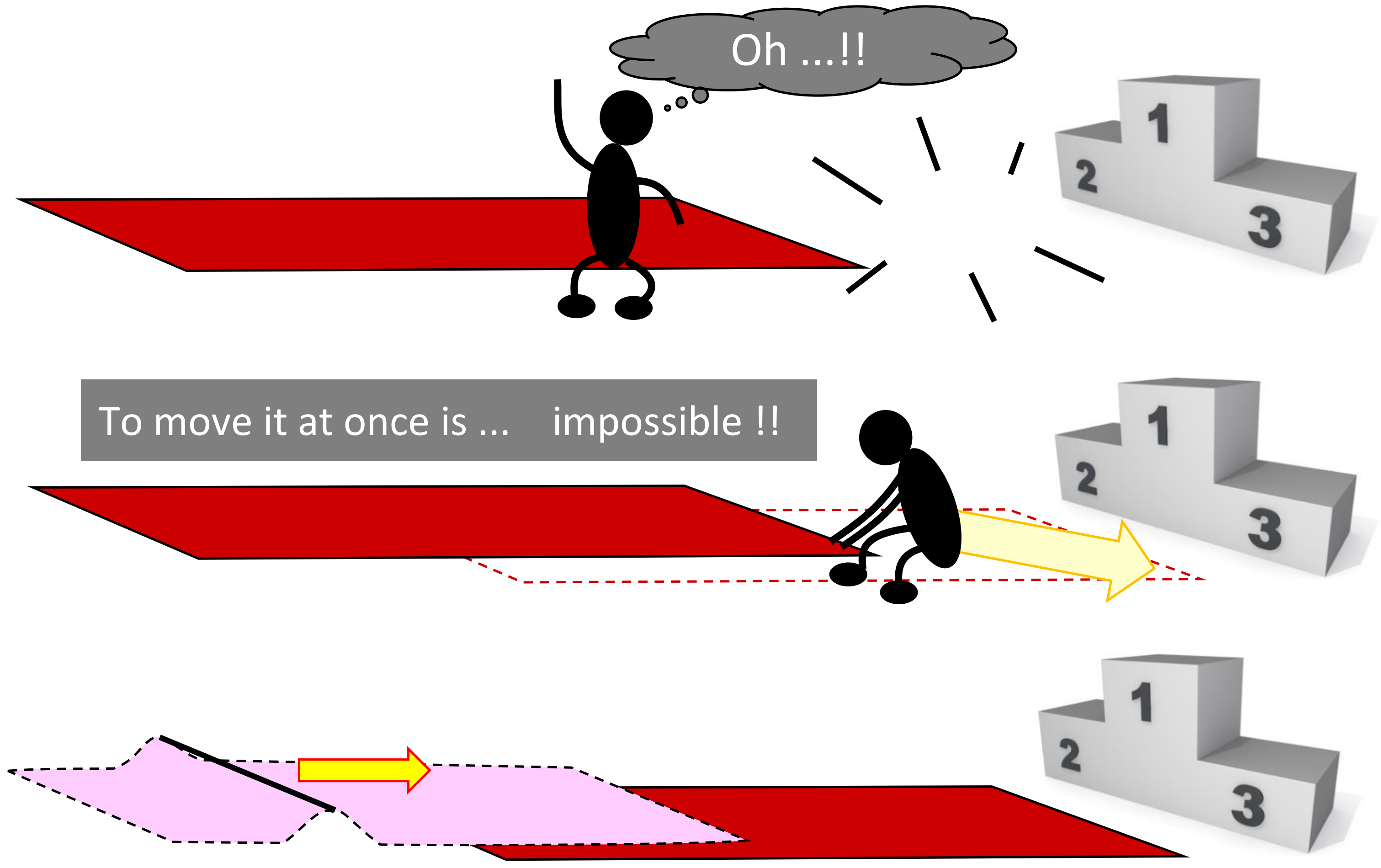
If we apply share force to a crystal including an edge dislocation, then, ...

plastic deformation due to dislocation glide

Due to its the nature of metallic bonding, dislocations can glide easily and metals are thus ductile.

Moving a carpet by the dislocation glide

How will you move and relocate a long heavy carpet ?

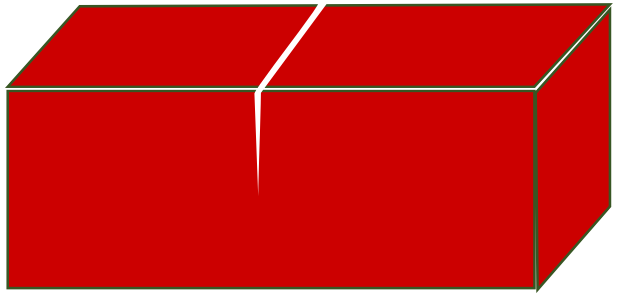


Repeated movement of small wrinkles can make a large advance.

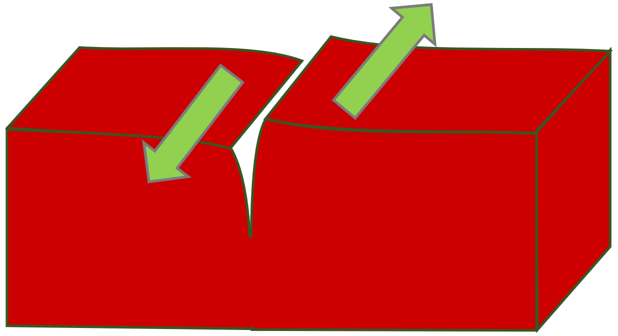
Another type: screw dislocation

Imagine that

A cheese bar ...

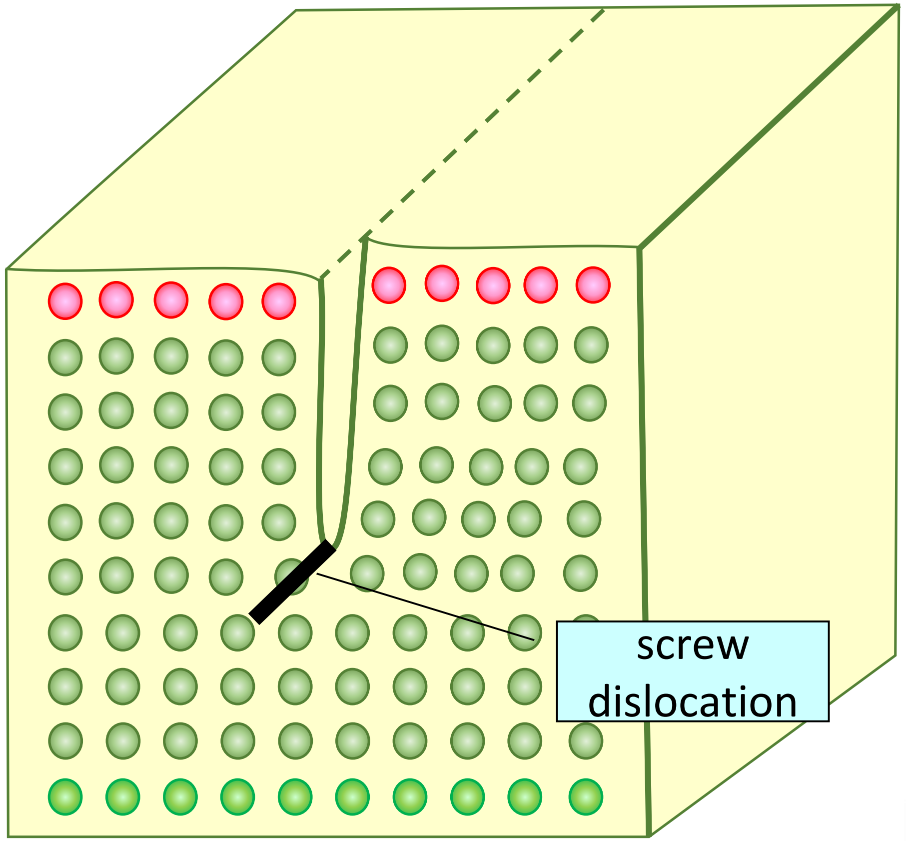


with a slit.



twist and re-conect

This is very difficult to understand this completely and I think it is enough to know the name, screw dislocation and its practical importance in deformation mechanism.



III. Mechanical Properties

Introduction

- When we control materials' deformation and failure, we must control stress, strain, stress concentration, stress intensity, temperature, loading modes, and environment.

Stress and Strain

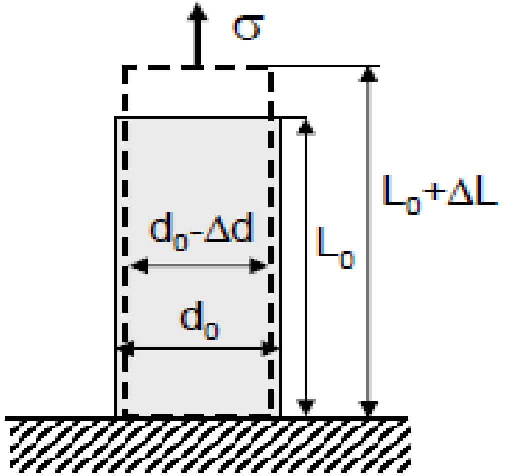
Any force or load applied on the material will result in stress and strain in the material. Stress represents the intensity of the reaction force at any point in the body as imposed by service loads, assembly condition, fabrication, and thermal changes. Stress is measured as the force acting per unit area of a plane.

$$\sigma(stress) = \frac{Force}{Area}$$

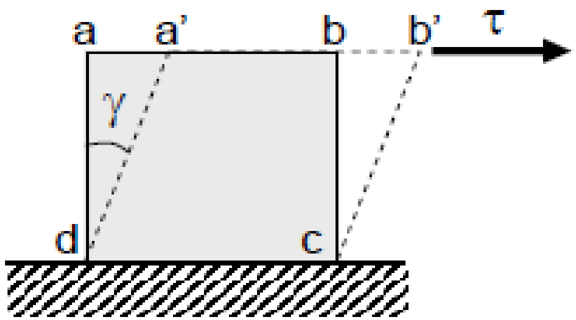
The alternation in the shape or deformations of a body resulting from stress is called strain. Tensile strain is expressed as elongation per unit length

$$\varepsilon(strain) = \frac{L - L_0}{L_0}$$

where L and L_0 is length after and before deformation, respectively.



Tensile strain



Shear strain, γ=aa'/ad

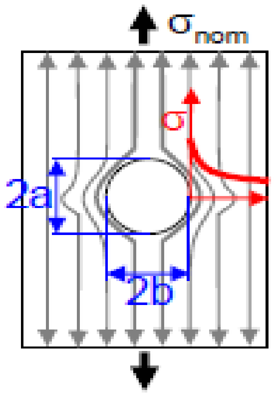
Introduction

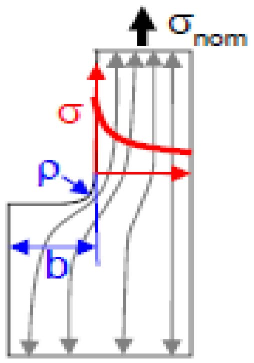
In structures, geometrical discontinuities, fillets and notches, and cracks in particular, give rise to a stress concentration, i.e. a local region where the stresses are higher than the nominal or average stress.

Stress concentration

At blunt notch (instead of a sharp cut), every discontinuities forms an interruption of load flow lines. (load low lines are imaginary lines indicating how one unit of load is transferred from one loading point to the other.) Local stress at a notch tip σ_l is higher than the nominal stress σ_{nom}. The ratio between local stress and nominal stress is called the theoretical stress concentration factor.

$$k = \frac{\sigma_l}{\sigma_{nom}} = 1 + 2\frac{b}{a} = 1 + 2\sqrt{\frac{b}{\rho}}$$



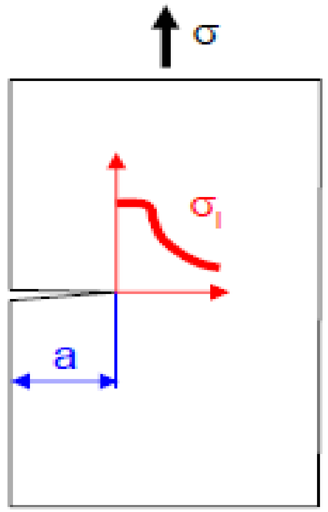


Stress intensity

The concept of stress concentration dose not provide a quantitative measure. Stress intensity factor, K, gives us the value of the stress intensity at tip of the crack, which remains constant for particular environmental conditions and geometry of a crack. The value of K is defined in general form as

$$K = C\sigma\sqrt{\pi a}$$

where C is shape factor which depends on the geometry and variety of conditions, a is the half-length of the crack.

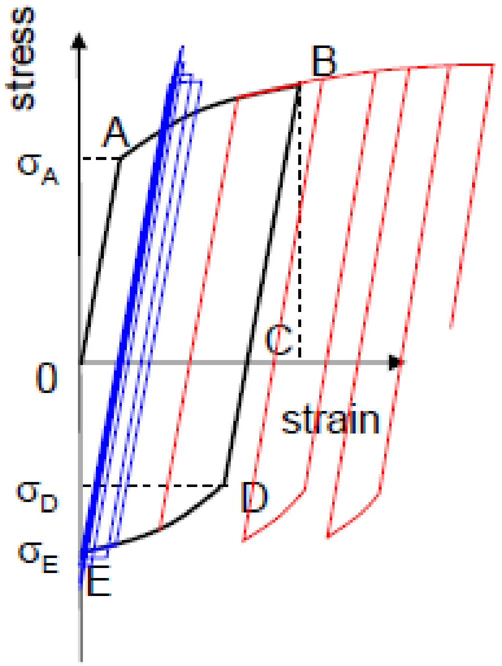


Failure Modes and Mechanism (1)

Metals can deform elastically and plastically.

(1) Elastic deformation
Hook's Law: $\sigma = E\varepsilon$, E: young modulus

(2) Plastic deformation
Plastic deformation occurs either by slip or by twining. (mainly by slip)
Slip occurs due to formation and moving of dislocation.
(Dislocation is imperfect arrangement of atoms.)
The force required to move a dislocation are many times smaller than those required to exceed the elastic limit of a perfect crystal.
Nonrecoverable deformation occur after removal of the stress.
Bauschinger effect: $|\sigma_A| > |\sigma_D|$
Residual stress, σ_E, exists after deformation to zero strain.



(3) Creep deformation (flow)
The slow and progressive deformation of a material with time under a constant stress.
Creep occurs if the stress is smaller than the elastic limit. Metals usually exhibit creep at a temperature T>0.35 Tm (Tm is the melting point), where the moving of dislocation is thermally activated.

(4) Cyclic deformation
When alternating (cyclic) stress or strain are loaded, usually stress-strain behavior shows

Failure Modes and Mechanism (2)

Metals fail in a ductile or a brittle manner.

(1) Ductile fracture

In macroscopic scale, material deforms plastically before it fractures. For example, strain to fracture is larger than 5%.

Burst, Ductile rupture, local distortion

(2) Incremental collapse

By combination of cyclic primary and secondary stresses, plastic deformation accumulates progressively.

primary stress ~ load-controlled stress (pressure, empty weight)

secondary stress ~ strain-controlled stress (thermal strain)

(3) Fatigue fracture

Material fails with ductile fracture surface, but the macroscopic deformation is too small.

Pressure and thermal stress change at normal reactor start-up and shut down, scrum etc..

Thermal striping, Earthquake, Fluid vibration, High cycle pressure wave caused by cavitations.

(4) Buckling

buckling is a failure mode characterized by a sudden failure of a structural member subjected to high compressive stresses, where the actual compressive stresses at failure are smaller than the ultimate compressive stresses that the material is capable of with standing. This mode of failure is also described as failure due to elastic instability.

(5) Brittle fracture

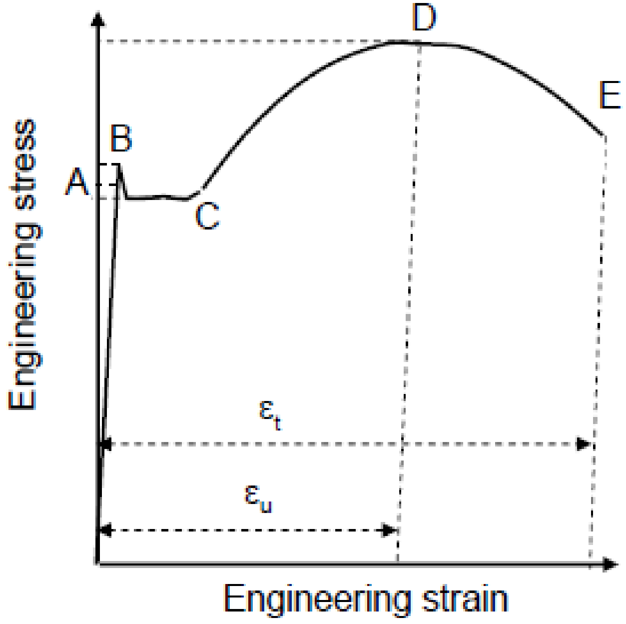
Material show little deformation before it fractures.

Cleavage fracture, intergranular fracture (creep, SCC)

Short Term Mechanical Properties

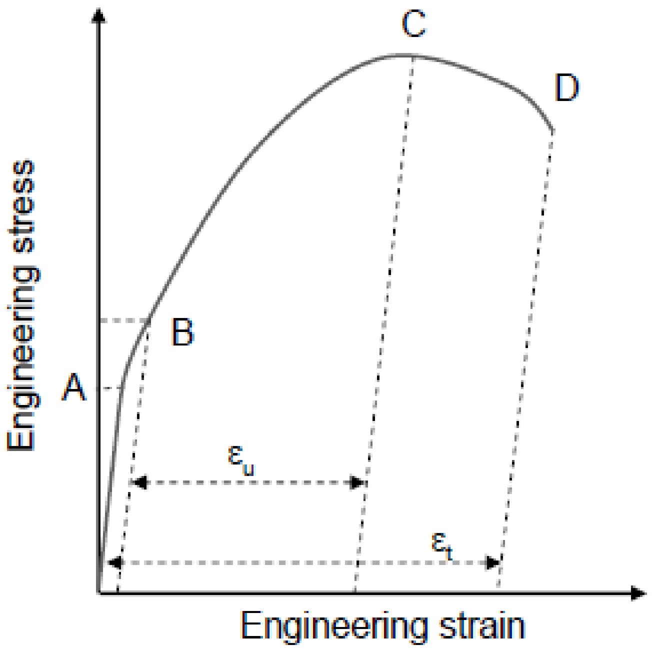
(1) Tensile properties

The ability of a material to resist breaking under tensile stress is one of the most important and widely measured properties of materials used in structural applications.



A: Elastic limit, B: Upper yield stress
C: Lower yield stress (σ_y), D: Ultimate tensile strength (UTS)
E: Fracture

Body-Centered Cubic (BCC) metal
(Low carbon steel, mild steel, low alloy steel, Martensitic steel)

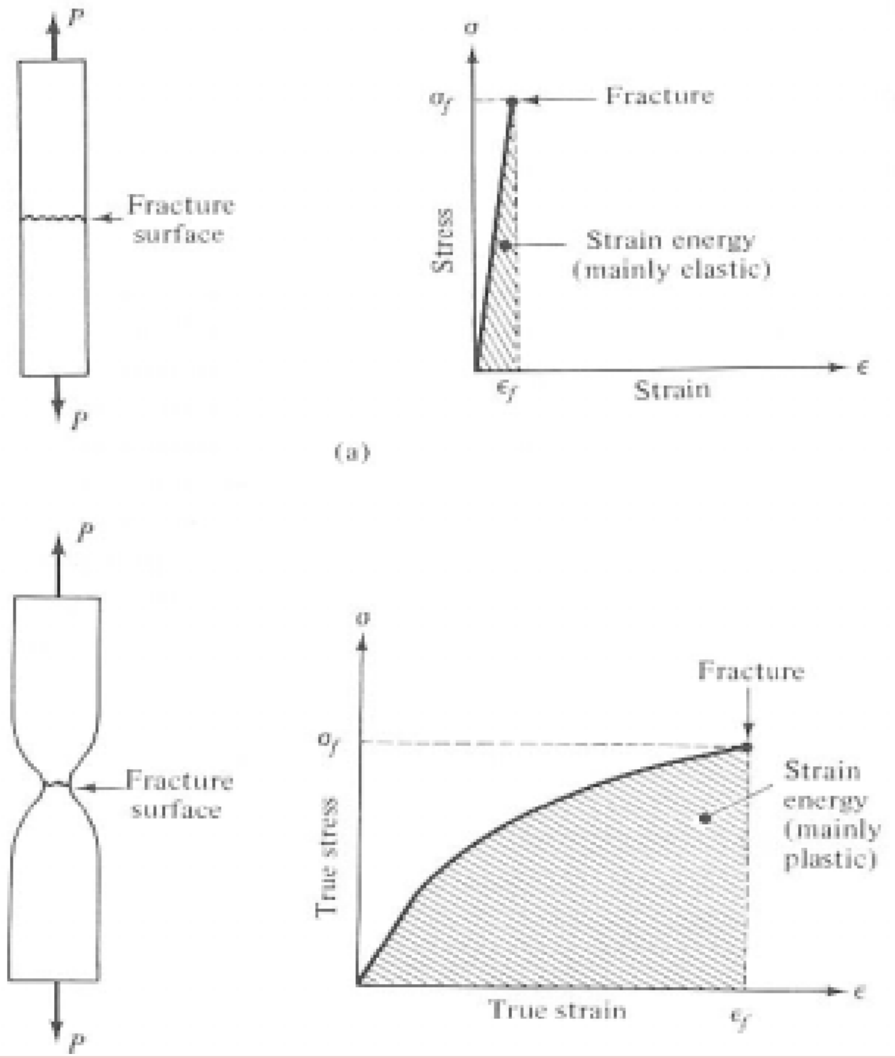


A: Elastic limit, B: 0.2% offset stress ($\sigma_{0.2}$)
C: Ultimate tensile strength (UTS), D: Fracture

Face-Centered Cubic (FCC) metal
(Austenitic steel, Ni-base alloy, Cu alloy)

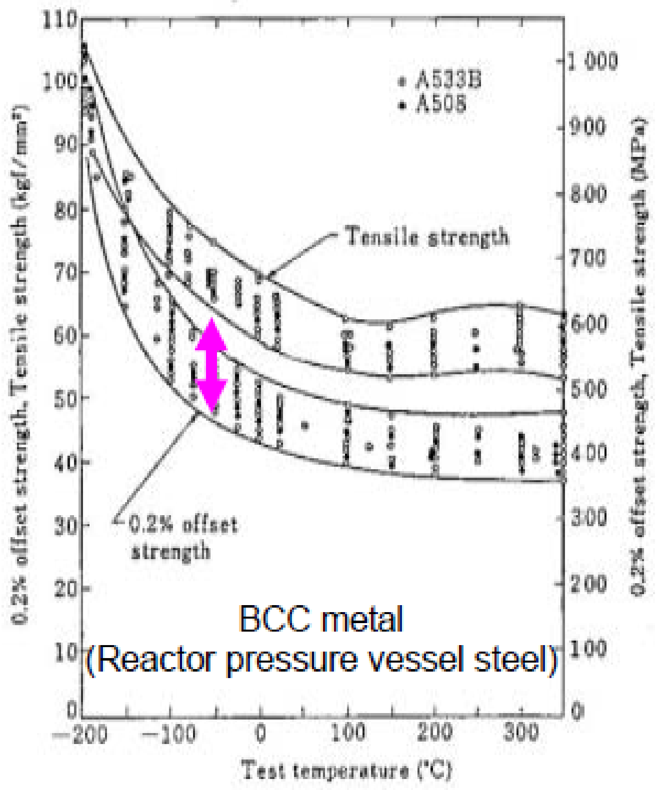
Short Term Mechanical Properties

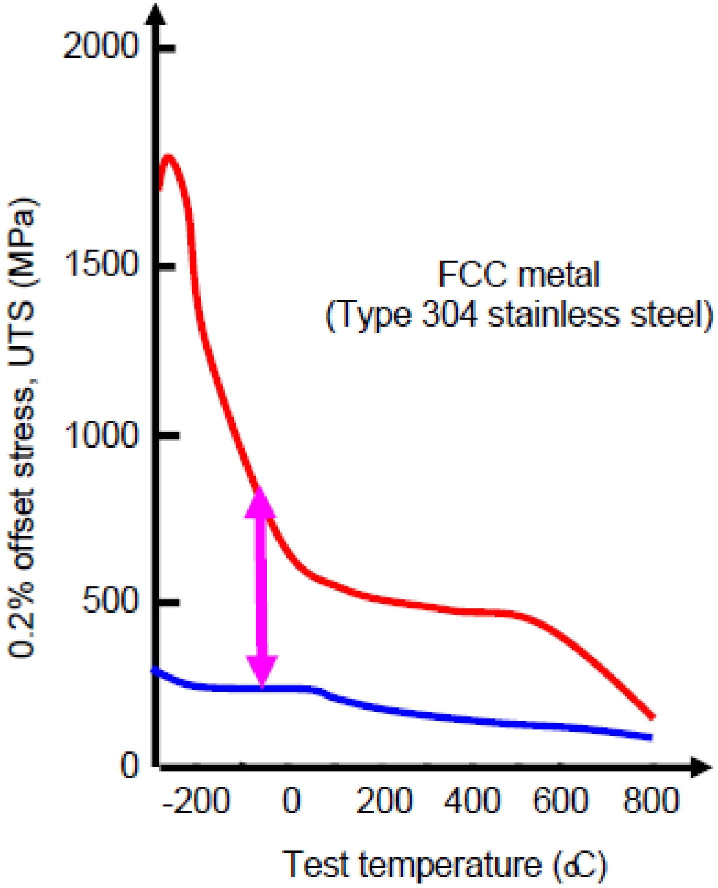
Ductile manner and Brittle manner



Short Term Mechanical Properties

Temperature dependence



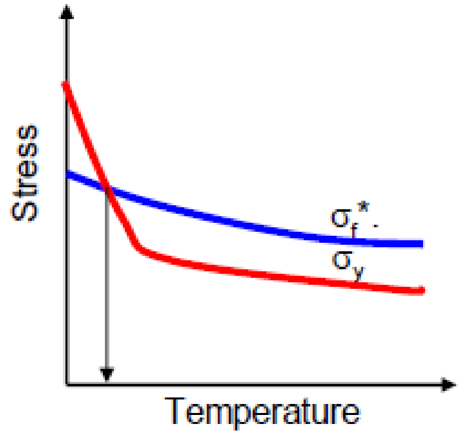


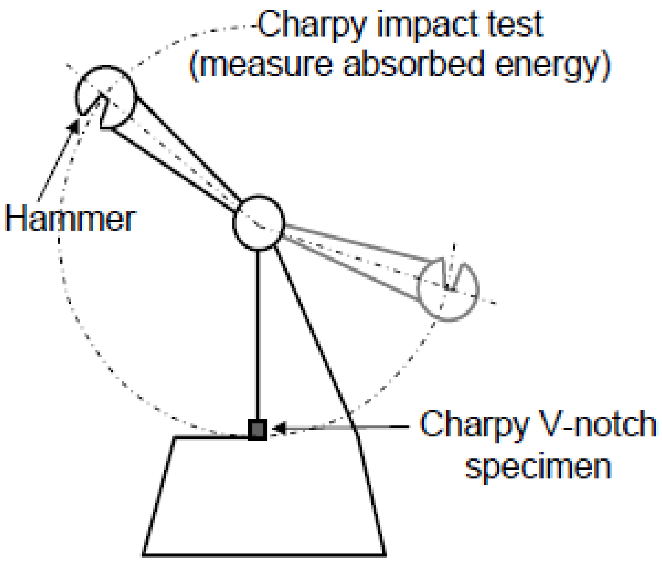
At low temperature, the difference between 0.2% offset stress and UTS is small in BCC metal. This affects impact property.

Short Term Mechanical Properties

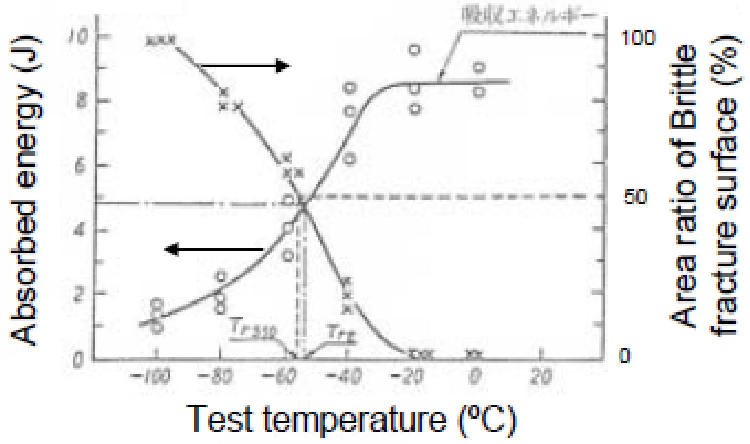
(2) Impact property

BCC metals fail by cleavage fracture at low temperatures. In cleavage fracture, the metal separates along crystal planes within the metal when the applied stress exceeds some critical value (the critical cleavage fracture stress: σ_f^*). Usually yield stress has a large temperature dependency. At sufficiently low temperature, the yield stress rises above the cleavage stress, so that failure occurs before there is significant plastic deformation. Precipitation hardening, cold work, or neutron irradiation increases σ_y, while σ_f^* decreases with increasing grain size.





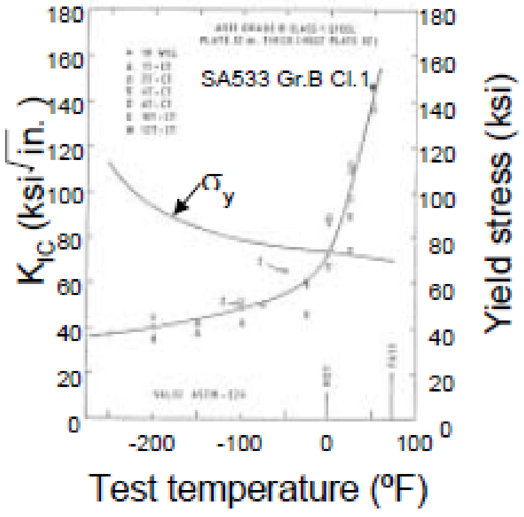
Parameter:
- nil-ductile transition temperature (T_{NDT})
- ductile-to-brittle transition temperature (DBTT)
- 50% fracture appearance transition temperature (50%FATT)
- upper shelf energy (USE)



Short Term Mechanical Properties

(3) Fracture toughness

Fracture processes are enhances by the presence of cracks since they concentrate stress and strain at the crack tip. Fracture mechanics is concerned with a description of stress and strain distribution at crack tips and the mechanism of crack propagation. Thus, fracture mechanics provides a basis for predicting conditions that could lead to component failure and which should be avoided.

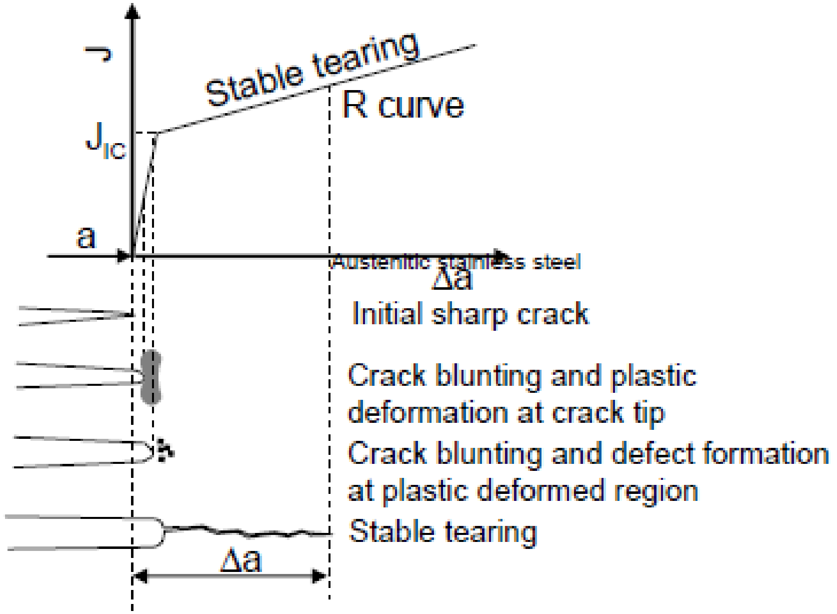


Linear elastic fracture mechanics: stress intensity factor K

When the stress intensity factor is larger than K_{IC} at crack tip, material fails in a brittle manner.

Elastic-plastic fracture mechanics: J-integral J

When the J-integral is larger than JIC at crack tip, cracks propagate in a ductile manner.



Fatigue Property

(1) Fatigue life

At temperature range from RT to 350ºC, there is little difference on fatigue lives.

Langer equation

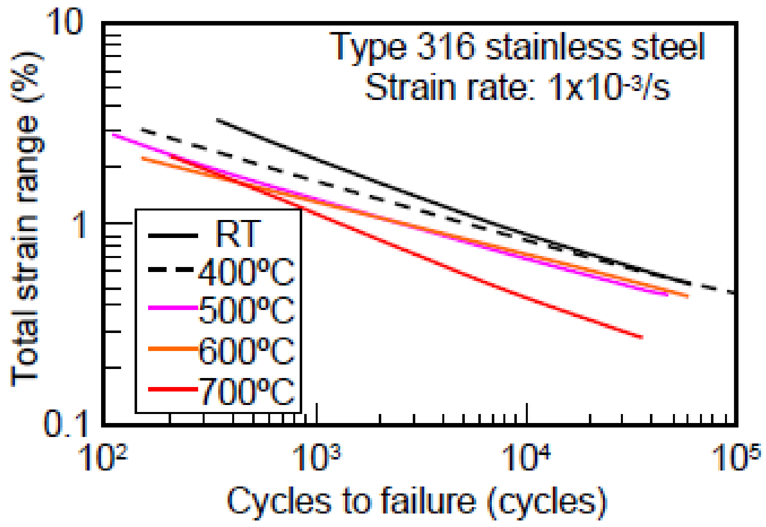
$$S_a = \frac{E}{4\sqrt{N_f}} \ln \frac{1}{1-RA} + B$$

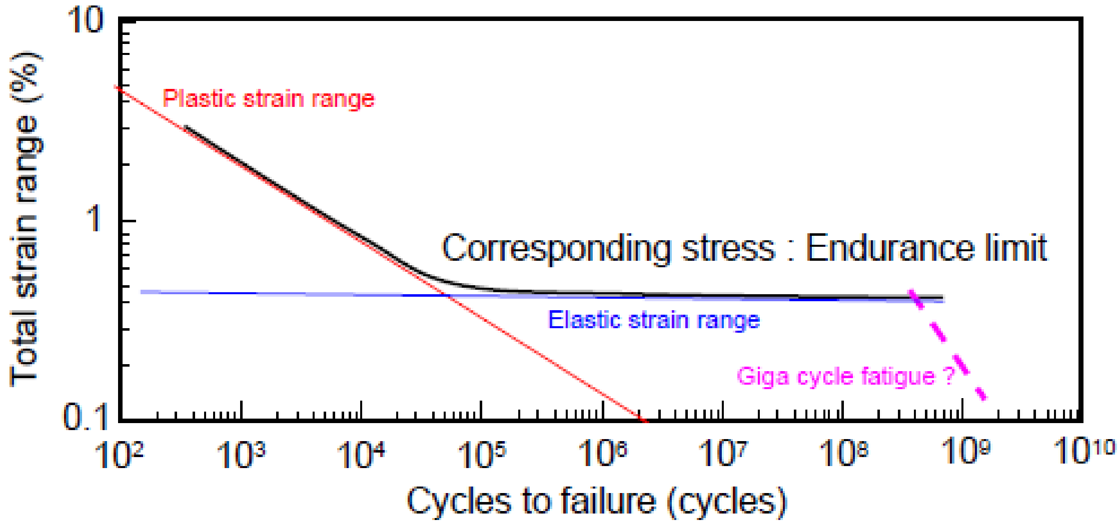
Universal slopes equation

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_{elastic}}{2} + \frac{\Delta\varepsilon_{plastic}}{2} = 3.5\frac{\sigma_{UTS}}{E} N_f^{-0.12} + D^{0.6} N_f^{-0.6}$$

$$D = -\ln(1-RA)$$

RA : reduction of area





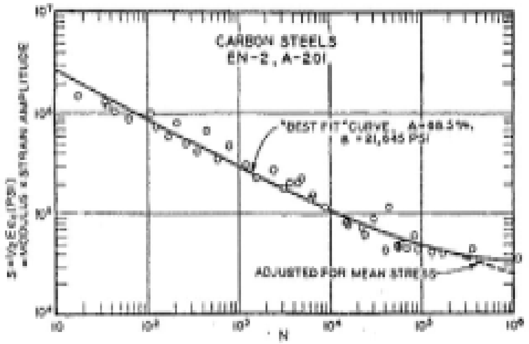
Fatigue Property

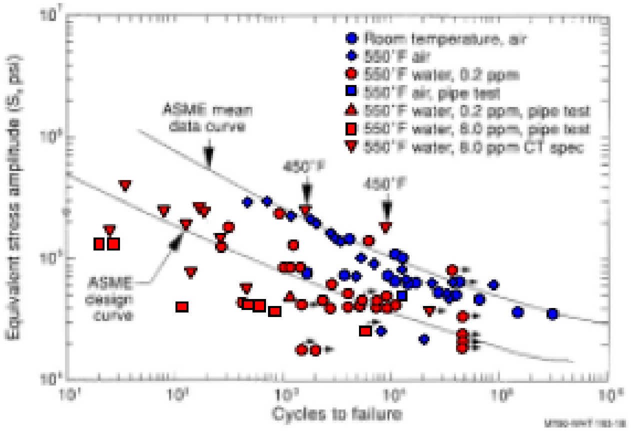
Design for Fatigue

The class 1 plant design analyses have considered the well-defined thermal transients such as plant startup and shutdown. (low cycle fatigue)

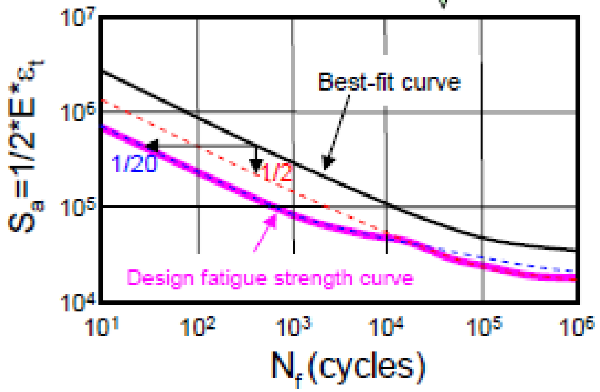
The turbulence in the mixing layer at the interface between the hot and cold coolant layer introduces cyclic thermal stress at the inside surface of the pipe in the vicinity of the mixing layer. (high cycle fatigue)

Best-fit curve by Langer equation





Environmental effects



Sa: pesudo-stress ampitude

A least-squares curve was fitted through the data, and a factor of 2 on stress or 20 on cycles, whichever was more conservative for a given point, was used to establish the design curve.

A factor of 20 is divided to sub factors.

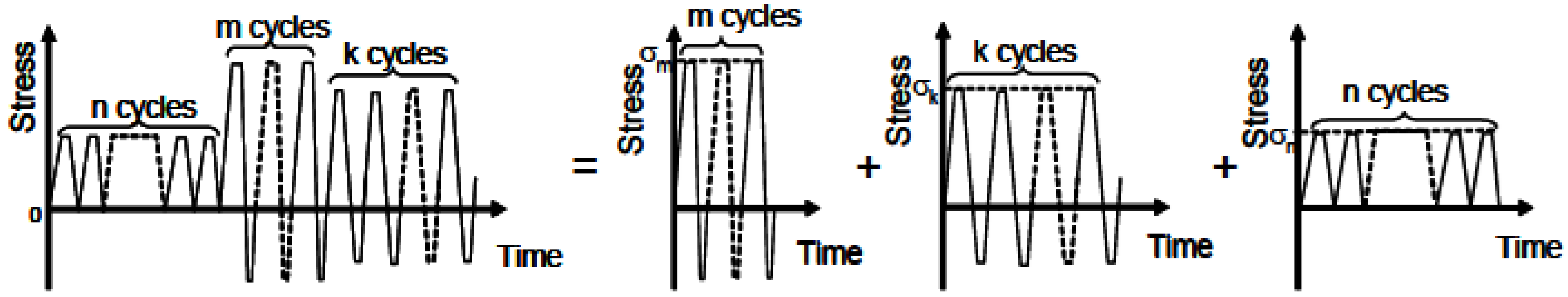
- deviation of fatigue lives : 2
- size effect : 2.5
- circumstantial effect, surface roughness : 4

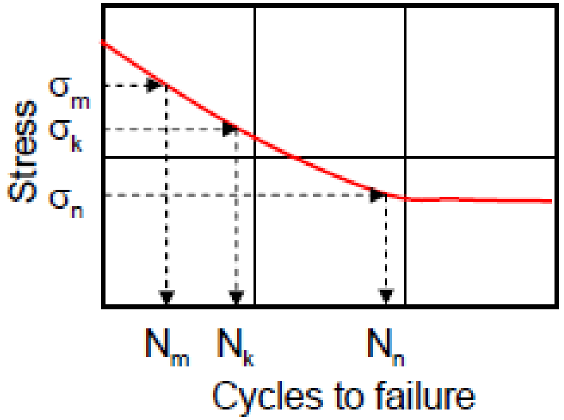
Fatigue Property

Fatigue damage evaluation

In Most real service application, the type of controlled stress fluctuations evident in laboratory experiments dose not exist. Instead a given stress level may prevail for a certain number of cycles, a different level for another number of cycles, and so forth.

Palmgren-Minor cumulative damage theory, or Minor's rule





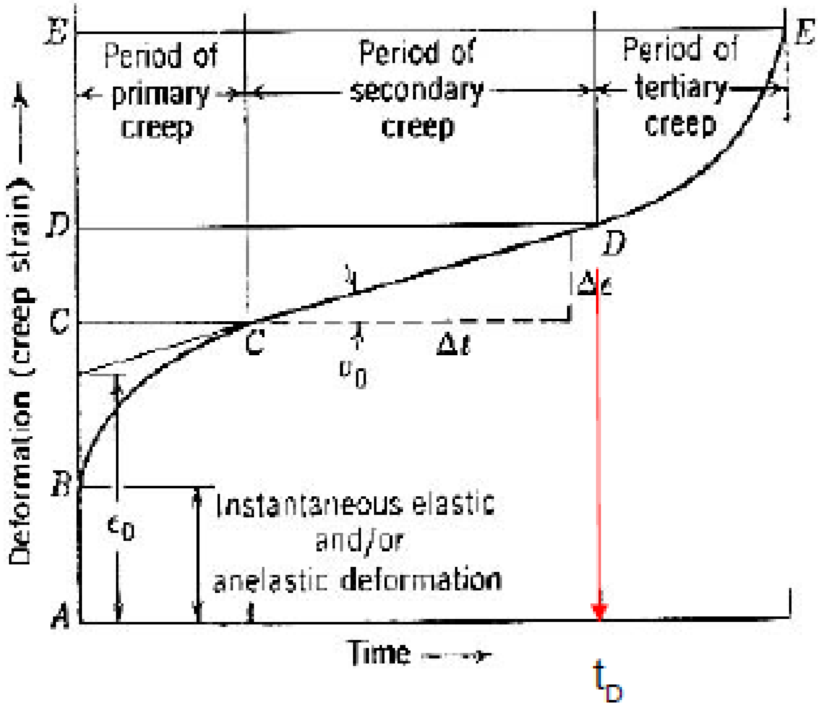
$$\phi_f = \frac{m}{N_m} + \frac{k}{N_k} + \frac{n}{N_n} = \sum_{i=k}^{n} \frac{n_i}{N_i}$$

When ϕ_f is equal to or larger than 1, fracture occurs.

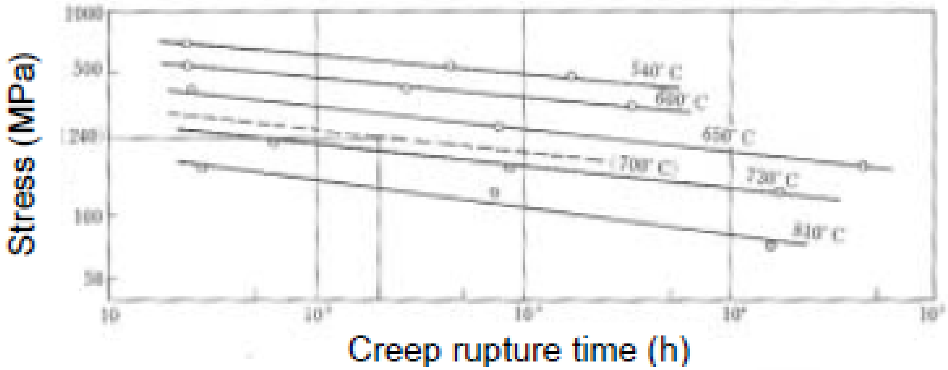
Creep Property

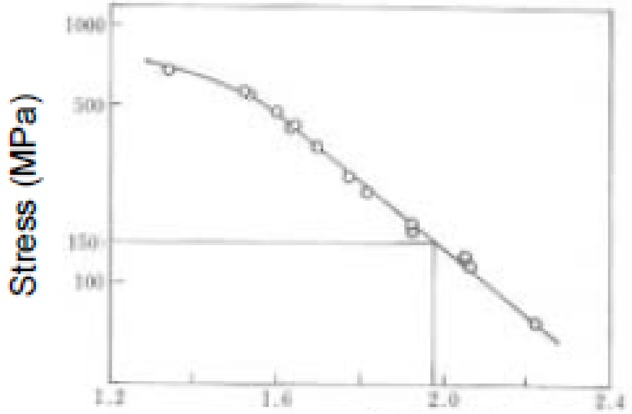
Usually creep is not considered in LWR conditions.

In ASME code section III, the use of ferritic steel and austenitic steel is restricted below 371 and 427 ºC, respectively, where the creep is ignored.



Minimum creep rate Δε/Δt and creep rupture time (t_D) is important.





Basic Irradiation Damage in Materials

1. Materials in nuclear engineering.
2. Basic Concepts of Radiation Damage.
3. Practical Effects of Radiation Damage.

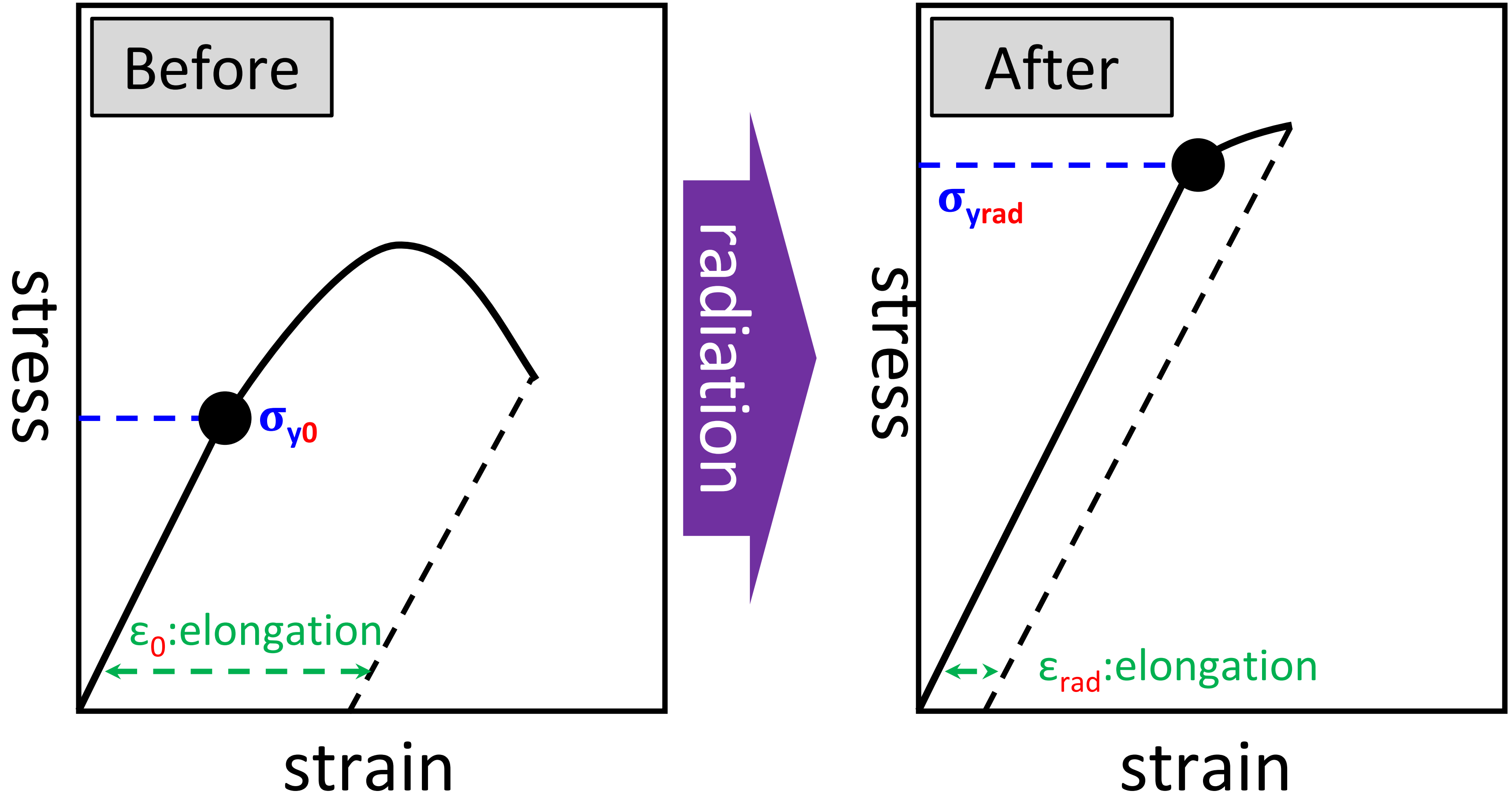
Radiation embrittlement of RPV

Various strengthening methods

Solid solution strengthening	18K gold. as mentioned previously
Precipitation hardening	Duralumin. Al added with a slight amount of Cu forms small intermetalic compounds after a heat treatment. Such small precipitates block dislocation glide.
Work hardening	thin steel plates used in automobile. The dislocation density is too high due to heavy deformation. These dislocations prevent other ones to glide and cut them.
・ ・ ・	
Radiation hardening	pressure vessel of LWR's. Various defects generated by irradiation stop dislocation glides.

Radiation hardening is mostly due to the increase of dislocation density and this is similar to work hardening. But **radiation enhanced precipitates** also have a special effects on RPV embrittlement.

Radiation hardening in s-s diagram



σ_{y0}:strength increases but ε_0:elongation decreases!

Materials science in nuclear

Material is an old technology and
has a long history before nuclear.

We know much about .....

strength | electric properties | cost | corrosion resistance | . . etc

For nuclear applications, we should also consider followings.

nuclear properties | radiation damage | reliability

Zircalloy clad tubes for LWR requires Hf-free Zr for the expected low neutron-absorption cross-sections.

Particle/target interactions

As the introduction to “Basic Concepts of Radiation Damage”, three important phenomena (interactions) in radiation will be explained. They are,

Rutherford Scattering, **Bragg Peak**, **BNCT** cancer therapy.

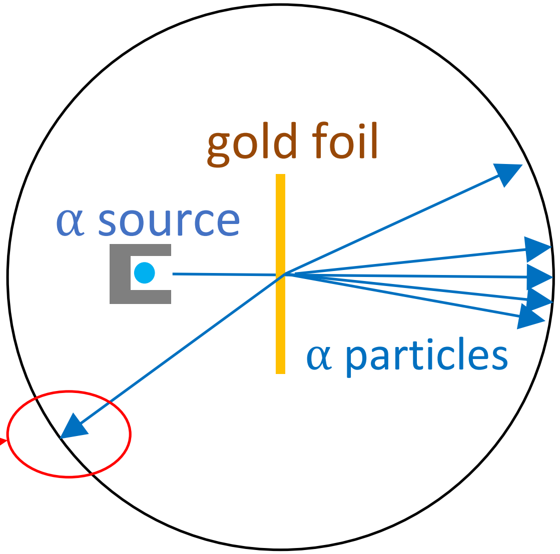
- Radiation -

1. I know how **RUTHERFORD SCATTERING** happens where most of energetic alpha particles injected into a thin gold foil pass through but a few particles are reflected back to the injection side.
2. I know high energy particles (mostly C and H ions) are used for the cancer therapy.
3. I know that the advantage of high energy particles in cancer therapy is their characteristic energy deposition along depth, called **BRAGG PEAK**.
4. I know another cancer therapy method, **BNCT**, where ^{10}B(n, α) reaction is used to kill cancer cells by the localized fission energy deposition.

Rutherford scattering

Nuclei of atoms have been thus discovered.

In 1909, Ernest Rutherford's research group conducted a scattering experiment of α particle beam from Ra through gold foil.
Scattering was, in general, very small but they also found that
few α particles were reflected back to the source side.



It was very surprising because structure of a atom was not well known at that time, while negative charge particles (electrons) were well recognized. J. J. Thomson proposed a "plum pudding model" where electrons are in homogeneous positive charge distribution (positive charge cloud), while Nagaoka's model had a concentrated positive charge at the center and surrounding electrons like rings of Saturn (called as a Saturnian model).

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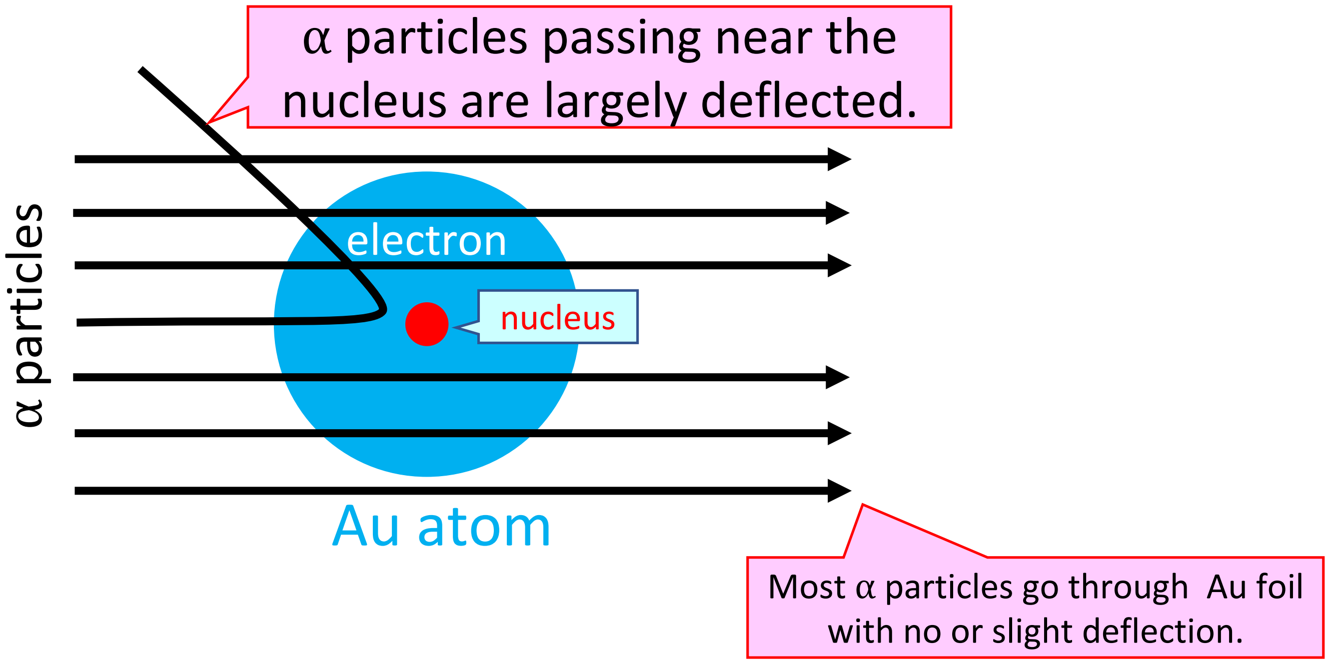
α's are reflected by the nuclei

Based on this results, Rutherford proposed an atom model with a nucleus in 1911, where
the atom has a heavy nuclei with a large positive charge
(planetary model).



This result is caused by collision with the nucleus.

Charged particle cancer therapy

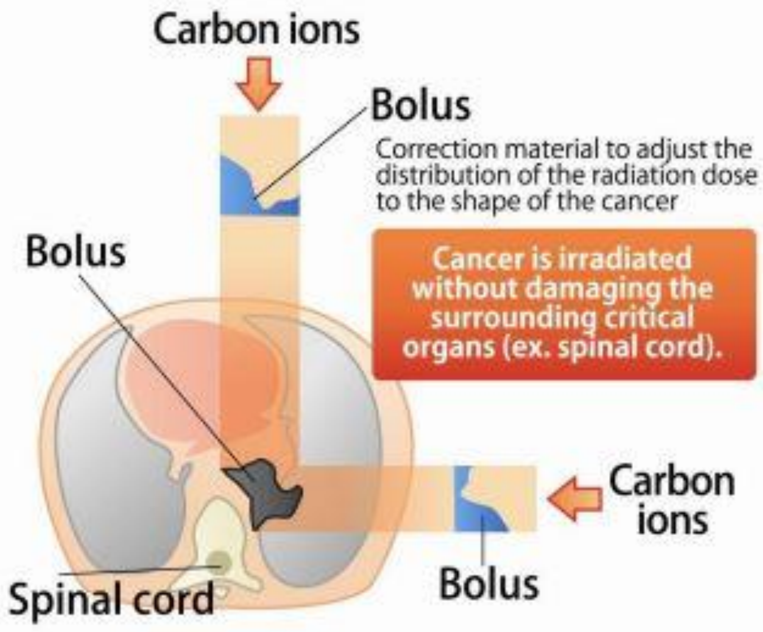
3 Advantages of Heavy Ion Therapy

1 Superior Dose Localization

Heavy ion therapy can severely damage the tumor while minimizing damage to surrounding tissues. Heavy ion therapy has less toxicity (adverse effects) than conventional radiotherapy.

2 Effective Against Cancers Which are Resistant to Conventional Radiations

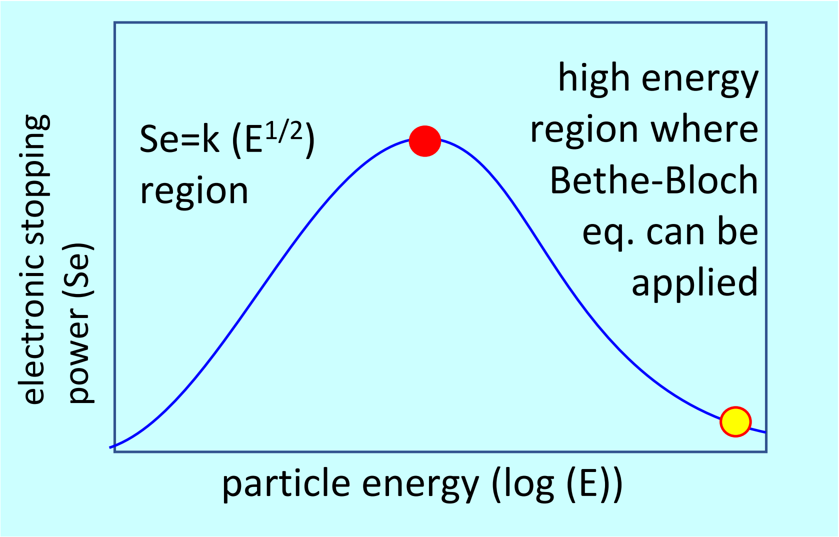
Heavy ion beams have stronger biological effects than X-ray. For example, heavy ion therapy is more effective against tumors such as osteosarcoma, which are difficult to cure with conventional X-ray radiotherapy.

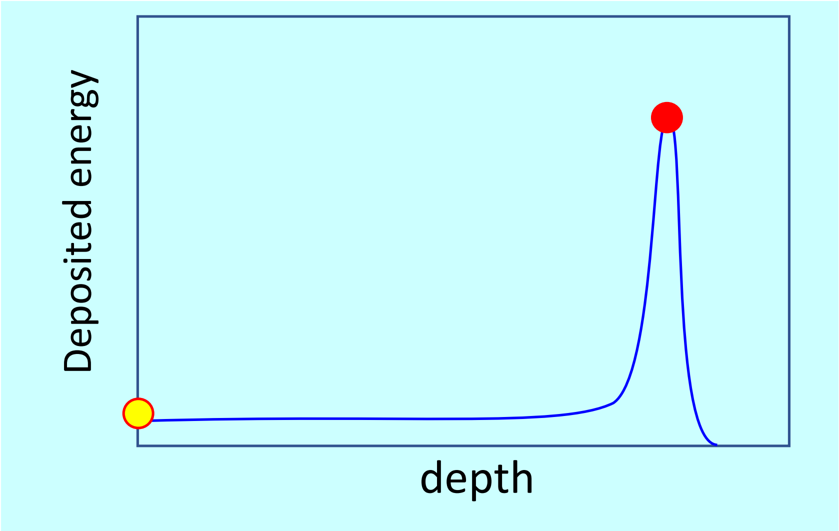


Types of cancers which heavy ion

from web-site of Gunma Univ., Heavy Ion Medical Center

Bragg peak





Electronic stopping Se (energy loss due to electron excitation) is a function of projectile energy and the profile peaks at intermediate energy region as shown in above left.
The energy deposition profile along the depth has, therefore, a peak at the end of the penetration depth. Note that horizontal energy scale in the left diagram is in log scale.

This result is caused by collision with electrons.

BNCT cancer therapy

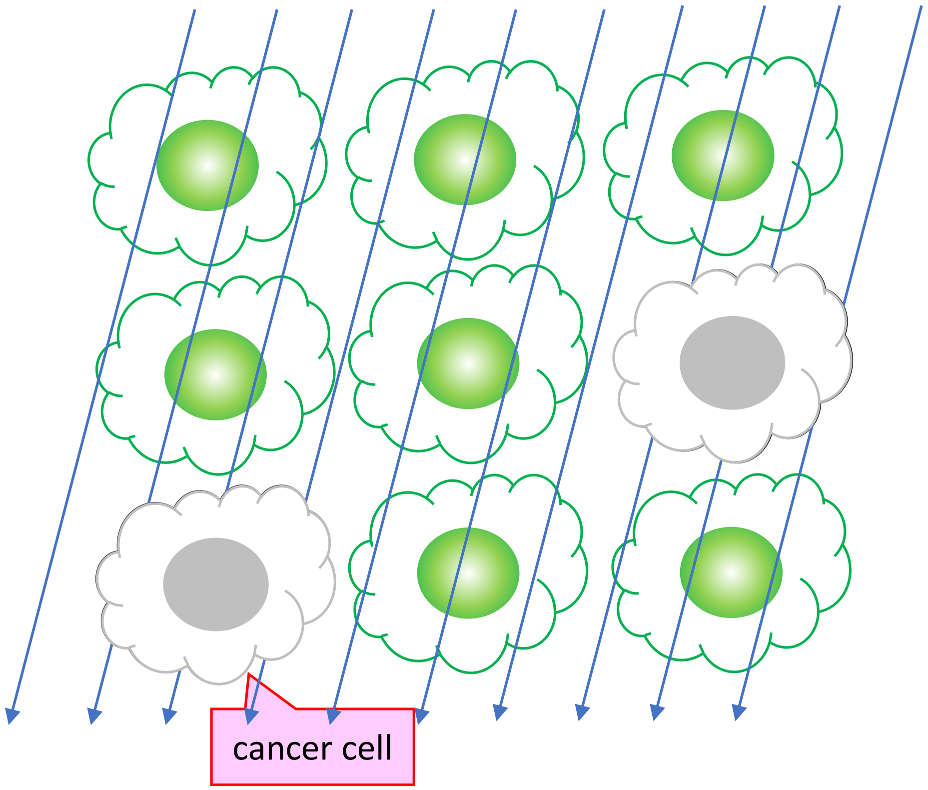
Large (n, α) cross-section of ^{10}B with thermal neutrons are well known. $^{10}B(n, \alpha)^{7}Li$, 3595 barn,

1. ^{10}B containing chemicals go to cancer cells.

2. Irradiate the organ with thermal neutrons.

3. Fission energy carried by α and ^{7}Li is deposited to the cancer cell leaving a slight side effects to healthy cells.

4. Cancer cells are killed.



This result is caused by nuclear reaction.

Summary of three phenomena

phenomena	type of interactions	effects to metallic targets	irradiated particle
Rutherford scattering	collision with nuclei	displacement damage *	ions (Neutrons can also make this effect)
Bragg peak in charged particle therapy	collision with electrons ●	heating	ions ●
BNCT therapy	nuclear reaction ●	transmutation damage	neutrons ●

- * Details of displacement mechanism will be given later.
- To understand radiation effects in NPP materials, you can forget about
  - nuclear reaction caused by high energy ions (●), and
  - neutron to electron collision (●).

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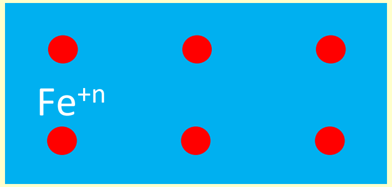
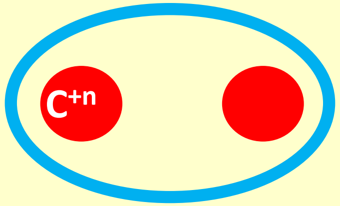
Electron excitation in metals

type of interactions	effects to metallic targets	Irradiated particle
collision with nuclei	displacement damage	ions, neutrons
collision with electrons	heating	ions
nuclear reaction	transmutation damage	neutrons

Metallic materials include many free electrons with various energy states. That's why they are conductive due to the free movement of these electrons.



<u>metallic bonding</u>
Many atoms share many electrons in various energy states.

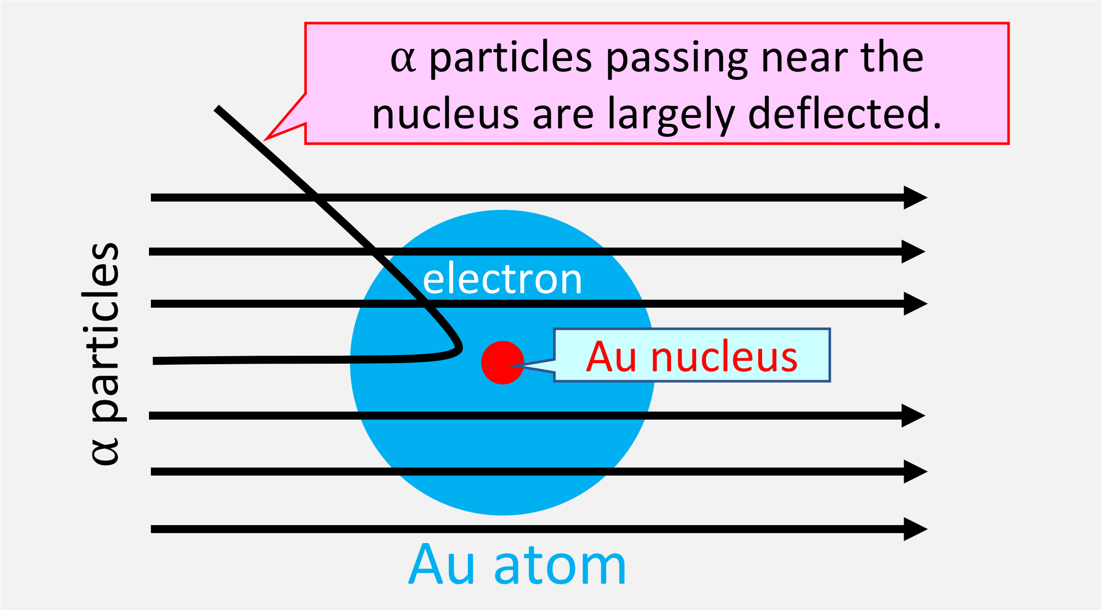


<u>covalent bonding</u>
Two atoms share some electrons in a specific energy state.

Electron excitation does not affect the metallic bonding of these solids.

Polymers, for example, are very sensitive to electron excitations.

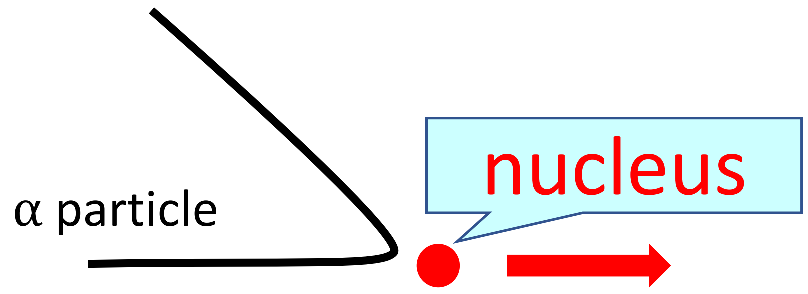
Displacement damage



In α irradiation to Au foil, Rutherford was interested in the deflected α particles,
but let’s think about the irradiated Au nuclei.

What will happen?

Particle/particle collision



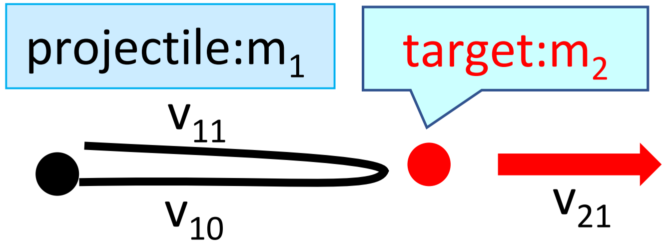
Conservation of momentum requires that the irradiated Au nucleus should move after the collision, receiving some energy from the α.   (Also remind the low of action and reaction!)

The amount of transferred energy varies depending on collisions.
The maximum energy transfer occurs in a head-on collision.

$$E_{max} = \frac{4\, m_1\, m_2}{(m_1 + m_2)^2}\, E_0$$

m_1 : projectile mass
m_2 : target mass
E_0 : projectile irradiation energy

Maximum energy transfer



m_1 : projectile mass
m_2 : target mass
v_{10} : projectile speed before collision
v_{11} : projectile speed after collision
v_{21} : target speed after collision
(v_{11} and v_{21} are unknown.)

conservation of energy

$$\frac{1}{2} m_1 v_{10}^2 = \frac{1}{2} m_1 v_{11}^2 + \frac{1}{2} m_2 v_{21}^2$$

conservation of momentum

$$m_1 v_{10} = - m_1 v_{11} + m_2 v_{21}$$

before | after collision

$$v_{21} = \frac{2 m_1}{m_1 + m_2} v_{10}$$

and so on....

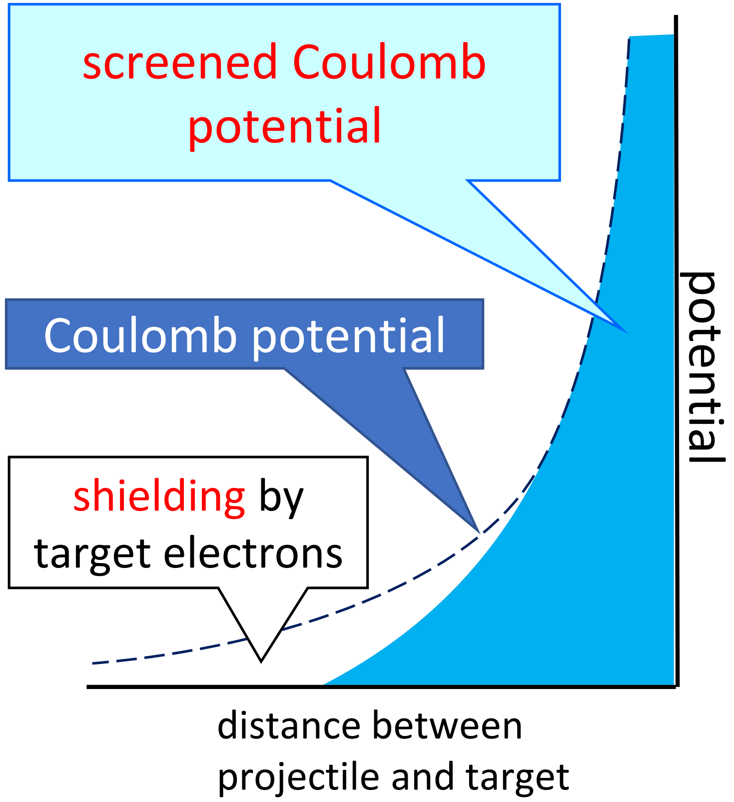
With two unknown parameters and two given equations, we can solve the equations (high school level physics) and the following equation is obtained.

$$E_{max} = \frac{4 m_1 m_2}{(m_1 + m_2)^2} E_0$$

Screened Coulomb potential

Rutherford scattering is the result of ion/ion collisions.
The real potential between projectile and target nuclei is described by **screened Coulomb potential**, which has relatively a shorter tail than that of simple Coulomb potential.

Screened Coulomb potential:
When distance between projectile and target nuclei is large, the projectile "feels" less positive charge of the target nuclei due to electrons around the target nucleus.

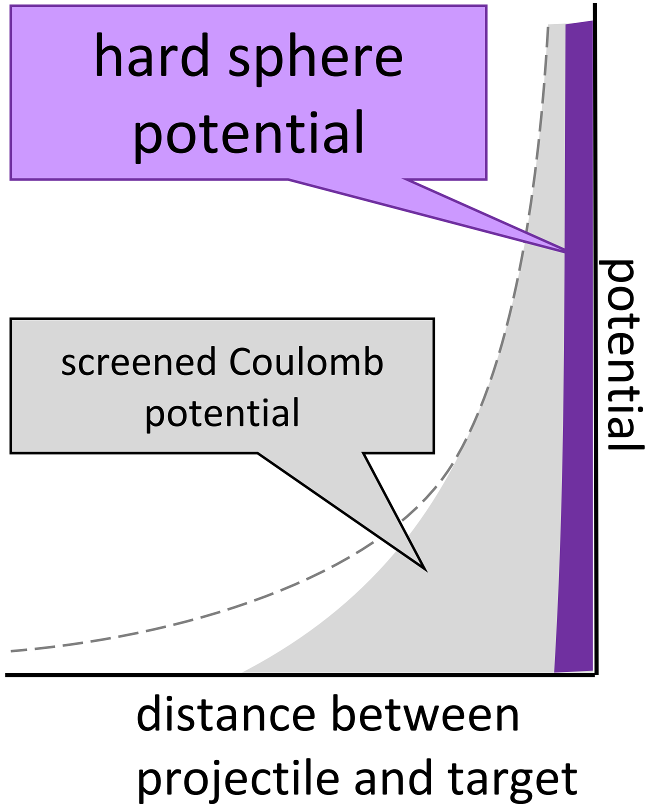


Neutron collision

Because neutrons have no electric charge, they do not “feel” the positive charge of target nuclei. They do not “feel” each other until the distance become very close.

Although high energy neutrons (>1MeV) show complicated collision behaviors, hard shere potential model shown in right figure is enough for most of LWR neutrons.

Neutrons “feel” or “see” smaller target nuclei.
Due to this smaller cross-section, neutrons have deeper penetration into materials.



Displacement damage

If a target atom receives **enough energy** from the projectile by a collision, the atom go away from it original lattice site.

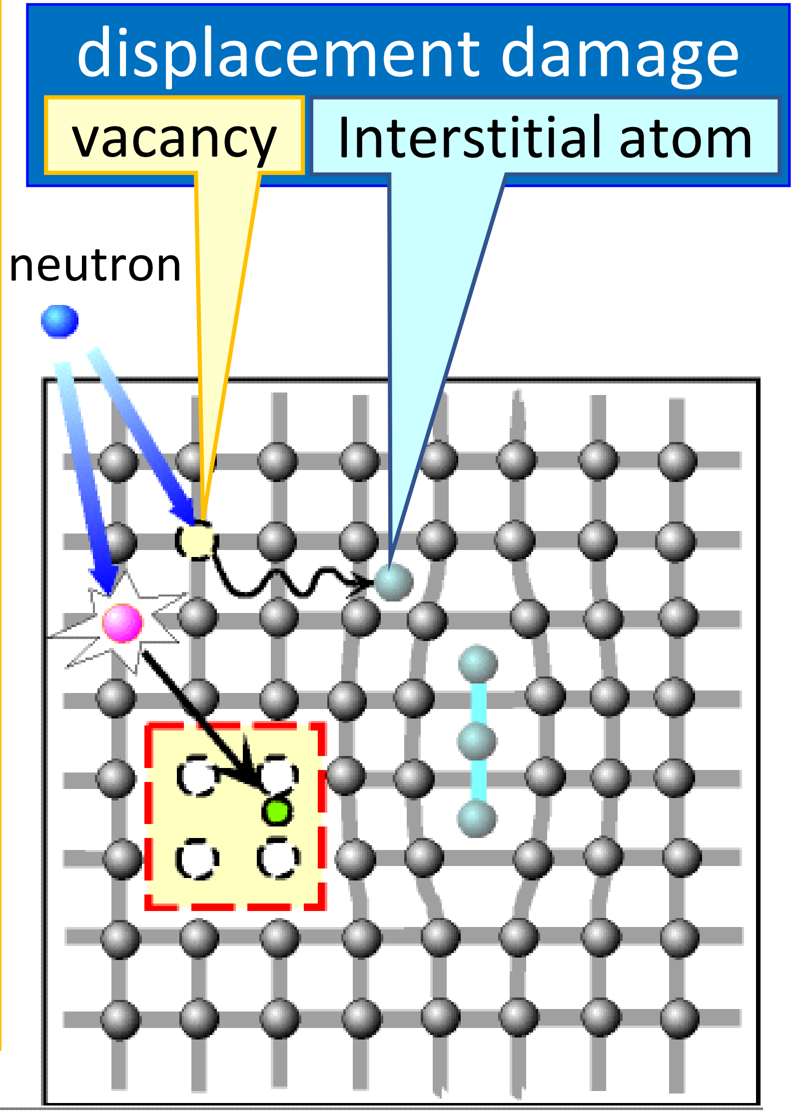
This is called as **displacement**.

If the receiving energy is too low, the hit atom will not be displaced.

The "**threshold energy** " for displacement, Ed, is almost 40 eV in many metals.

A simple displacement makes an **interstitial atom** and a **vacancy**.

The set of these two point defects is called a **Frenkel pair**.

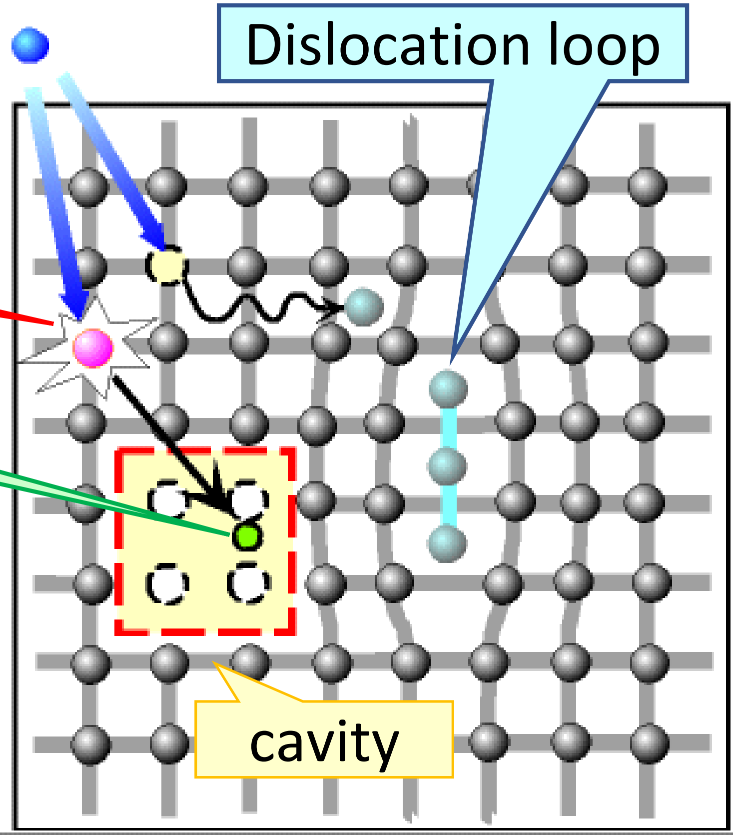


Defect clusters, transmutation

transmutation damage

induced activity

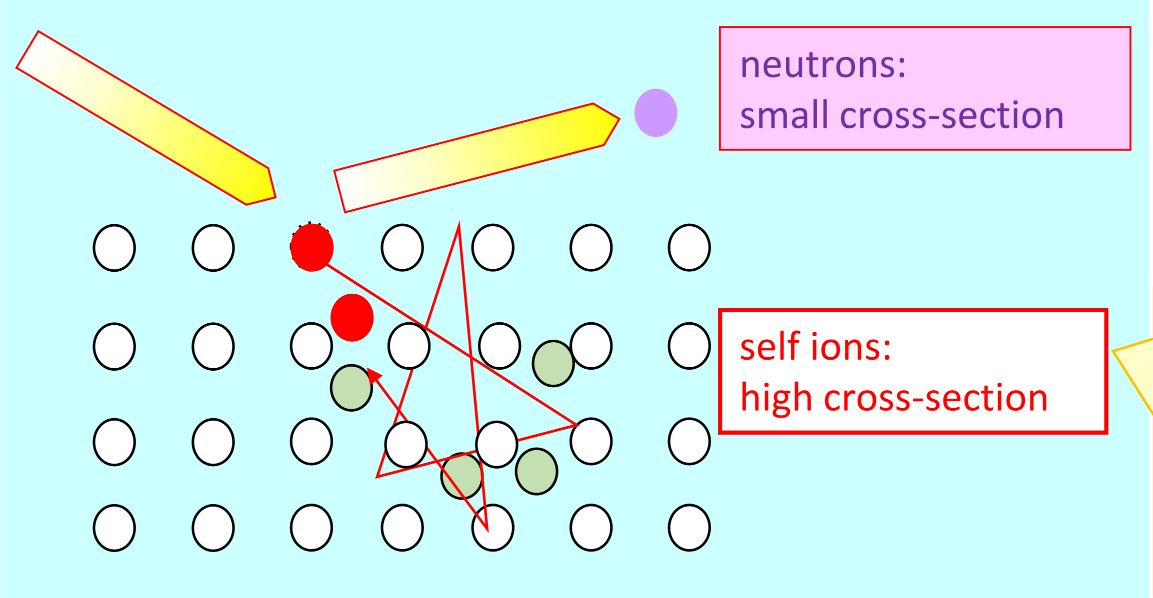
He, H



Neutrons also make transmutations.
The target become **radioactive** and generated He and H affect further microstructural evolutions.

Interstitial atoms and vacancies move around the target material and, **mostly**, disappear by **mutual recombinations** (v + i).
Some defects form **defect clusters**, such as dislocation loops and cavities, collecting same type of point defects (v + v, or i + i).

Cascade damage



The lattice atom directly hit by the neutron is called **PKA**, primary knock-on atom.

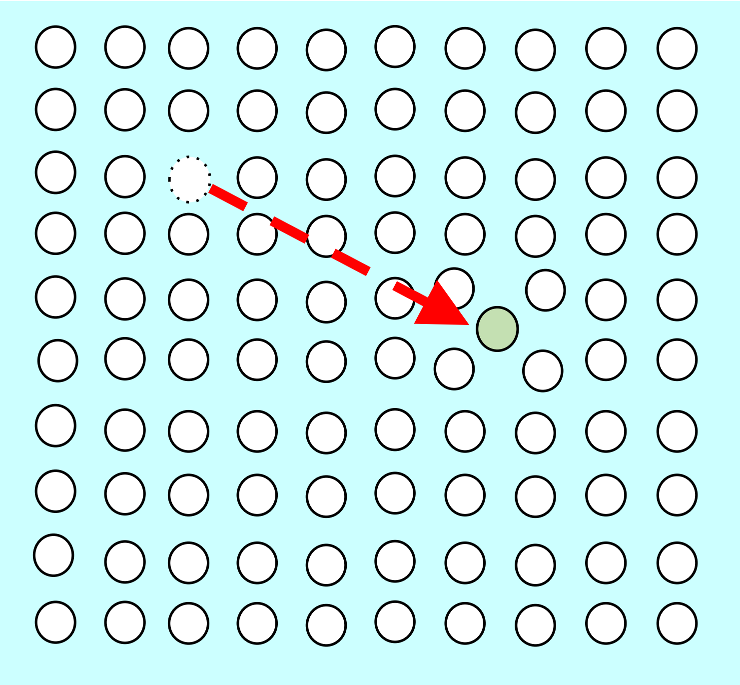
Remember that neutrons have less collision cross-sections than ions. When some energy of neutron is transferred to a target atom, it will generates the next ion to ion collision very soon.

Cascade damage is thus formed.

Cascade damage enhances mutual recombination.

Weak particles, such as electrons, can not make cascade damage and the effect is relatively large due to less mutual recombination in these cases.

DPA



100 lattice atoms

1 vacancy and
1 interstitial atom

0.01 dpa

The unit of displacement damage is DPA, displacement per atom.
If 1% of target lattice atoms have expe meaningful expression! ent,
the damage level is called 0.01 dpa.
Remember that most of point defects disappear by <u>mutual recombination</u>.
The material can survive even after 1 dpa damage!
Reactor internal components of PWR experience up to ~100 dpa.

Two major radiation effects in LWR’s

radiation embrittlement of reactor pressure vessels (ferritic steels)

and

irradiation assisted SCC of reactor core components (stainless steels).

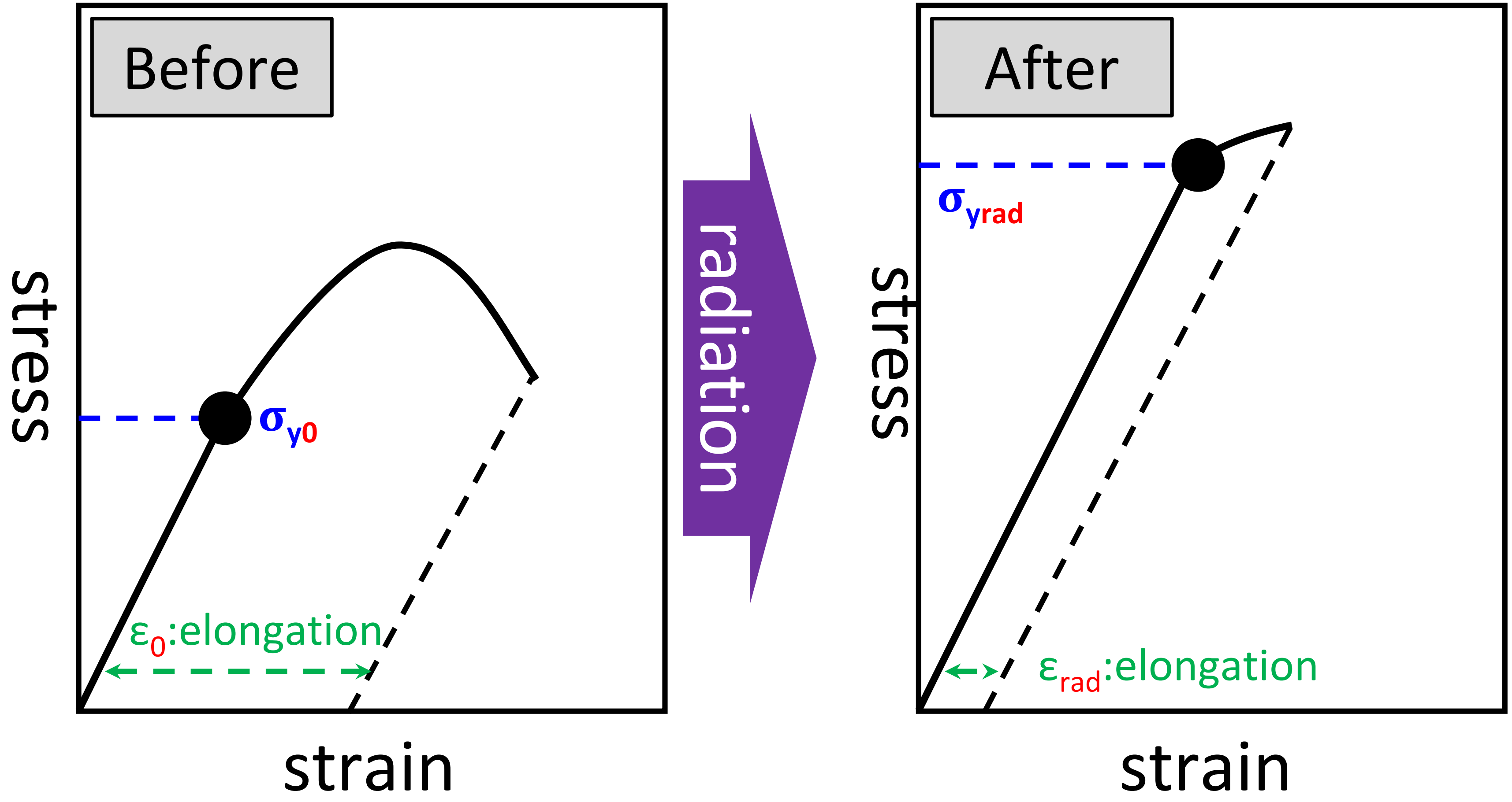
Radiation embrittlement of RPV

Various strengthening methods

Solid solution strengthening	18K gold. as mentioned previously
Precipitation hardening	Duralumin. Al added with a slight amount of Cu forms small intermetalic compounds after a heat treatment. Such small precipitates block dislocation glide.
Work hardening	thin steel plates used in automobile. The dislocation density is too high due to heavy deformation. These dislocations prevent other ones to glide and cut them.
▪ ▪ ▪	
Radiation hardening	pressure vessel of LWR's. Various defects generated by irradiation stop dislocation glides.

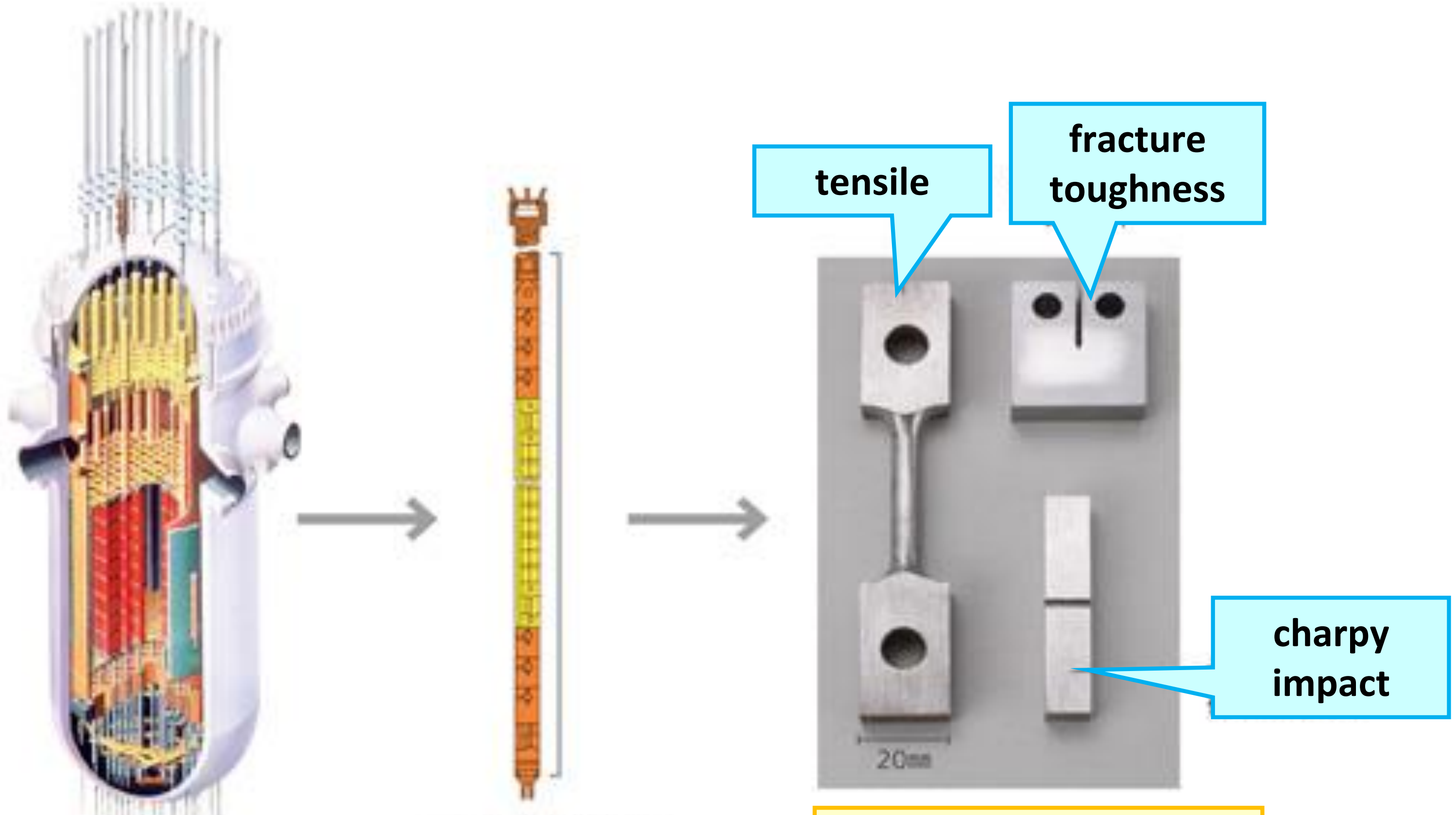
Radiation hardening is mostly due to the increase of dislocation density and this is similar to work hardening. But **radiation enhanced precipitates** also have a special effects on RPV embrittlement.

Radiation hardening in s-s diagram



σ_{y0}:strength increases but ε_0:elongation decreases!

Monitoring the radiation damage



Reactor pressure vessel (RPV)

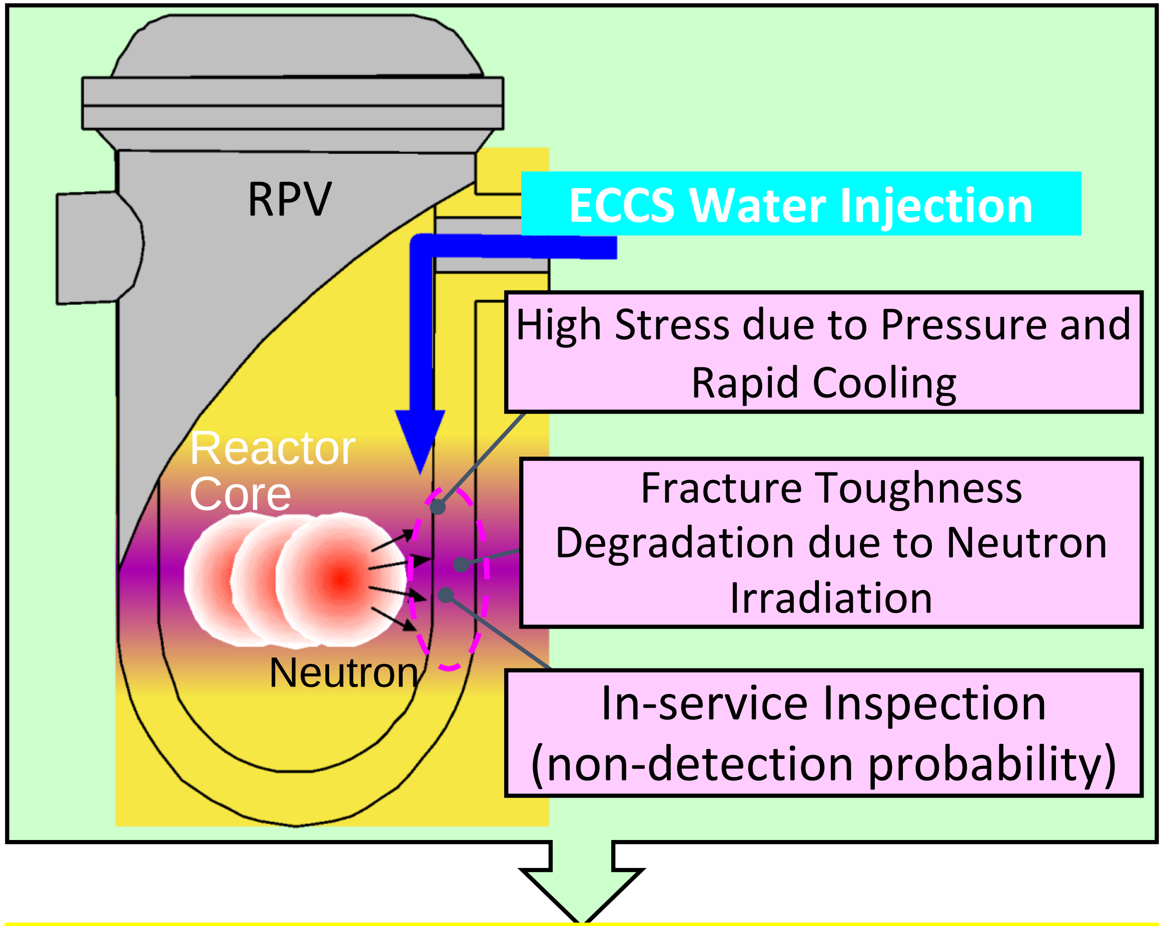
capsule for surveillance test

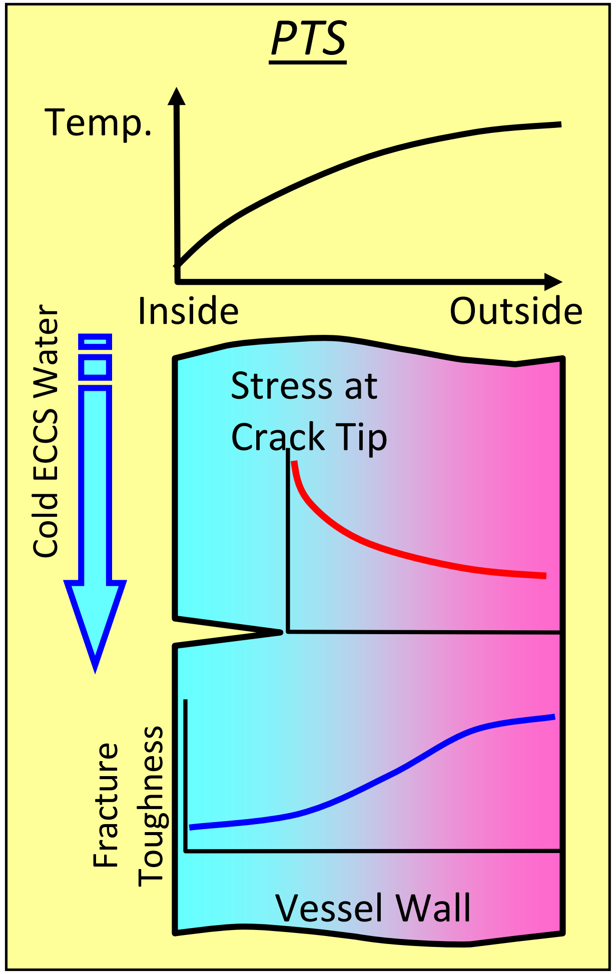
Various surveillance test pieces

Surveillance pieces made of the same material are irradiated in the RPV, and the test results can predict the degradation of the vessel in future.

Pressurized Thermal Shock

- Injection of ECCS water into RPV during



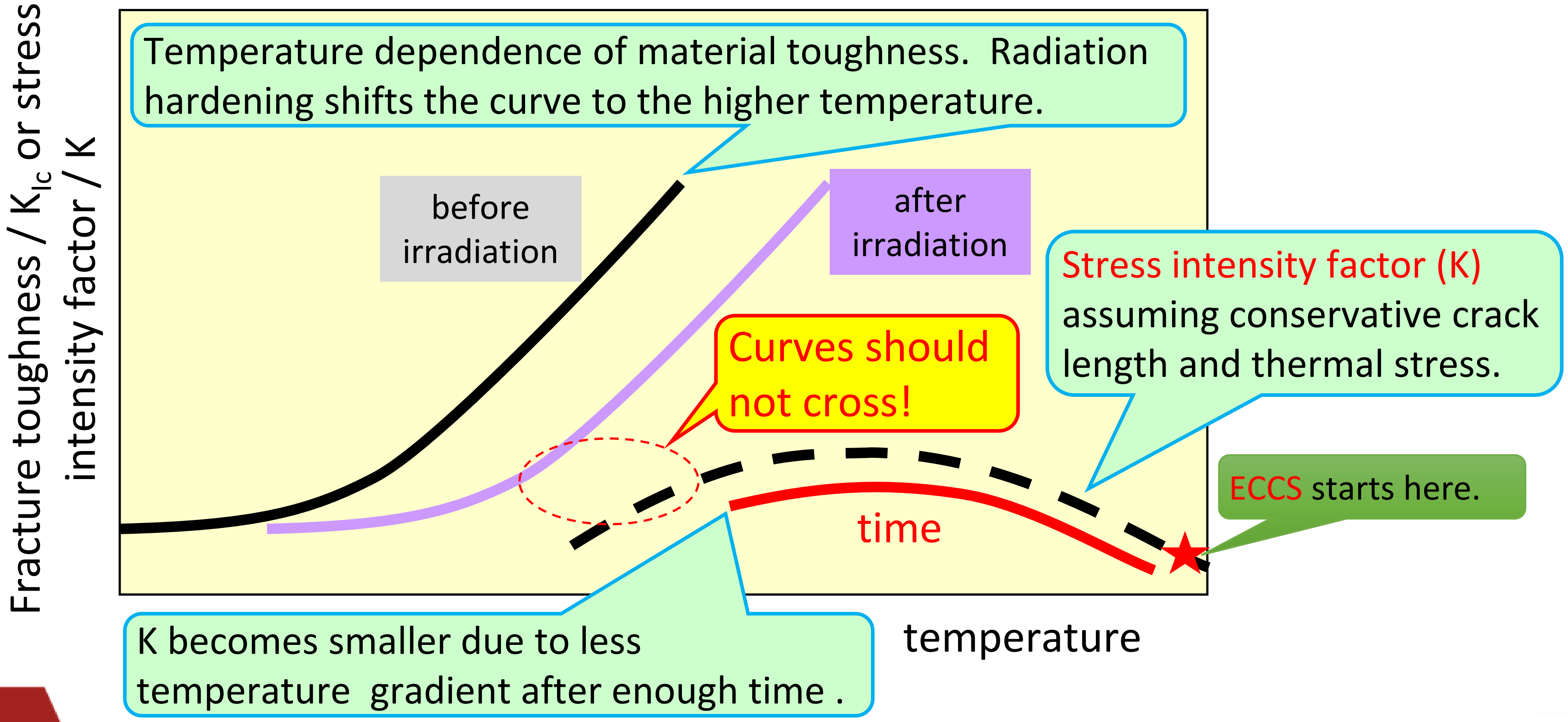


✓Non-ductile fracture must be avoided.

✓Deterministic analysis method is prescribed in Codes/Standards.

Evaluation of RPV integrity

Operation of ECCS (emergency core cooling system) cools core and the RPV rapidly. RPV integrity under induced thermal stress is predicted using stress intensity factor as shown below.

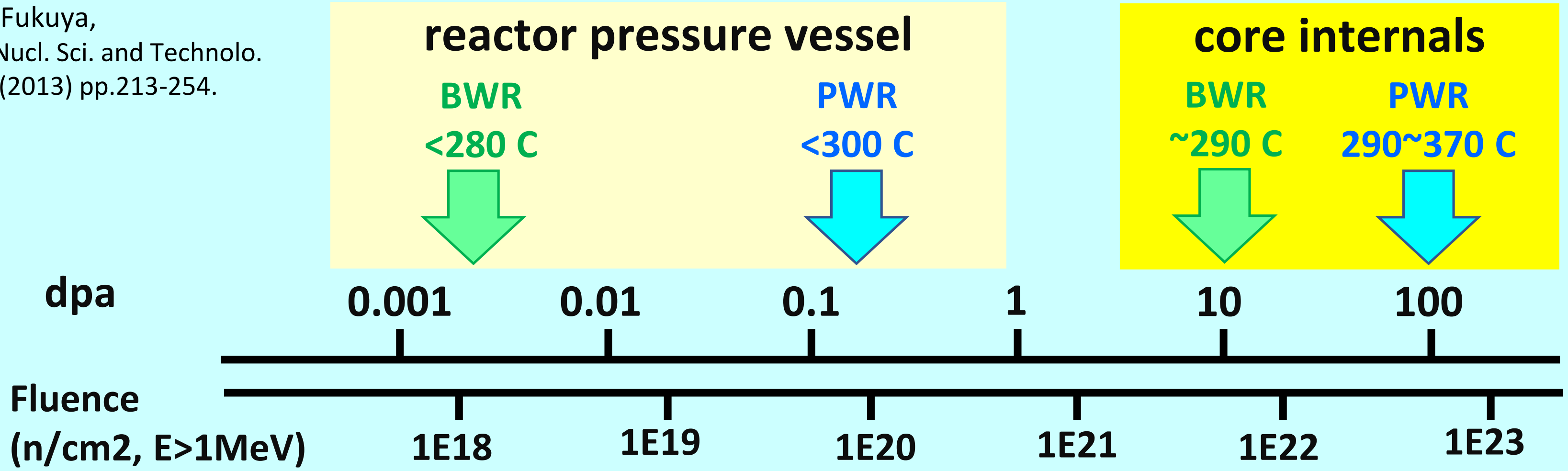


Prevention of RPV embrittlement

Eliminating harmful impurities such as P, Cu, S from the steel is important.   Don't forget about welding wires!

Embrittlement of RPV steel is a hot issue, but current efforts in this area seems to be mostly for the life prediction of RPV's **we are now using**.
Note that neutron irradiation to vital components depends on the design.
Even in current design, neutron damage in BWR's is much lower in PWR's.

K. Fukuya,
J. Nucl. Sci. and Technolo.
50(2013) pp.213-254.



Maximum fluence or dose and typical temperature for 40-years operation of a reactor pressure vessel and core internals.

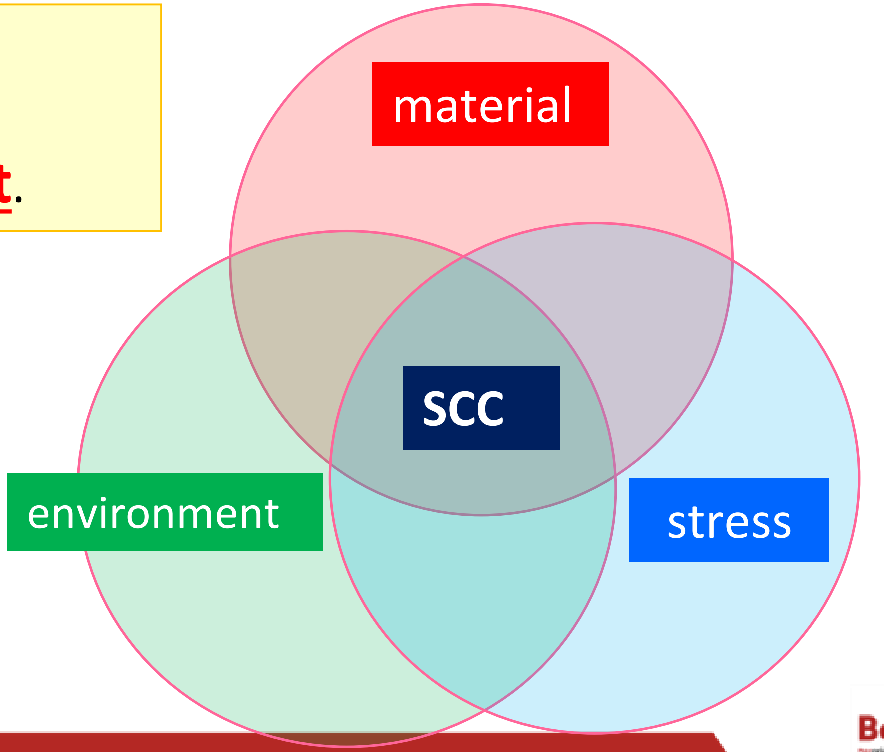
Irradiation assisted SCC (IASCC)

A quick review of normal SCC

Stress-corrosion-cracking (SCC) of austenitic stainless steels and high-Ni alloys has been a large material issue in various components of reactors, including those out of the reactor core, such as steam generator pipes in PWR.

SCC is the results of the combination of three major factors;
material, **stress** and **environment**.

Radiation affects them !



Typical SCC conditions

material

- **sensitization** of stainless steels (Cr-depletion at the grain boundary due to preferential precipitation of $M_{23}C_6$ (Cr-rich carbide) at GB).
- surface hardened layer due to machining

stress

Welding and machining affect both material and stress.

- **residual stress** after welding, or machining,
- thermal stress

environment

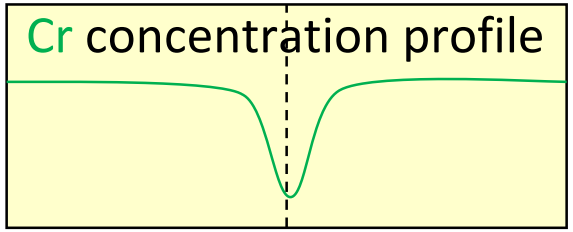
- dissolved oxygen or hydrogen
- impurities (Cl^- etc.)

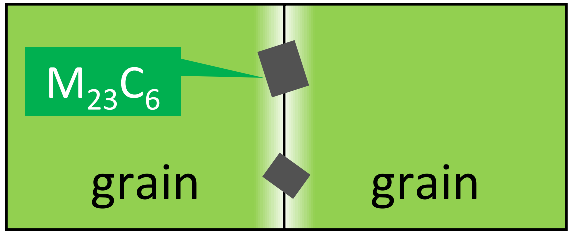
Sensitization due to weld

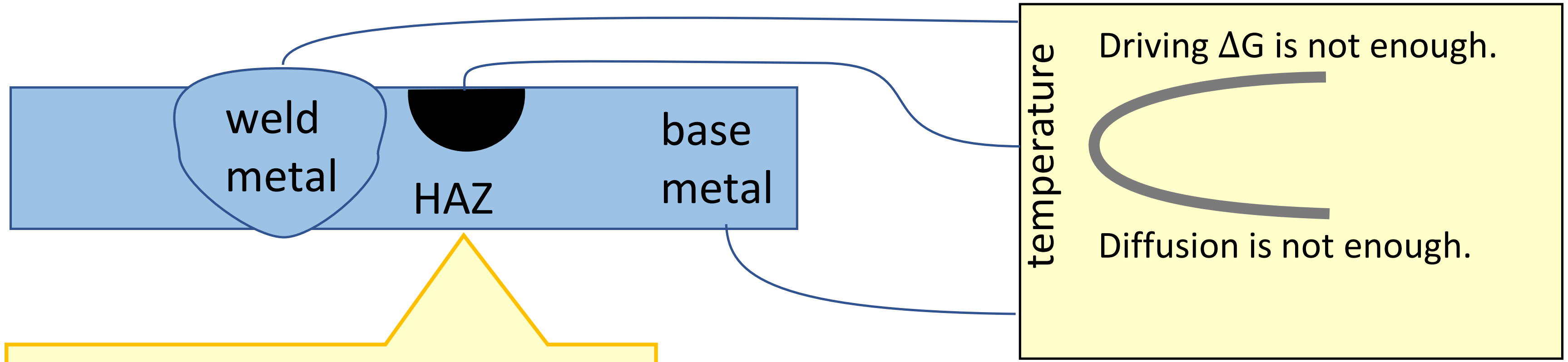
In some types of precipitates, they are formed at grain boundaries first due to their surface energy. **(heterogeneous precipitation)**

->Remember a cloud-chamber !

Cr-rich $M_{23}C_6$ precipitates consume matrix Cr, leaving a less corrosion-resistant Cr-depletion zone along GB.







The highest sensitization sometimes occurs at HAZ (heat affected zone).

Time-temperature-precipitation (TTP) diagram for $M_{23}C_6$, showing a typical “C” shape.

Radiation effects on SCC conditions

material

- radiation **hardening** mostly due to fine dislocation loops.
- change of deformation mode due to **dislocation channeling** (formation of localized heterogeneous deformation band)
- local compositional change at grain boundary due to **radiation induced segregation**
- very fine bubbles due to transmutation helium -> then?

Recent studies have shown that hardening, localized deformation due to fine i-loops, GB segregation are the major reasons of IASCC

stress

IASCC shows always inter-granular cracking, while normal SCC shows both TG and IG cracking.

- relaxation of residual stress due to **radiation creep**

environment

Radiation may relax the stress conditions in general but may increase the stress at the crack tip in some cases.

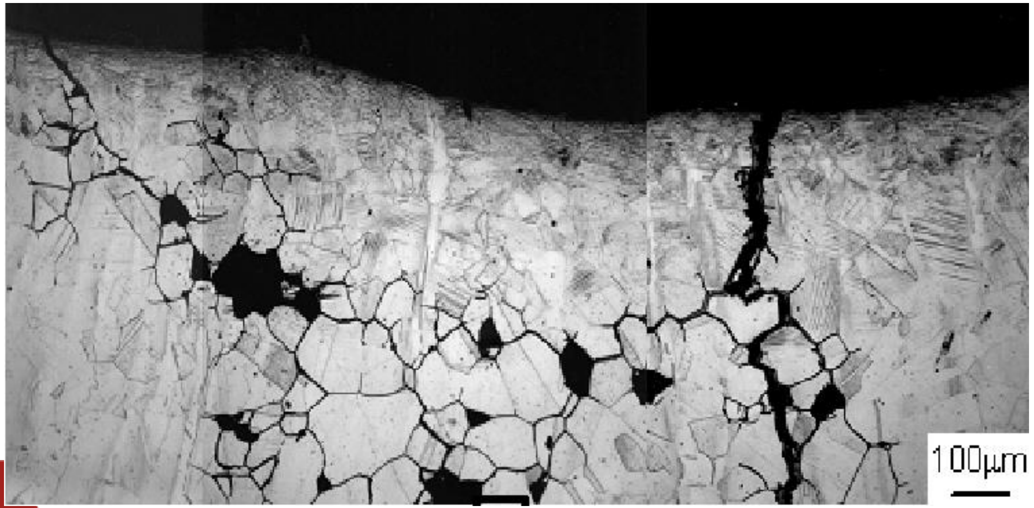
- **radiolosys**, formation of H_2O_2

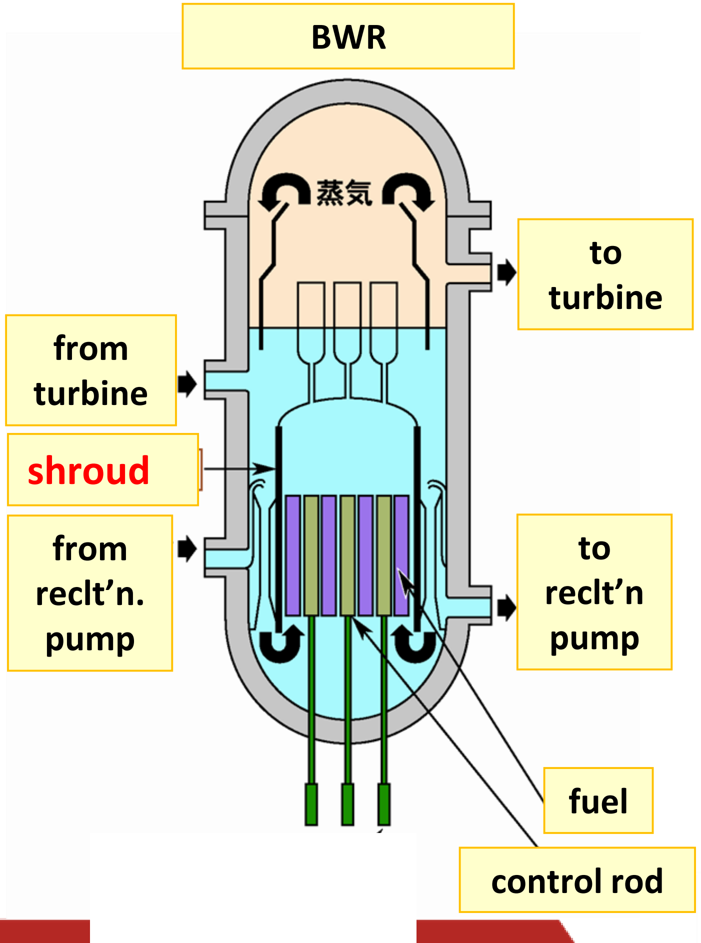
SCC at BWR shroud

The core shroud in BWR is a large stainless steel cylinder within the RPV that srounds the fuel assemblies.
The core shroud controls water flows as shown in the figure.

The cracks started at the surface layer highly work-hardened due to machining, followed by inter-granular crack growth.
This cracking is considered to be normal SCC rather than IASCC because of the low irradiation dose.

JAEA report on Fukushima daini #3 shroud





Prevention of (IA)-SCC

Prevention of (IA)-SCC should be also considered in three conditions.

material

- more SCC-resistant materials such as **low carbon type 316** (but still has some susceptibility to SCC).
- careful welding and machining (also effective to reduce stress) .

stress

- careful welding and machining

environment

The first countermeasure you have to do !

- **elimination of Cl^-** from the water
- controlling of other water chemistry, especially hydrogen injection

LWR's have experienced many SCC issues in various components, but most of them are overcome by the combination of countermeasures.

Transmutation damage

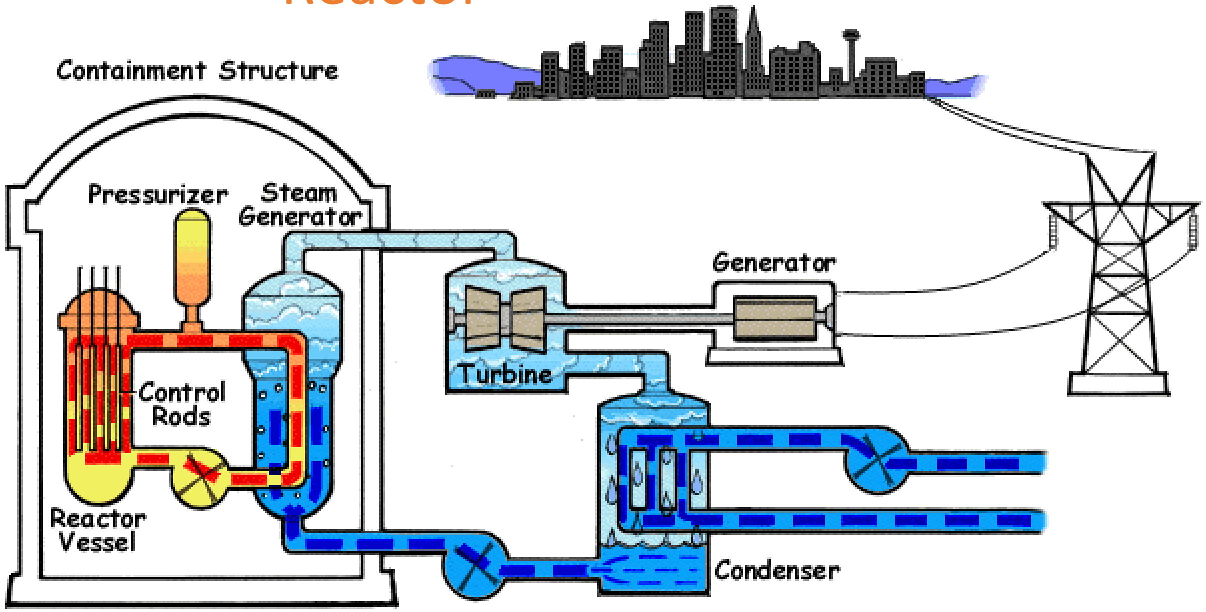
From the practical stand point, you should also know some minor effects of transmutation damage.

Ni usually contains Co as impurity and irradiated austenitic stainless steels become very radioactive due to ^{60}Co. Dissolved Co deposits various part of the piping and increases the **radioactivity of the system** including the piping out of the reactor

Ni has a special transmutation chain $^{58}Ni\ (n, \gamma)\ ^{59}Ni\ (n, \alpha)\ ^{56}Fe$ and **generates helium under thermal neutron environment**. Helium will not affect the material properties very much at the operation temperature of LWR's but over 600 C, helium "precipitates" at grain boundaries(GB) and weaken GB. **Welding** of irradiated austenitic stainless steels become, therefore, very difficult.

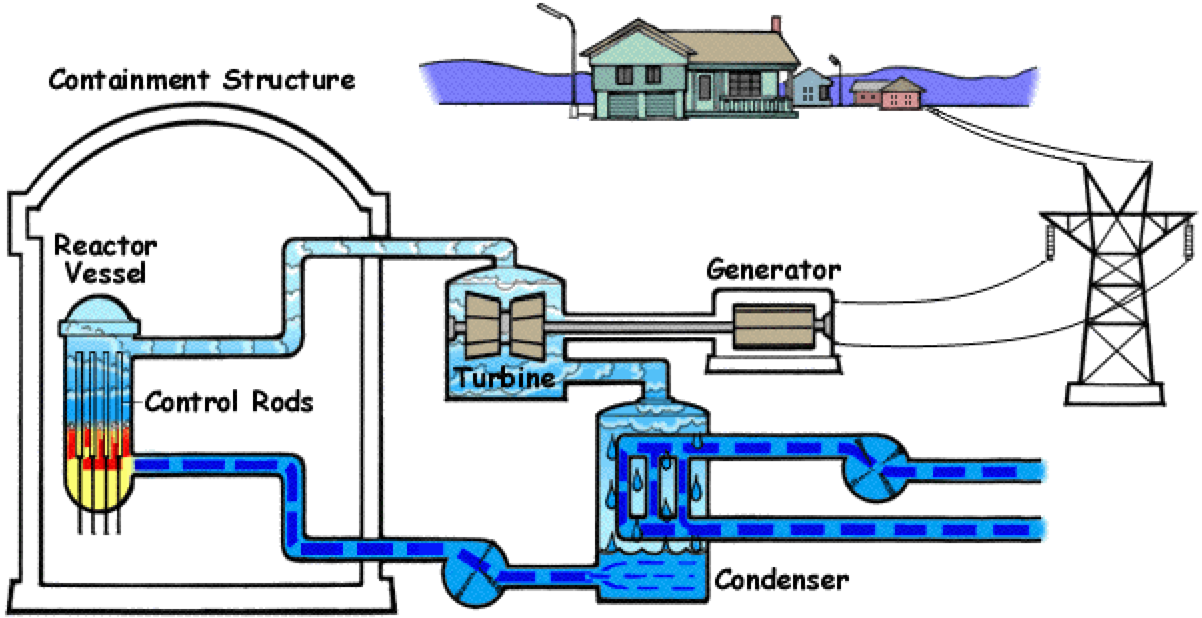
IV. Materials for LWR

Pressurized Water Reactor



https://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

Boiling Water Reactor



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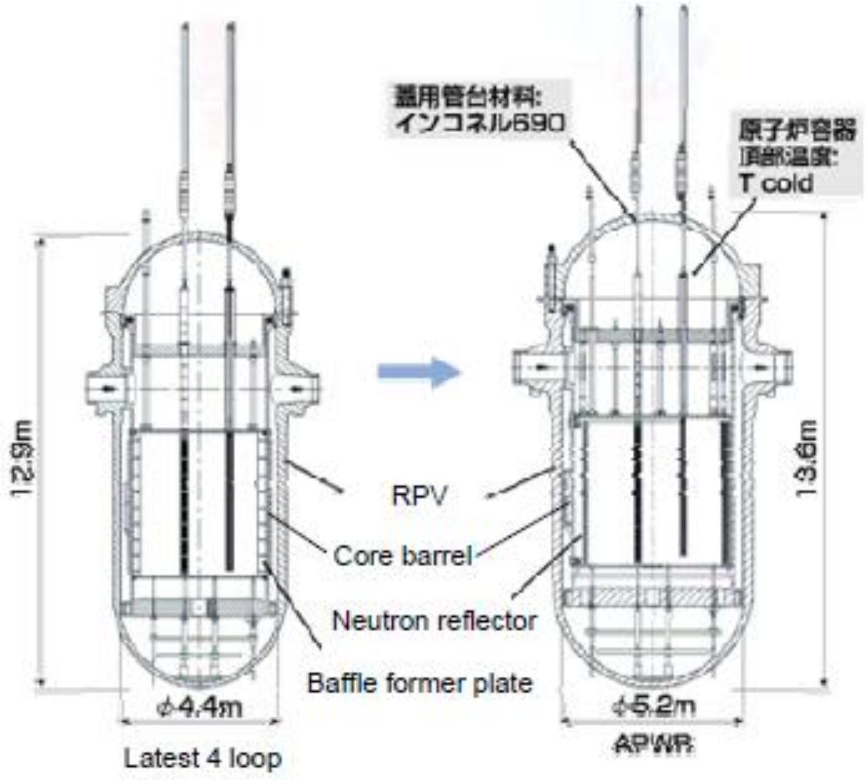
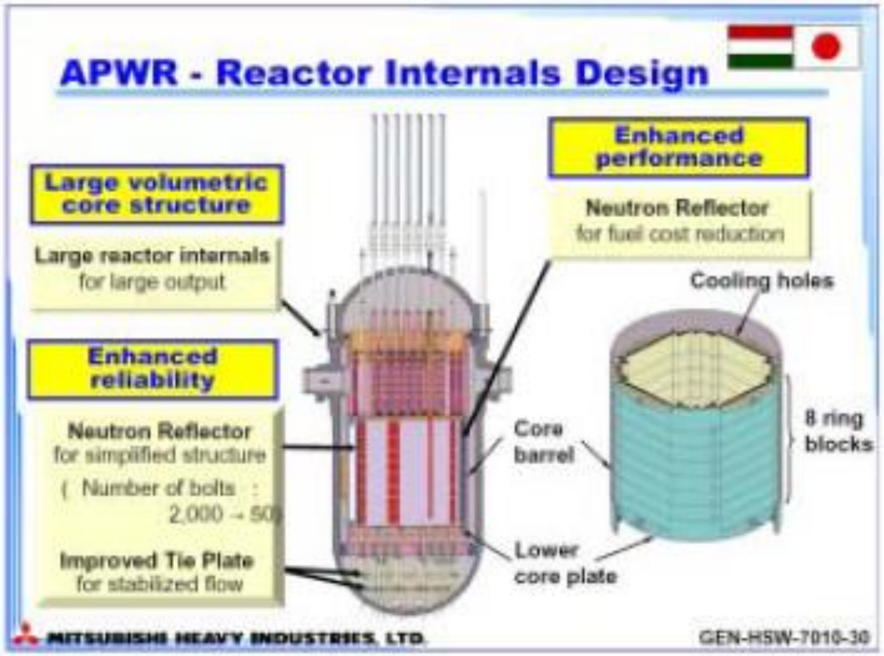
Major Components and Degradation Mechanisms

1. **Reactor pressure vessel**
   Radiation embrittlement, Primary water stress corrosion cracking(PWSCC), Boric acid corrosion
2. **Reactor coolant piping and safe ends**
   Low and high cycle thermal fatigue, Thermal embrittlement, High cycle mechanical fatigue
3. **Steam generator**
   PWSCC, Intergranular stress corrosion cracking (IGSCC), Intergranular attack, Pipe fretting, Denting, Corrosion fatigue, High cycle fatigue, Wastage
4. **Reactor coolant pumps**
   Thermal embrittlement, boric acid corrosion, high cycle mechanical and thermal fatigue
5. **Pressurizer**
   Low cycle thermal fatigue, PWSCC
6. **Control rod drive mechanism**
   Thermal embrittlement, PWSCC, wear, insulation breakdown
7. **RPV internals**
   Irradiation induced stress corrosion cracking (IASCC), High cycle mechanical fatigue, IGSCC, Stress relaxation, IG cracking
8. **Feedwaterpiping and nozzles**
   High and low cycle thermal fatigue, Flow accelerated corrosion (FAC), SCC

Advanced Pressurized Water Reactor

- Larger reactor pressure vessel
  - Longer distance from core, reduction of neutron fluence at RPV (~1/3)
- Neutron reflector
  - Thick ring block structure : nuclear heating, high displacement damage





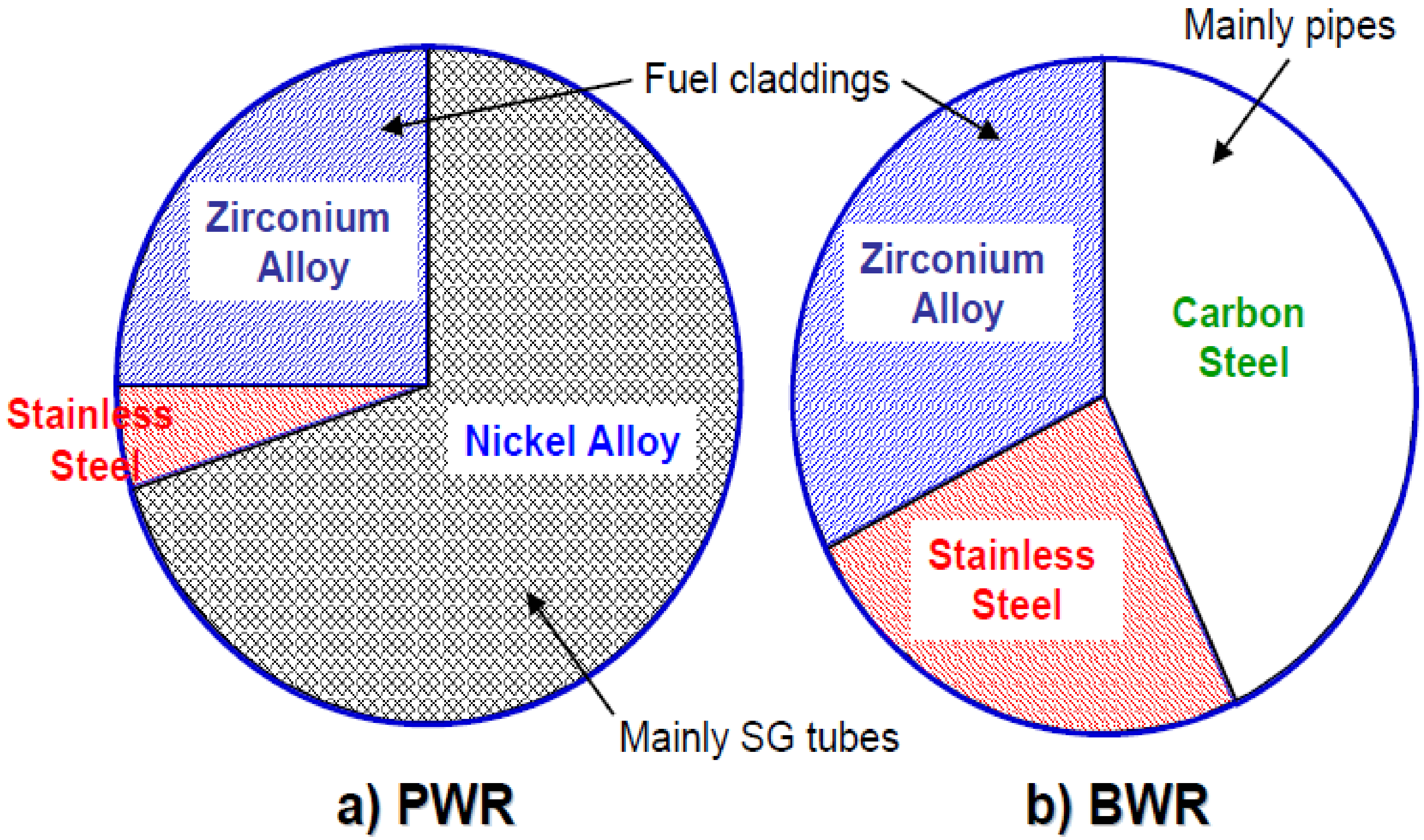


Fig. 1.2.4 Major materials in primary system shown by the ratio of their wetted surface area

By S. Uchida, JAEA

Components	Parts	BWR	PWR
Reactor Pressure Vessel (RPV)	Vessel and Head Cladding Stud Bolt	Low alloy steel: SA533 Gr.BCl.1 SA508 Cl.2, SA508 Cl.3 Stainless steel: Type 308L high-strength low alloy steel: SA540 Gr.BCl.3	Low alloy steel: SA533 Gr.BCl.1 SA508 Cl.2, SA508 Cl.3 Stainless steel: Type308L high-strength low alloy steel: SA540 Gr.BCl.3
RPV Internal (RPVI)	Core Support Plate Shroud Core internals, etc. Support/Bolt, etc.	Low carbon stainless steel: Type304L, Type316L Nickel alloy: Alloy 600, Alloy X750	Stainless steel: Type 304 Cold-worked type 316 SS Nickel alloy:Alloy X750
Fuel Assembly	Fuel cladding Channel Box	Zircaly-2 Zircaly-4	Zircaloy-4
Steam Generator (SG)	Shell Tubesheet Tube	Nil.	Low alloy steel: SA533 Gr.BCl.2 Low alloy steel: SA508 Cl.3 Nickel alloy: Alloy 600, Alloy 690
Piping	Pipes	Low carbon stainless steel: Type304L, Type316L Carbon steel: SA106 Gr.B	Stainless steel: Type304, Type316 Carbon steel: SA516 Gr.70

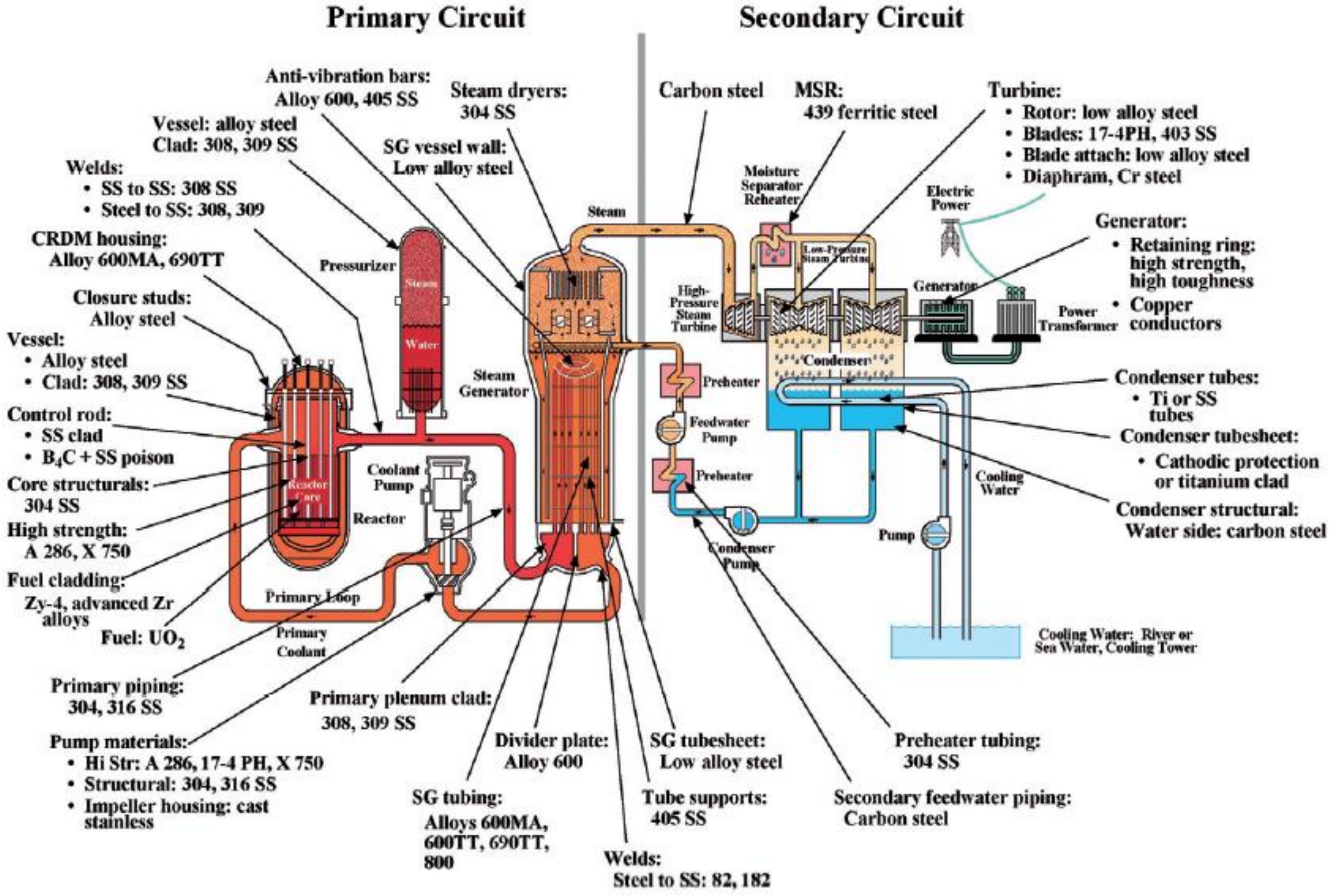
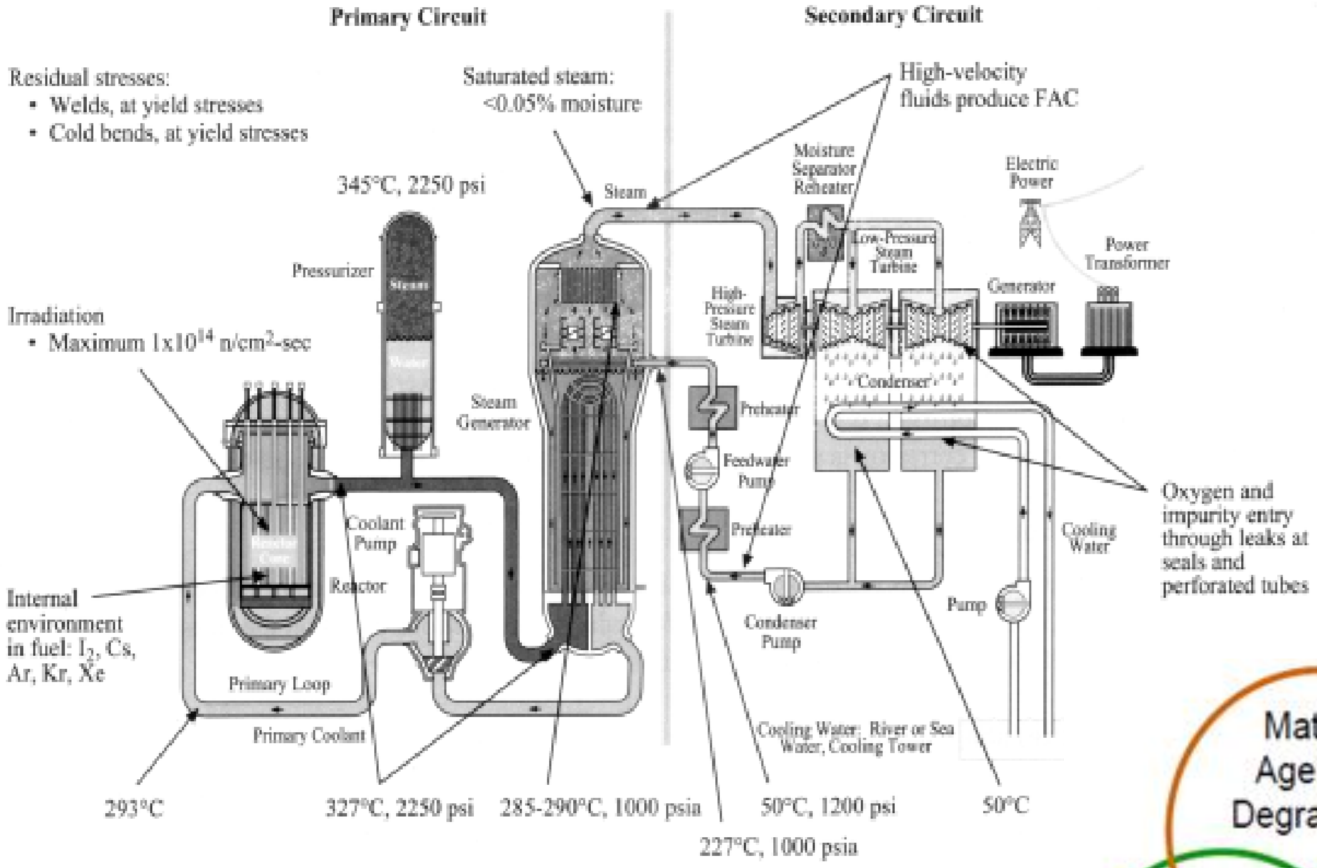
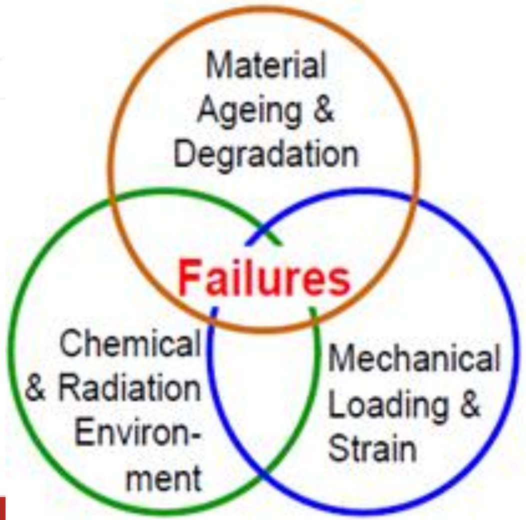


Fig. 1 Outline of PWR Components and Materials. Courtesy of R. Staehle.


Primary Circuit
Secondary Circuit
Residual stresses:
• Welds, at yield stresses
• Cold bends, at yield stresses
Saturated steam:
<0.05% moisture
High-velocity
fluids produce FAC
345°C, 2250 psi
Steam
Moisture
Separator
Reheater
Electric
Power
Pressurizer
Steam
Water
Low-Pressure
Steam
Turbine
Power
Transformer
Generator
High-
Pressure
Steam
Turbine
Irradiation
• Maximum 1x10^{14} n/cm^2-sec
Condenser
Steam
Generator
Preheater
Feedwater
Pump
Coolant
Pump
Preheater
Oxygen and
impurity entry
through leaks at
seals and
perforated tubes
Cooling
Water
Reactor
Internal
environment
in fuel: I_2, Cs,
Ar, Kr, Xe
Condenser
Pump
Pump
Primary Loop
Primary Coolant
Cooling Water: River or Sea
Water, Cooling Tower
293°C
327°C, 2250 psi
285-290°C, 1000 psia
50°C, 1200 psi
50°C
227°C, 1000 psia


Material
Ageing &
Degradation
Failures
Chemical
& Radiation
Environ-
ment
Mechanical
Loading &
Strain

Plan-Do-Check-Act Activities of AMP

PLAN

2. Definition of SSC Ageing M. Progr.

Integrating Ageing management activities

- *Coordinate AM activities*
- *Document AMP*
- *Optimize AMP based on current understanding, self assessment and peer review*

Improve AMP

ACT

Minimize expected degradation

DO

5. SSC Maintenance : Mitigation, Repair and Replacement

Managing Ageing Effects

- *Criteria for maintenance work*
- *Mitigation/repair of SSC*
- *Vibration Control*
- *Mitigation/repair of SSC adjacent*
- *Chemical/Physical treatment*
- *SSC replacement*

1. Undersatanding SSC Ageing

Key to effective AM

- *Materials Properties*
- *Stressors & Operating Conditions*
- *Ageing Mechanism*
- *Degradation sites*
- *Condition indicators*
- *Consequences under Normal & DBA*

3. SSC Operation

Managing Ageing mechanisms

- *Follow operating guidelines*
- *Control of stressor (temp, water chem, impurity etc) and environment of SSC*
- *Removal of Secondary side crevice impurity*

CHECK

4. SSC Insp, Monitoring & Assesment

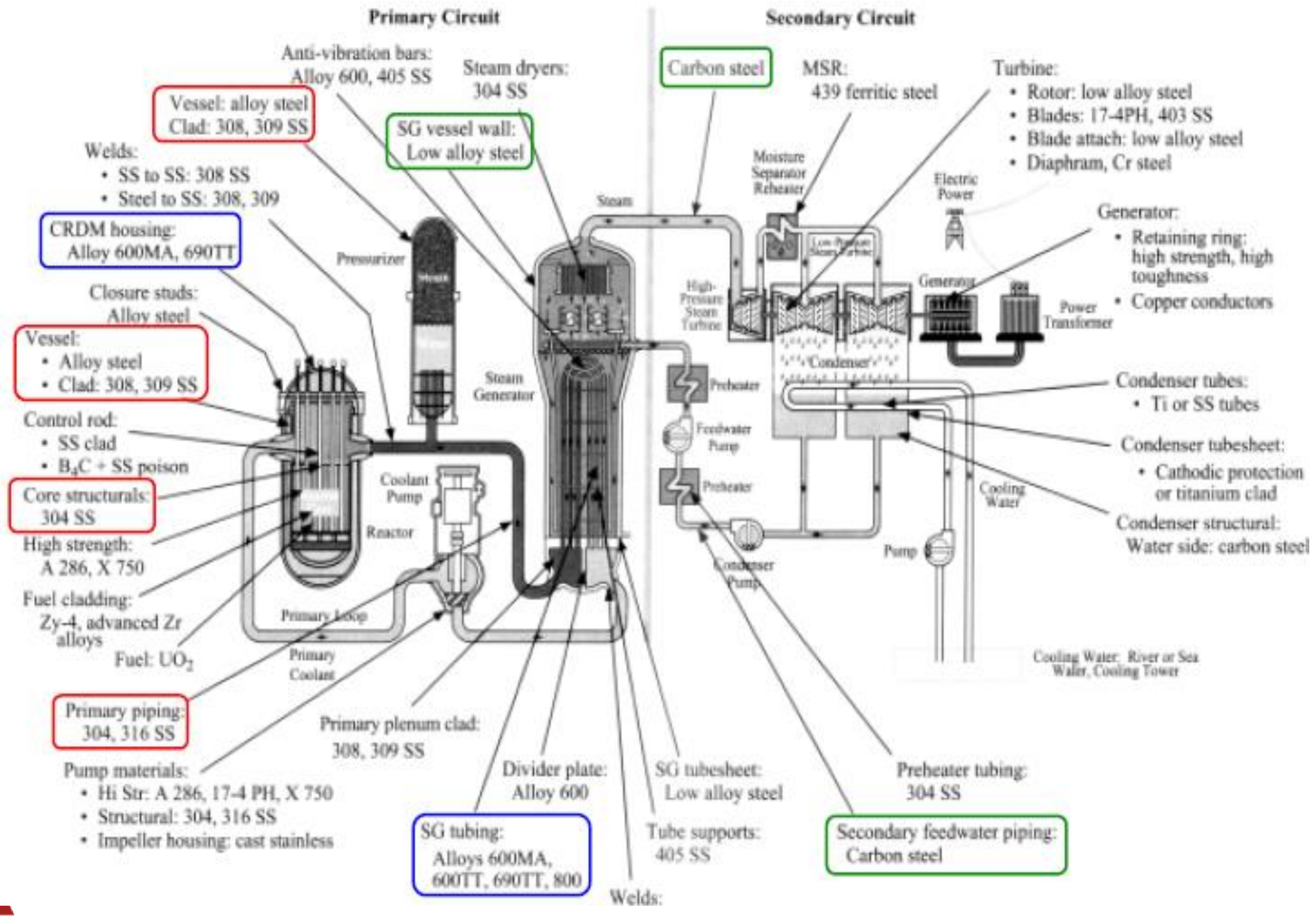
Detecting and Assessing Ageing Effects

- *SSC inspection*
- *Boundary SSC inspection*
- *Fatique monitoring*
- *Leak rate monitoring*
- *Fitness for service assessment*
- *Consequences under Normal & DBA*

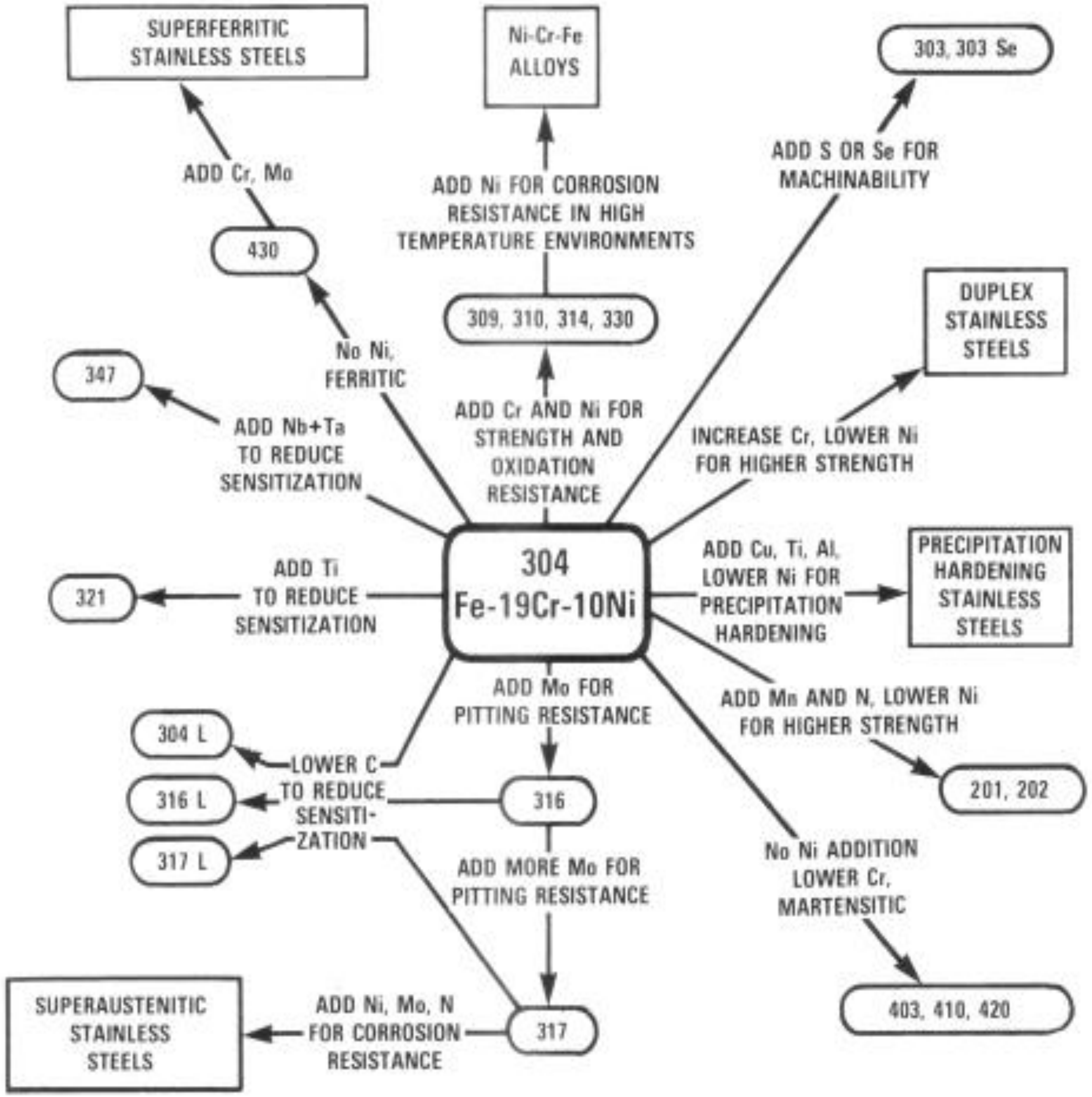
Correct unaccepable degradation

Check for degradation

PWR - Stainless Steel



Stainless Steel



Requirements of nuclear material properties

2 main categories: general and special properties

General properties	Special properties
➢Mechanical strength,Ductility ➢Structural integrity ➢Fabricability, machinability ➢Corrosion resistance ➢Heat transfer properties ➢Thermal stability ➢Compatibility ➢Cost	➢Neutronics properties ➢Induced radioactivity ➢Irradiation stability ➢Chemical interactions ➢Particle inter diffusion ➢Ease of fuel reprocessing

WELDING

Welding is important not only for construction but also for maintenance (repair, replacement of component).

(1) Type of welding process

Shielded metal arc welding, (SMAW)Submerged-arc welding, (SAW)Gas shielded are welding, Inert-gas arc welding: Tungsten-inert-gas (TIG), Metal-inert-gas (MIG) CO2 arc welding, Laser beam welding

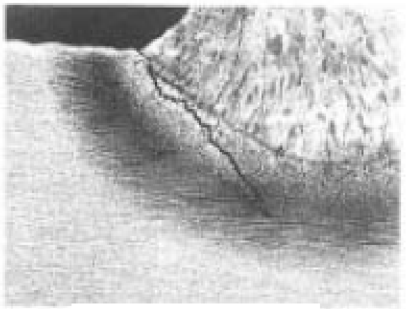
(2) Important parameter in welding process

Groove shape: RPV, internals Butt joint
Heat input power:
Minimum preheat and interpass temperature
Post weld heat treatment

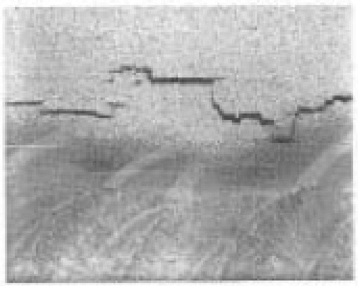
(3) Weld defects

● : often ▲ : occasionally

Material	Hot cracking	Cold cracking		Lamellar tear	SR cracking
		Delayed crack	Quenching crack		
Low carbon steel		▲		▲	
Low alloy steel		●			●
Cr-Mo steel		●			●
Martensitic stainless steel	▲	●	▲		
Austenitic stainless steel	●				▲
Ni-base alloy	●				
Cu alloy	●				▲



Delay cracking

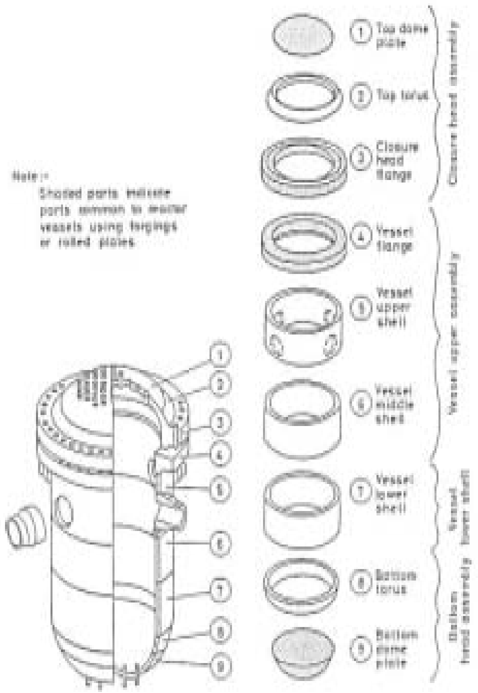


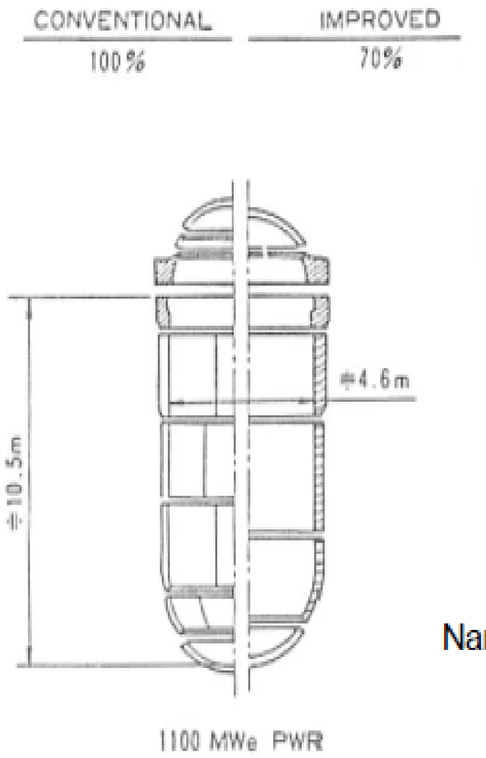
Lamellar tear

Hot cracking

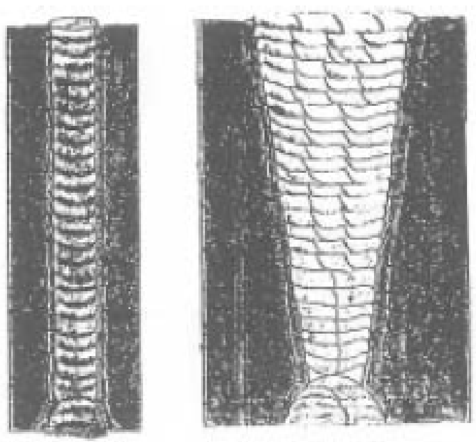
Position of welding

- Reactor pressure vessel (RPV), Vessel support, ⇨ Heavy steel
  Reduce weld lines.





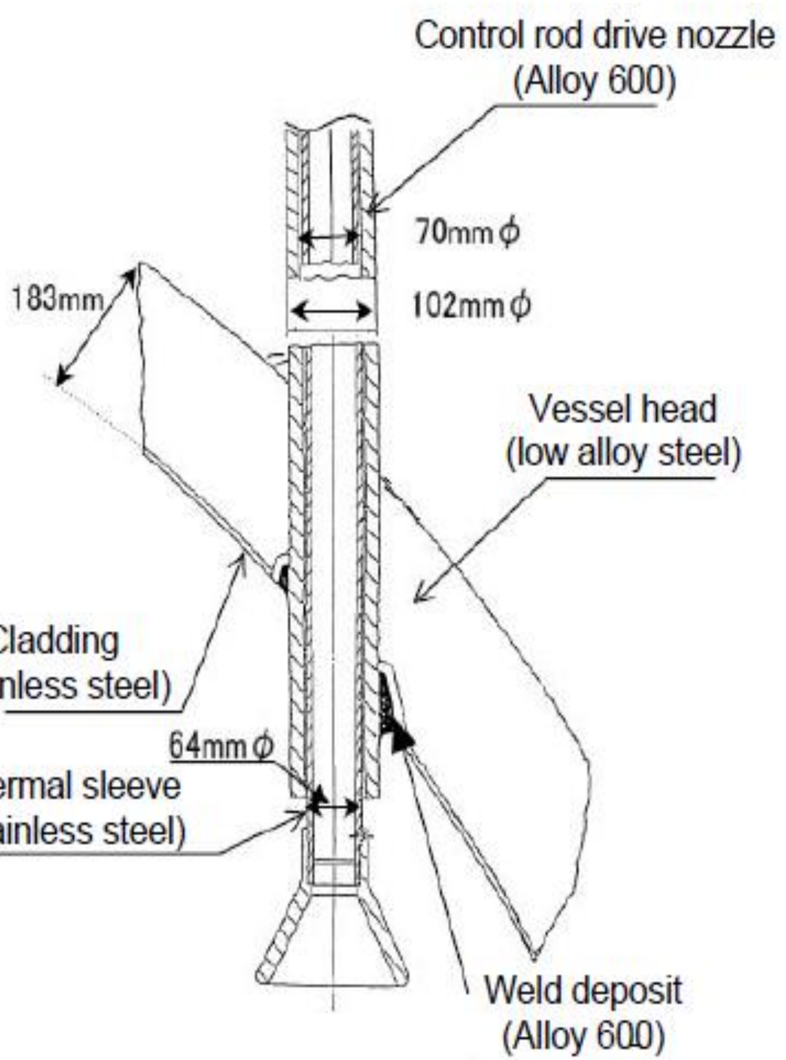
New | Old



Narrow groove MIG | SAW

No longitudinal weld lines

- RPV head, control rod drive nozzle



J-groove weld

Degradation – Material Issues

1. Reactor pressure vessel

Radiation embrittlement, Primary water stress corrosion cracking(PWSCC), Boric acid corrosion

2. Reactor coolant piping and safe ends

Low and high cycle thermal fatigue, Thermal embrittlement, High cycle mechanical fatigue

3. Steam generator

PWSCC, Intergranular stress corrosion cracking (IGSCC), Intergranular attack, Pipe fretting, Denting, Corrosion fatigue, High cycle fatigue, Wastage

4. Reactor coolant pumps

Thermal embrittlement, boric acid corrosion, high cycle mechanical and thermal fatigue

5. Pressurizer

Low cycle thermal fatigue, PWSCC

6. Control rod drive mechanism

Thermal embrittlement, PWSCC, wear, insulation breakdown

7. RPV internals

Irradiation induced stress corrosion cracking (IASCC), High cycle mechanical fatigue, IGSCC, Stress relaxation, IG cracking

8. Feedwaterpiping and nozzles

High and low cycle thermal fatigue, Flow accelerated corrosion (FAC), SCC

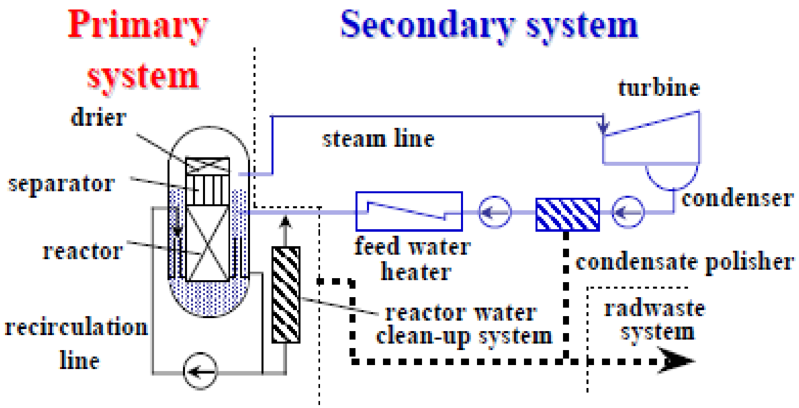
Water Chemistry

Structural materials of PWR/BWR are exposed to the high-temperature cooling water. In the corrosive environments, chemical interactions between the materials and water caused various kindof material degradation and consequent problems on the components. Therefore, a quality of cooling water or water chemistry is one of the most important issue for the operation of NPPs.

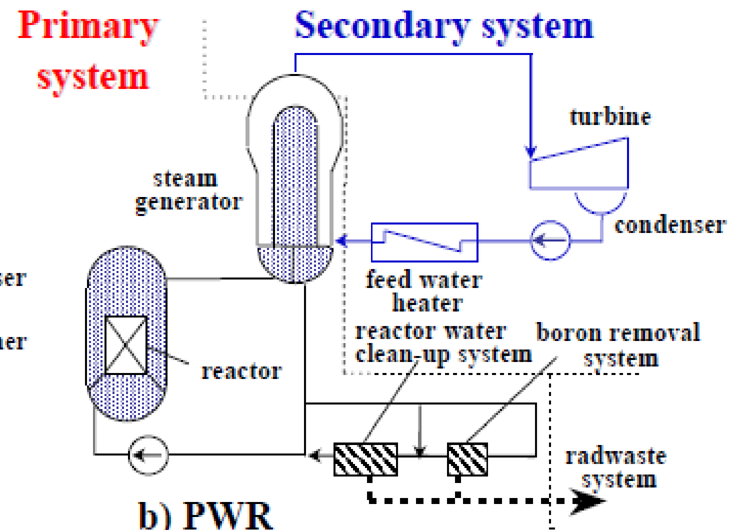
Water Chemistry

Comparison of cooling system of BWRs and PWRs

item		BWR	PWR
reactivity control		control rod + void (core flow rate)	control rod + chemical shim (B)
corrosion control	pH	neutral [pH_{RT}: 5.6-8.6]	alkaline [pH_{RT}>9]
	$[O_2]$	200 ppb [HWC : <10 ppb]	<1 ppb
	$[H_2]$	20 ppb [HWC : 50 ppb]	2 ppm
turbine dose rate		during operation ^{16}N during plant shutdown ^{60}Co, ^{51}Cr	dose rate free



a) BWR



b) PWR

Water Chemistry

Major interactions
between cooling water and structural materials

PWR (PWR primary)	PWR (secondary)	BWR
SCC of stainless steel	SCC of SG tubing	SCC
SCC of nickel alloy (PWSCC)	wall thinning	erosion-corrosion
	denting	
Radioactive corrosion product accumulation (dose rate buildup)	IGA	Radioactive corrosion product accumulation (dose rate buildup)
	pitting	
	erosion-corrosion	

Water Chemistry

Latest problems related to water chemistry

- Latest experiences with problems related to water chemistry are as follows.

  1) Increasing occupational exposure

     Challenge to more dose reduction by water chemistry improvement

  2) Stress corrosion cracking of BWR core shrouds

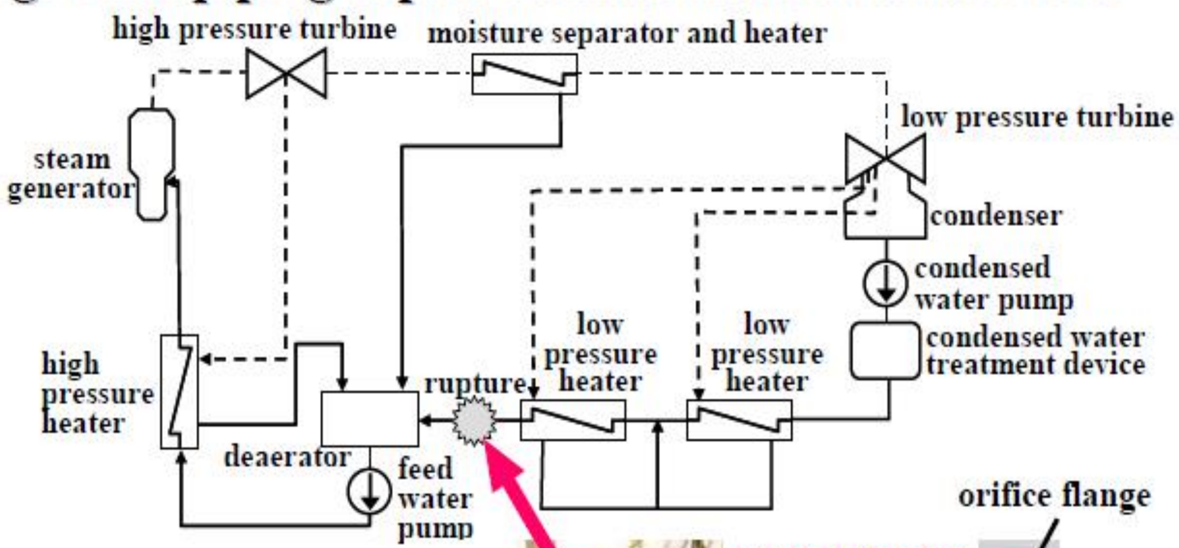
     Mitigation of corrosive conditions by water chemistry control

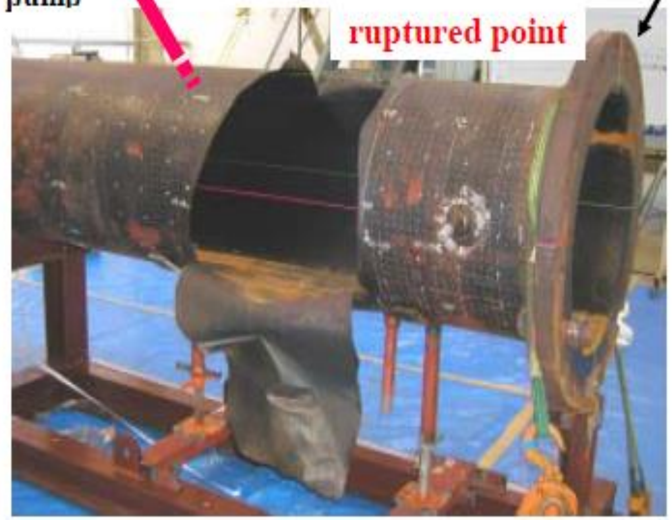
  3) Flow accelerated corrosion of PWR feed water piping

     Water chemistry improvement applying experience with BWR and fossil plants

Degradation – Material Issues

Large scale piping rupture accident at Mihama-3 NNP



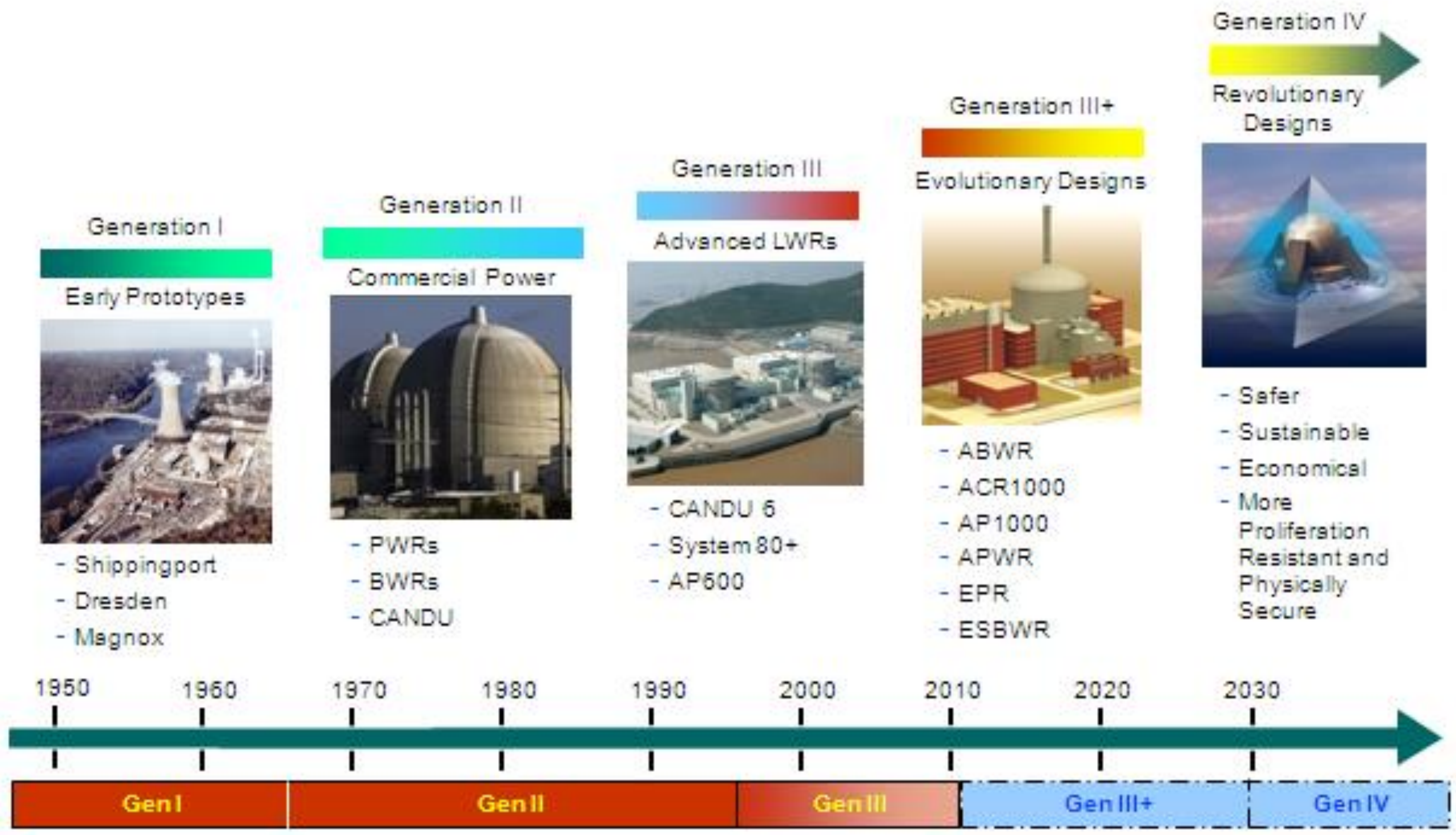


Parameter	
Operating time	185,700 h
Outer diameter	560 mm
Initial thickness	10 mm
Pressure	0.93 MPa
Temperature	142 °C
Flow velocity	2.2 m/s
pH	8.6 - 9.3
DO*	< 5 ppb

*DO: dissolved oxygen

V. Materials for Gen-IV Reactors

Evolution of Nuclear Reactors



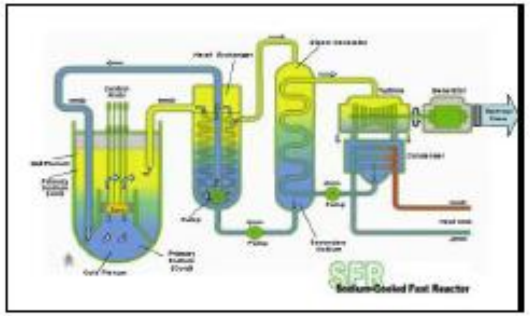
Evolution of Nuclear Reactors in The World

5 Characteristics of GEN-IV Reactors

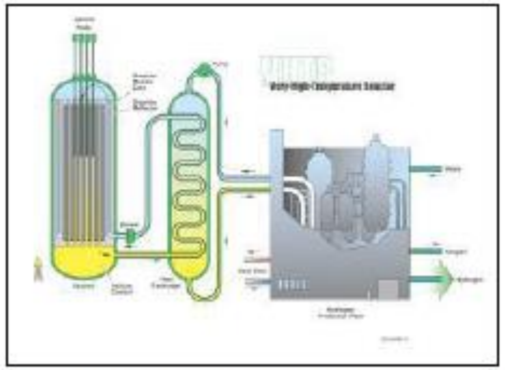
U.S. DOE (*Department of Energy*) and Generation IV International Forum (GIF)

- Optimal: Nat. Uranium
- Minimal: Radioactive Waste
- High: Safety
- Non: Proliferation
- Competitive: Economic

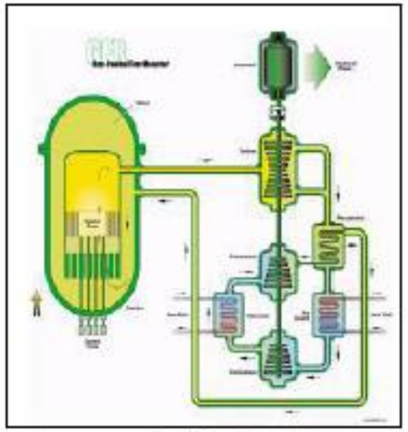
6 Type GEN-IV Reactors



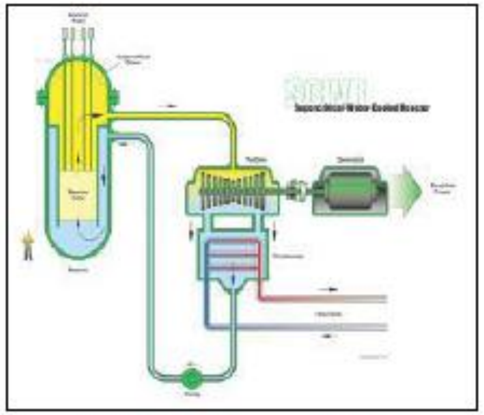
Sodium-cooled Fast Reactor (SFR)



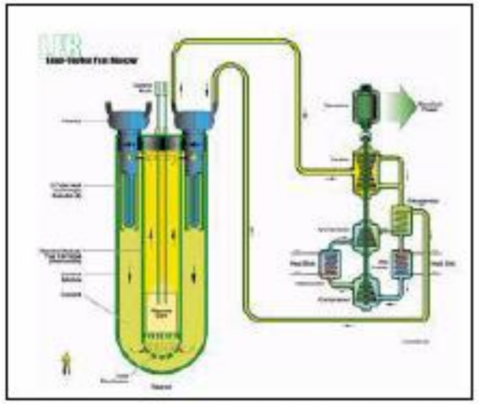
Very High Temperature Reactor (VHTR)



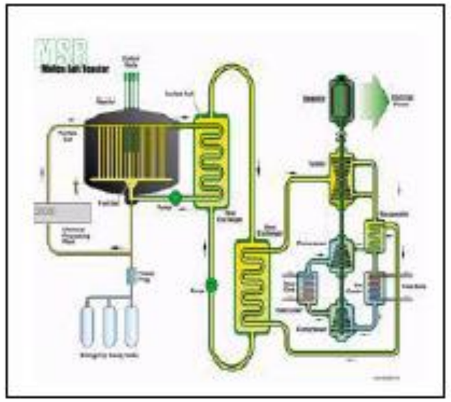
Gas-cooled Fast Reactor (GFR)



Supercritical Water-cooled Reactor (SCWR)



Lead-cooled Fast Reactor (LFR)



Molten Salt Reactor (MSR)

6 Type of GEN-IV Reactors

Type	Coolant	Neutron Spectrum	Doses (dpa)	Outlet Temperature (°C)
SCWR	Water	Thermal/Fast	10-40	550
SFR	Sodium (Na)	Fast	90-160	550
LFR	Pb/ Pb-Bi	Fast	50-130	550-800
GFR	He	Fast	50-90	850
MSR	Salt	Thermal	100-180	700-800
VHTR	He	Thermal/Fast	7-30	1000

3 Issues - Advanced Reactors

1. **Irradiation.**
2. **Temperature.**
3. **Chemical Hazard.**

HIGH

Advanced Materials:
New, Innovative and Alternative

Advanced Materials- Advanced Reactors

Table 7
Main characteristics of GIV nuclear fission reactor systems [66–75].

Reactor type	Fuel	Coolant	Moderator	Neutron spectrum	Core outlet temperature (°C)	Dose (dpa)	Candidate cladding material
Super critical water-cooled reactor (SCWR)	UO_2 (thermal) MOX (fast)	Water	Water	Thermal or Fast	~ 550	10–40	Zr alloys Austenitic stainless steel F/M steels Ni–based superalloys ODS alloys
Sodium-cooled fast reactor (SFR)	UPuC/SiC U–Pu–Zr MOX	Liquid Na	–	Fast	~ 550	90–160	F/M steels ODS alloys
Lead-cooled reactor (LFR)	Nitrides, MOX	Liquid Pb alloys	–	Fast	550–800	50–130	Austenitic stainless steel F/M steels ODS alloys SiC Refractory alloys
Gas-cooled fast reactor (GFR)	(U, Pu)O_2 Carbide fuel (U, Pu)	He	–	Fast	~ 850	50–90	ODS alloys Refractory alloys SiC
Molten salt reactor (MSR)	Salt	Molten salt	Graphite	Thermal	700–800	100–180	No cladding
Very high temperature reactor (VHTR)	TRISO UOC	He	Graphite (thermal)	Thermal or Fast	1000	7–30	ZrC coating SiC coating

* TRISO: Tristructural isotropic fuel, a type of micro fuel particle consisting of a fuel kernel composed of uranium oxide (sometimes uranium carbide) in the centre, coated with four layers of three isotropic materials.

Review

Selection of fuel cladding material for nuclear fission reactors

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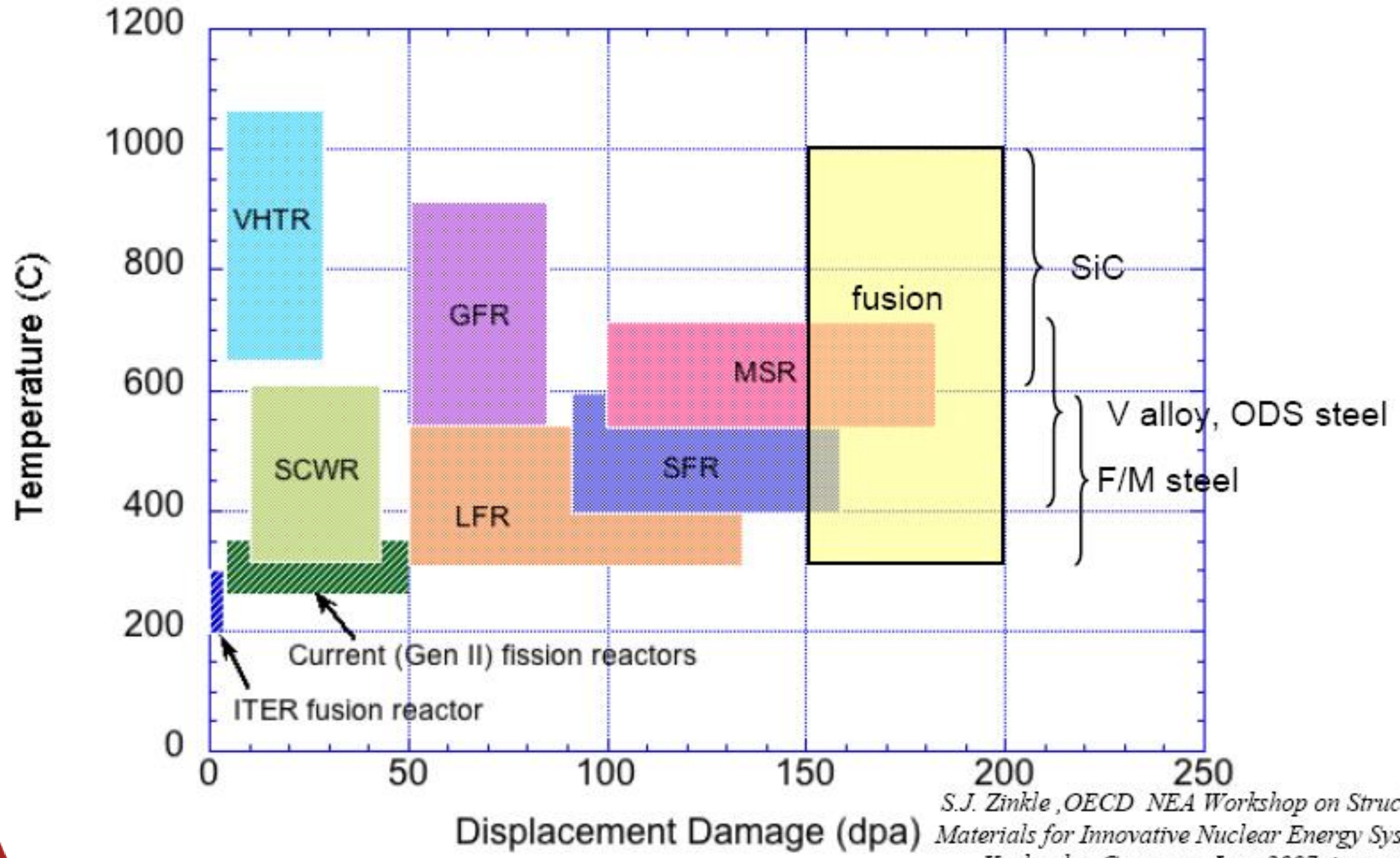
Universidade de São Paulo, Dep. Engenharia Metalúrgica e de Materiais, Escola Politécnica, Brazil

Engineering Failure Analysis 18 (2011) 1943–1962



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5. Dr. Takashi Tsukada – JAEA, Lecture notes.
6. Dr. Abu Khalid Rivai – BRIN, Lecture notes.

Thank you for your attention

ありがとうございます

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