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Innovative Nuclear Energy Systems: Reactor Design and Structural Designs

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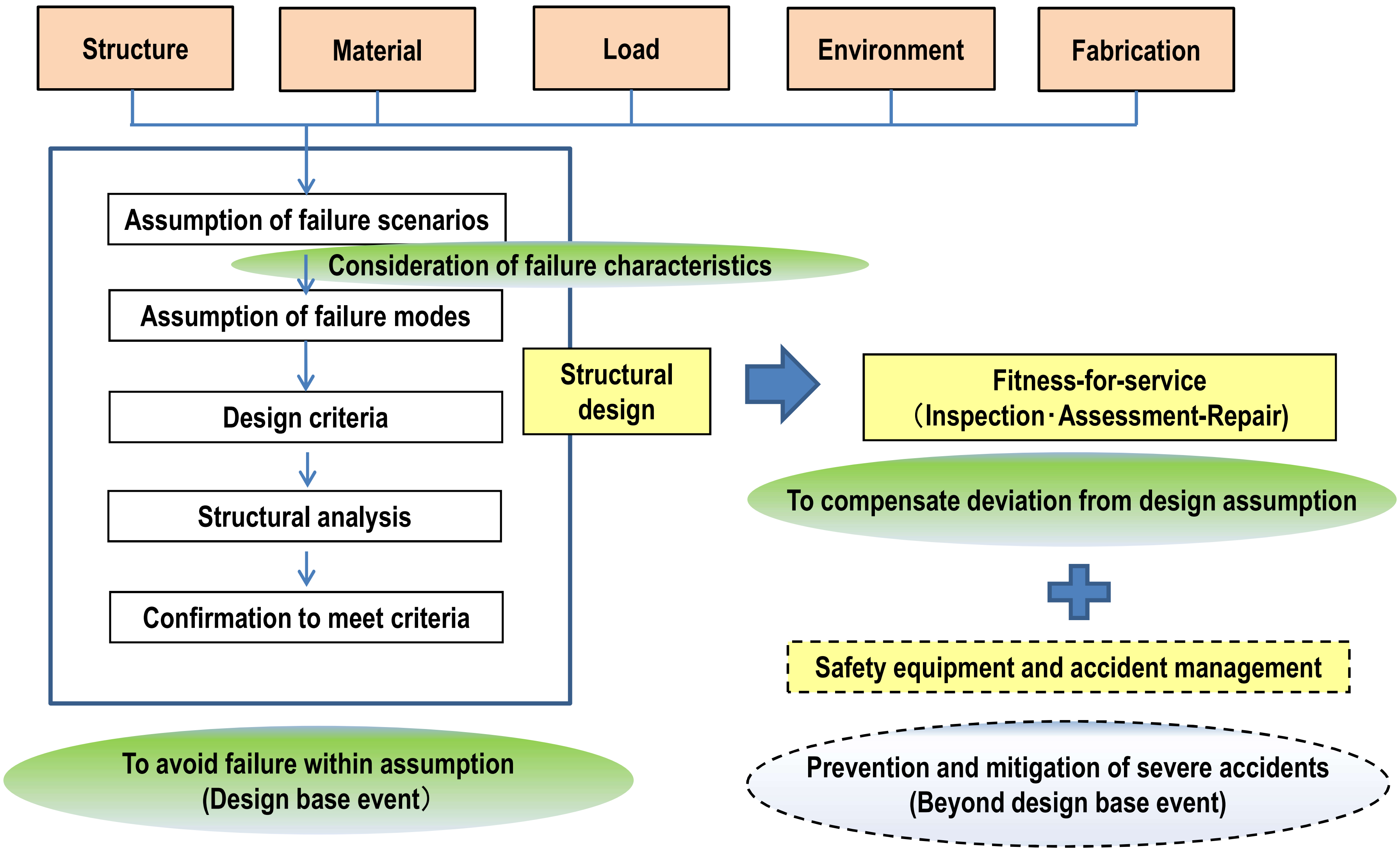
Content

1. ***Integrated Managements in Terms of Material, Design, Manufacturing, Inspection and Maintenance Features of Structural Conditions of FRs***
2. ***Component Design of FR***
3. ***Inspection and Maintenance***

1. Integrated Managements in Terms of Material, Design, Manufacturing, Inspection and Maintenance



Approach to ensuring structural integrity of reactor facility

Ref: Fast Reactor System Design, Naoto Kasahara Ed., Springer.

Relationship between failure modes and countermeasures

Failure modes	Material	Design	Fabrication	Inspection	Fitness-for-service
Brittle fractures	◎	○Requirement for ductility	△Delayed fracture Heat treatment	○ Defect size	○Defect assessment Monitoring of nil-ductility transition temperature (NDTT)
Ductile fractures	△	◎		△ Plate thickness	△Thinning assessment
Buckling		◎	△Tolerance		△
Excessive deformation		◎			△
Fatigue		◎	○Finishing	○ Defect size	○Defect assessment Monitoring of operating transients

Ref: Fast Reactor System Design, Naoto Kasahara Ed., Springer.

1.1 Structural Design Methods for Nuclear Components

rational design : keep the risk at an appropriate level.

→ imposing design margin according to *safety importance* and *loading frequency*

Component Classification based on safety significance

Class 1 Component	Components forming reactor coolant boundary (e.g., reactor vessel, IHX, primary pump)
Class 2 Component	Component forming reactor cover gas boundary, safety systems, etc. (e.g., secondary main pipe, guard vessel, primary cover gas system)
Components of less safety significance	Class 3 components etc. (e.g., steam generator, secondary cover gas system)
Class MC vessel	Metal containment vessel

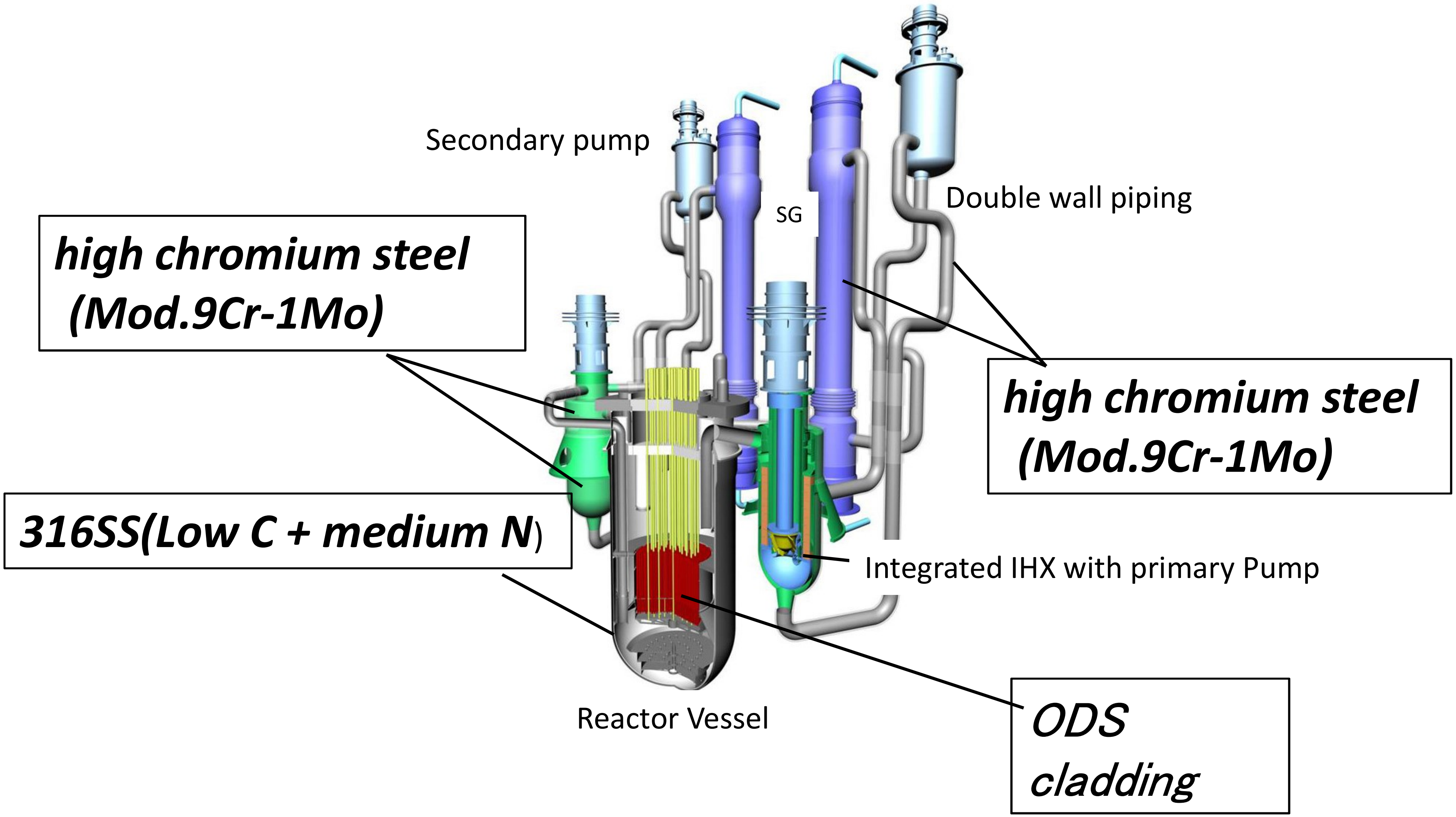
Condition classification based on the frequency of occurrence of loading

Service condition I	Normal operating conditions of nuclear reactor facility
Service condition II	Conditions deviated from normal operating conditions due to single failure of component, misoperation or other causes
Service condition III	Conditions requiring emergency shutdown due to a failure or abnormality of reactor facility
Service condition IV	Conditions where an abnormal situation assumed in reactor safety design occurs
Testing Condition	Conditions where pressure exceeding the maximum service pressure is applied during a pressure test

Ref: Fast Reactor System Design, Naoto Kasahara Ed., Springer.

1.2 Structural Material of FRs

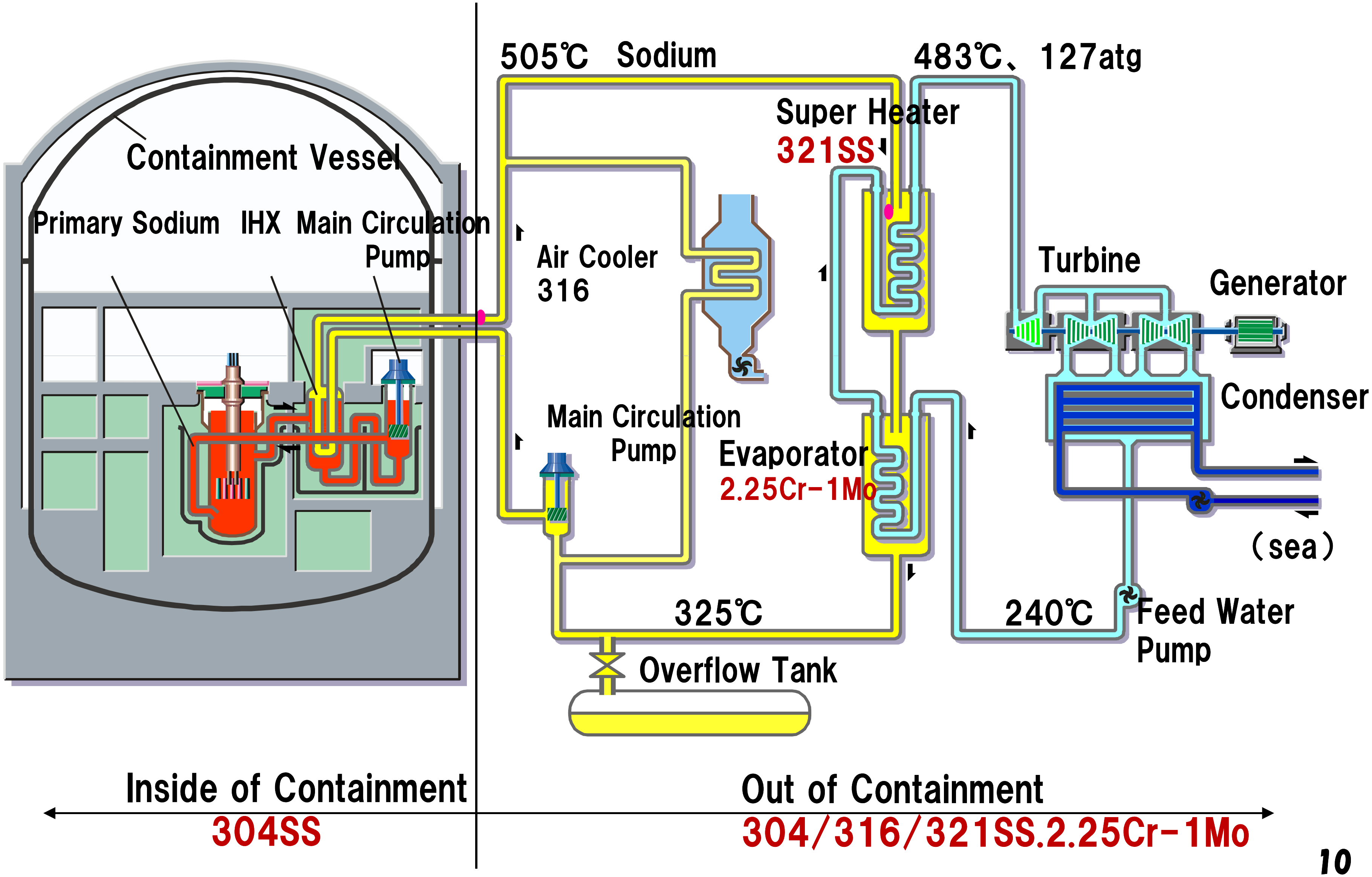
Materials employed in GenIV SFR



Property of Materials Employed in GenIV SFR

316SS (Low C + Medium N)	It is excellent in high temperature strength and ductility, corrosion resistance, workability and has low degree of embrittlement and hardening due to neutron irradiation. 2.5%Mo is added to improve corrosion resistance, high temperature strength etc. Restriction on Carbon content, and addition of Nitrogen with low to medium extent.	Reactor Vessel
Mod.9Cr–1Mo	Developed in ORNL(US), followed by Japan etc. **Mod.9Cr-1Mo steel has been used for boiler components in ultra-supercritical fossil power plants**.	IHX–Pump Piping Integrated SG

materials employed in MONJU

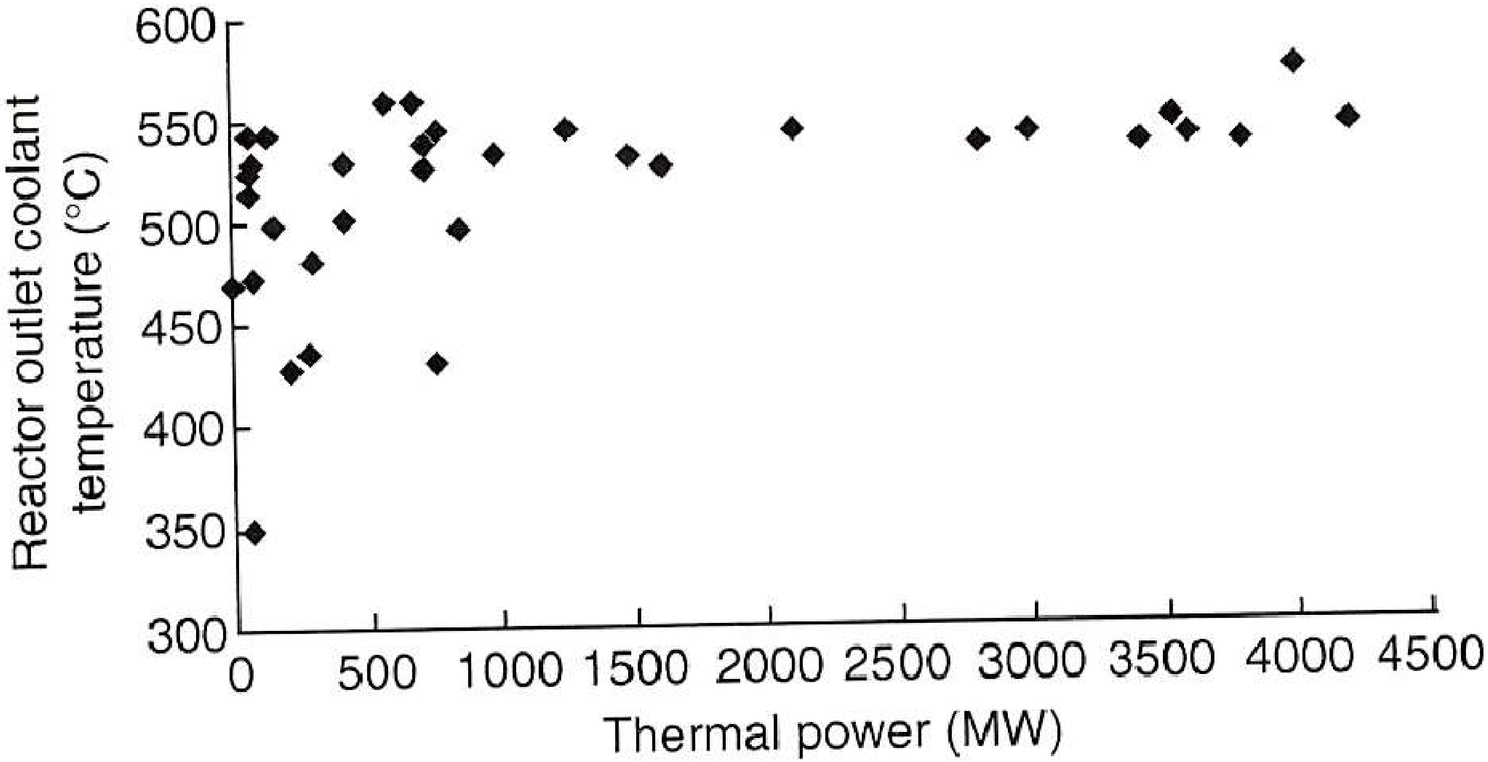


Property of Materials Employed in MONJU

304SS	It is excellent in high temperature strength and ductility, corrosion resistance, workability, weldability, and has low degree of embrittlement and hardening due to neutron irradiation. Restrictions on C and Co.	Reactor Vessel, IHX, etc
316SS	2.5%Mo is added to improve corrosion resistance, high temperature strength etc.	Air Cooler
321SS	Improve inter-granular corrosion resistance by adding Ti.	Heat transfer Tube of Super Heater
2.25Cr-1Mo	Low alloy steel. Proven material in fossil power plant, in particular heat exchangers.	Evaporator

1.3 Structural Design of FRs

(1) Loading Conditions Specific to the Use of Sodium



Ref: Fast Reactor System Design, Naoto Kasahara Ed., Springer.

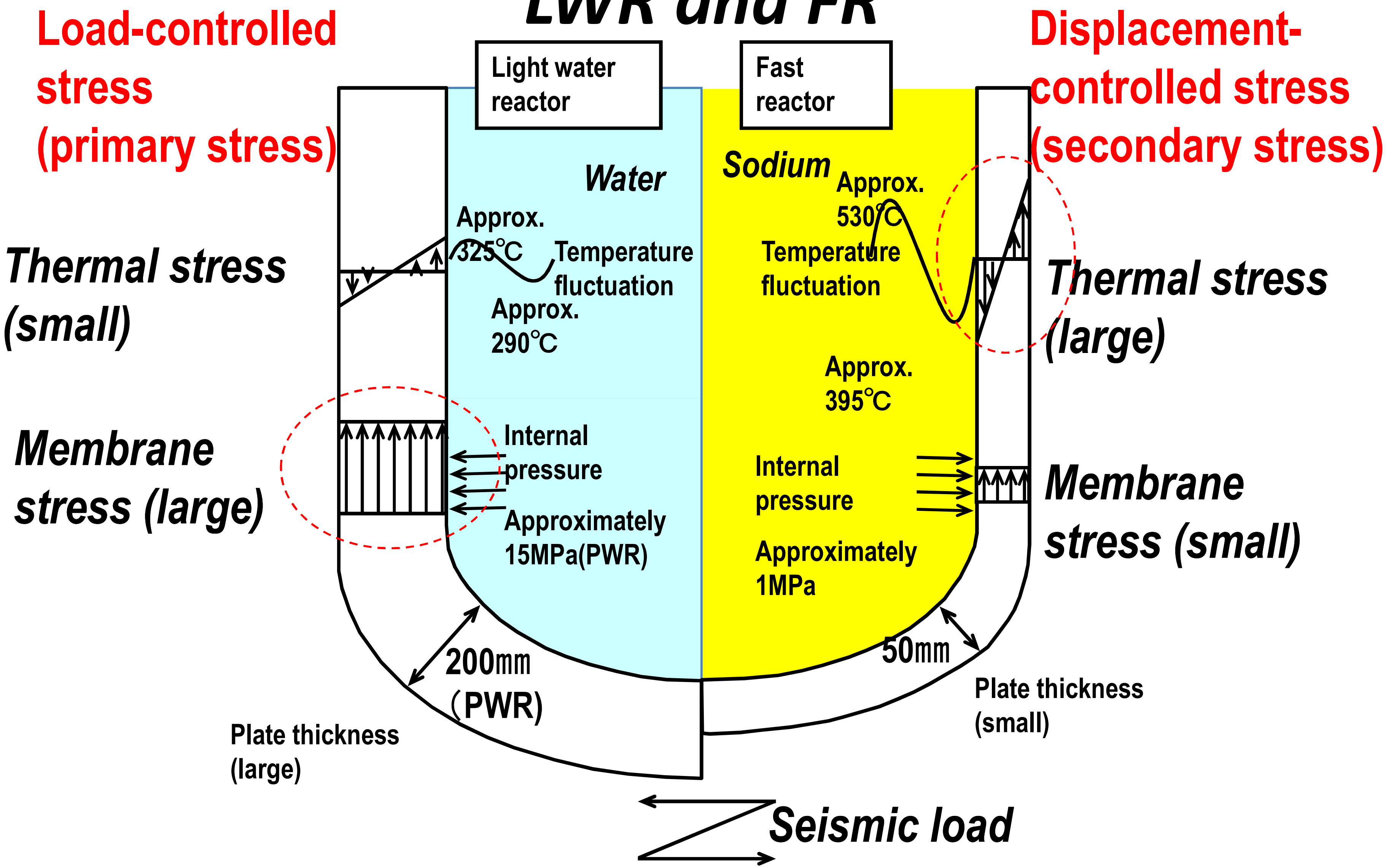
Comparison of Operating Condition with LWR

	LWR*1	FBR*2	Feature of FBR
Material	Ferrite Steel	Austenitic SS	Ductile Material
Coolant	Water	Sodium	High Boiling Point
Operating Temperature	320℃	529℃	High Temperature
Temperature difference	30℃	132℃	High Thermal Stress
Operation Pressure	≒16MPa	≒0.5MPa (Pump Outlet)	Low Pressure

＊1：PWR

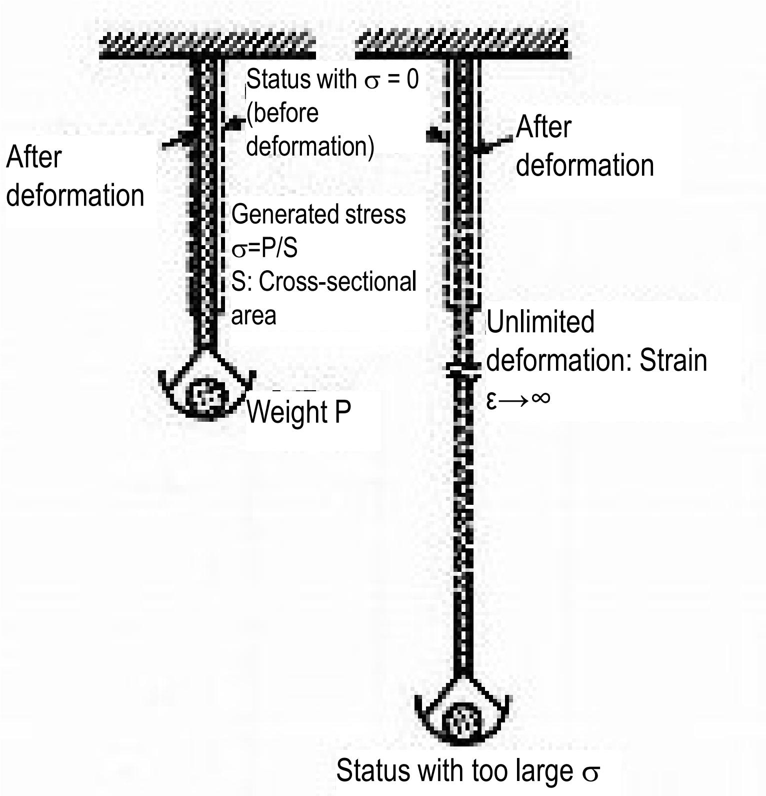
＊2：Monju

Comparison of loading conditions between LWR and FR

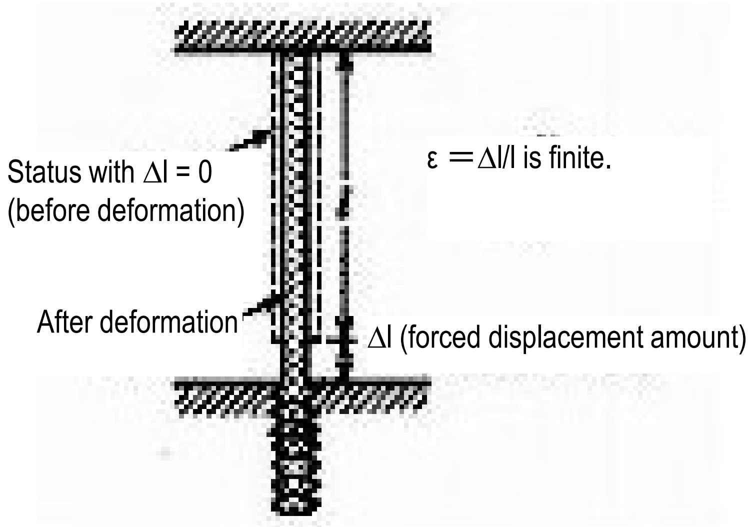


Ref: Fast Reactor System Design, Naoto Kasahara Ed., Springer.

Load-controlled stress versus Displacement-controlled stress



Load-controlled stress (primary stress)

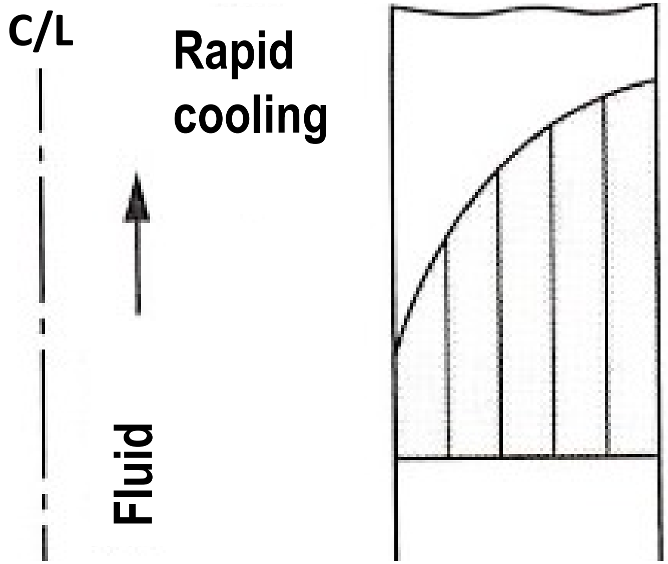


Displacement-controlled stress (secondary stress)

(2) Types of Thermal Loads

- Generally speaking, the effect of thermal transients on structural material in FRs are more severe than those in LWRs.
- Coolant; Heat transfer characteristic
- Structural material; Thermal conductivity, Thermal expansion rate

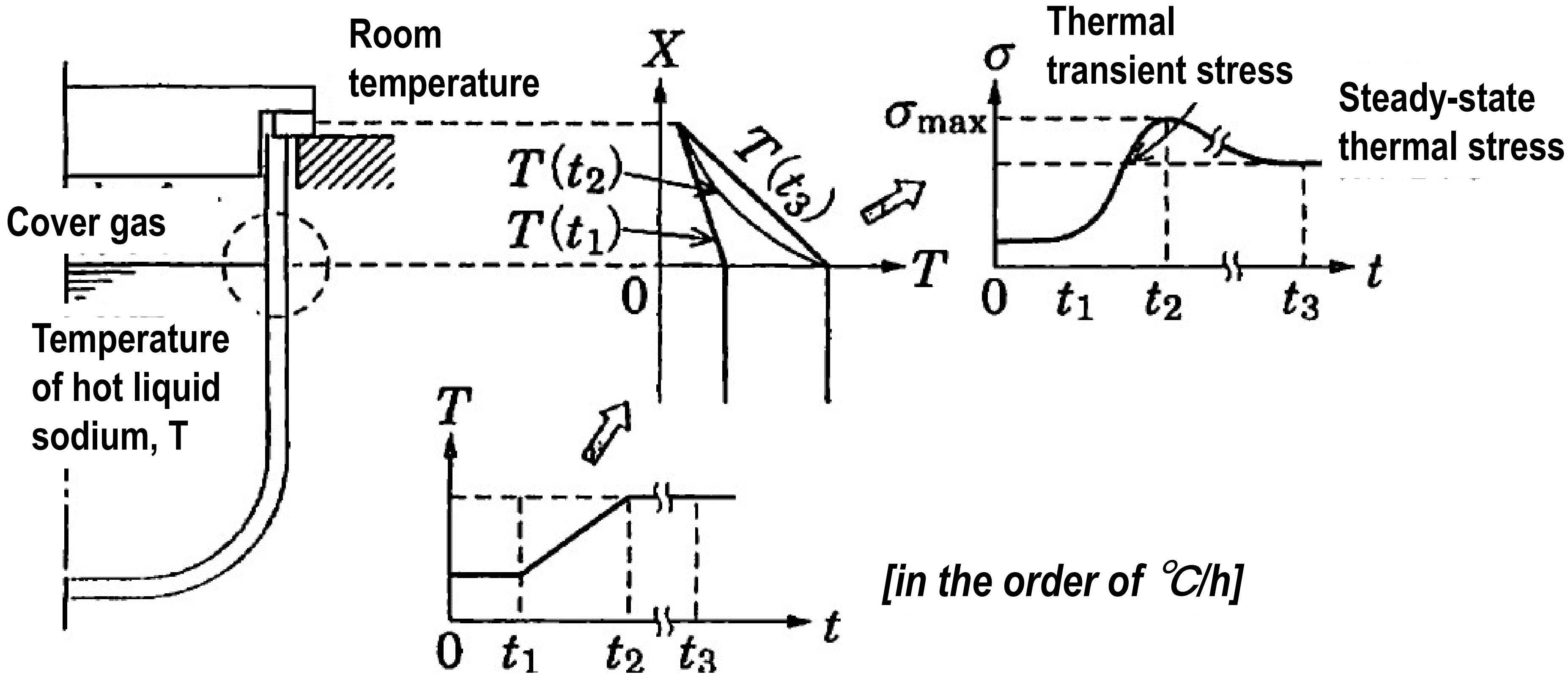
Typical Thermal Stresses in Fast Reactor
(a) Through-thickness temperature gradient



Temperature gradient may occur during steady-state conditions.

[in the order of °C/s]

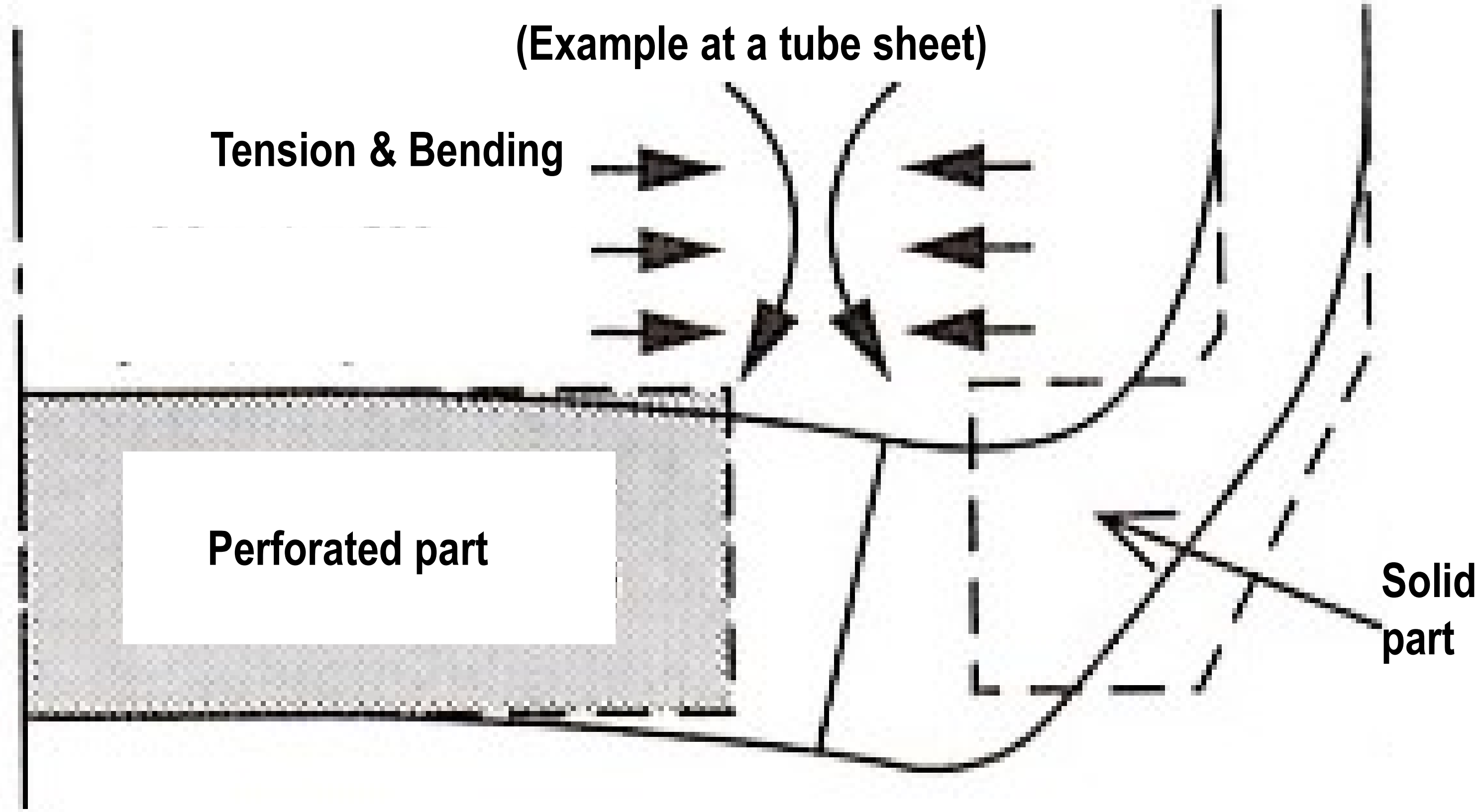
(b) Axial temperature gradient near sodium surface



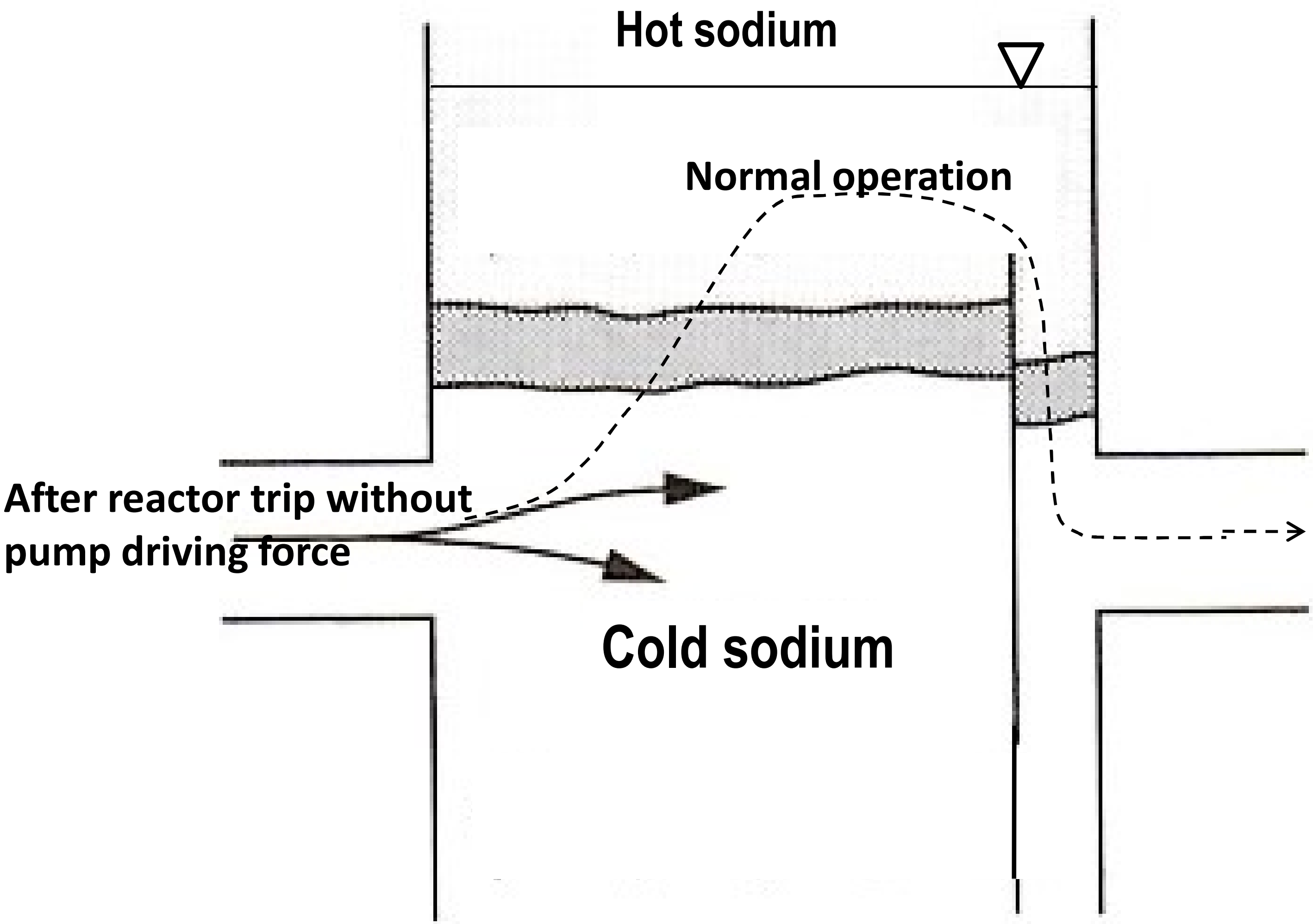
[in the order of ℃/h]

(c) Hoop force

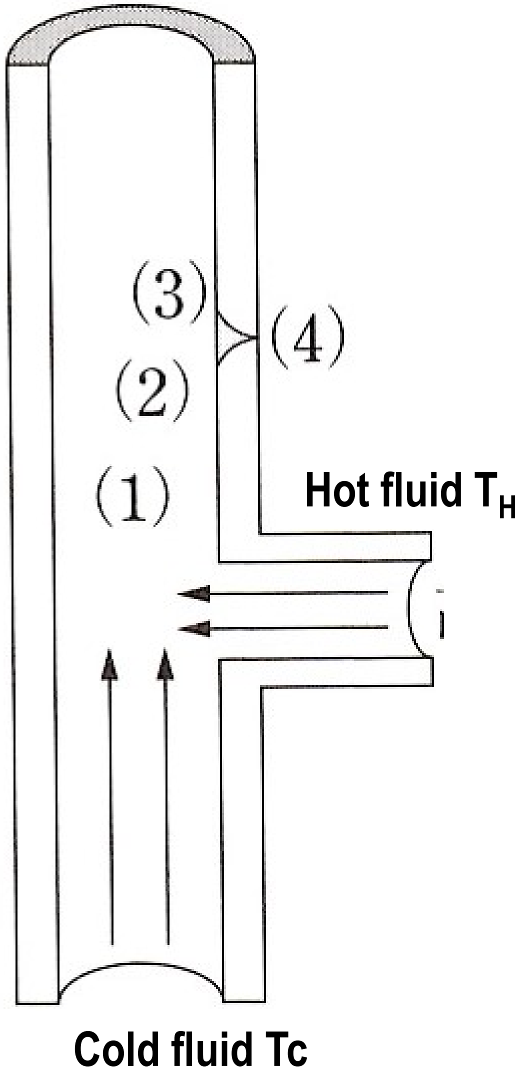
Binding force is exerted between perforated part that rapidly follows thermal transient and solid part that slowly follows.

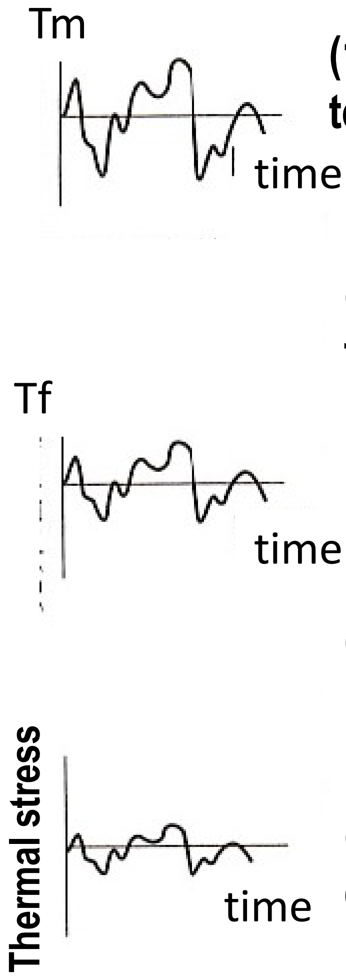


(d) Thermal stratification



(e) Thermal striping-1





(1) Main stream temperature change Tm

⬇

(2) Boundary layer temperature change Tf

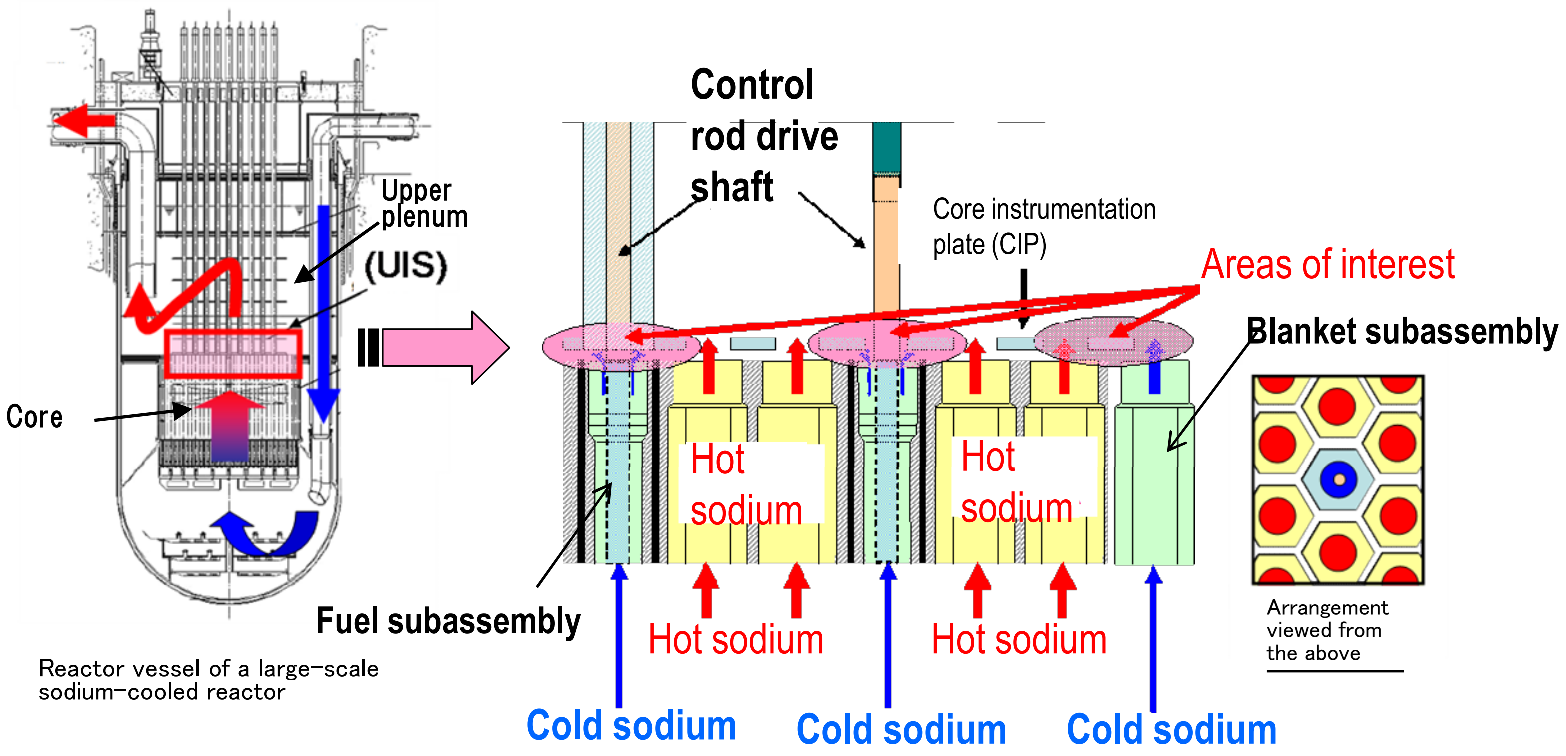
⬇

(3) Temperature change in structure

⬇

(4) Stress changes due to constraint

(e) Thermal striping-2



Schematic Diagram of Thermal Striping Phenomenon in the Lower Part of Core Internals

(3) Failure Modes Assumed in FRs

Failure modes	Material	Design	Fabrication	Inspection	Fitness-for-service
Brittle fractures	◎	○Requirement for ductility	△Delayed fracture Heat treatment	○ Defect size	○Defect assessment Monitoring of nil-ductility transition temperature (NDTT)
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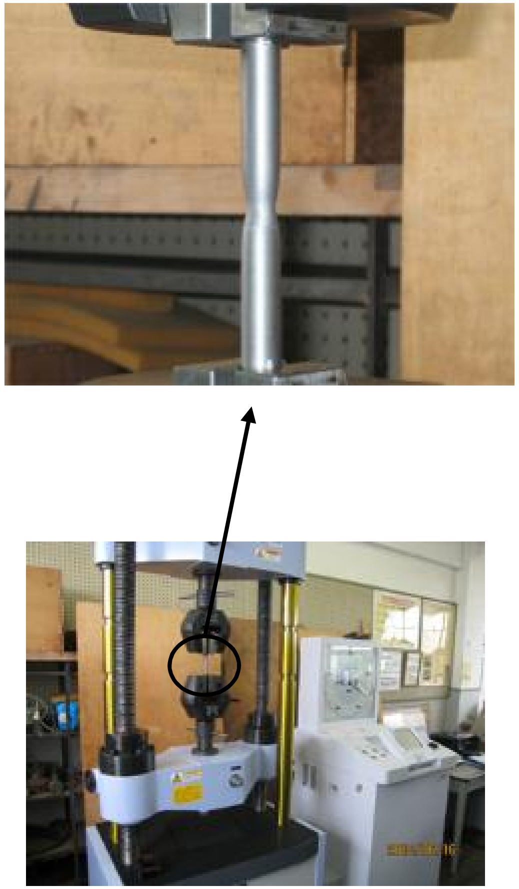
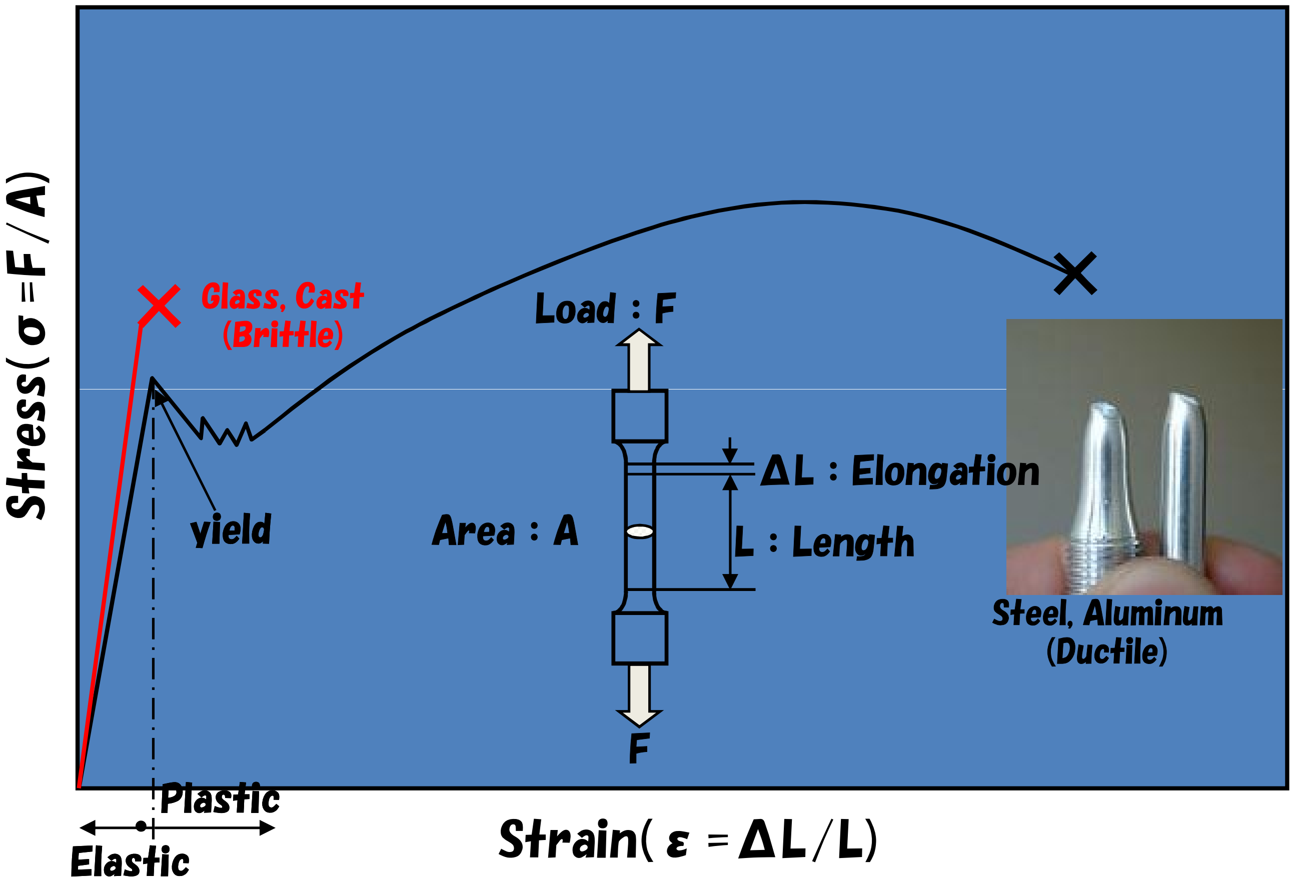
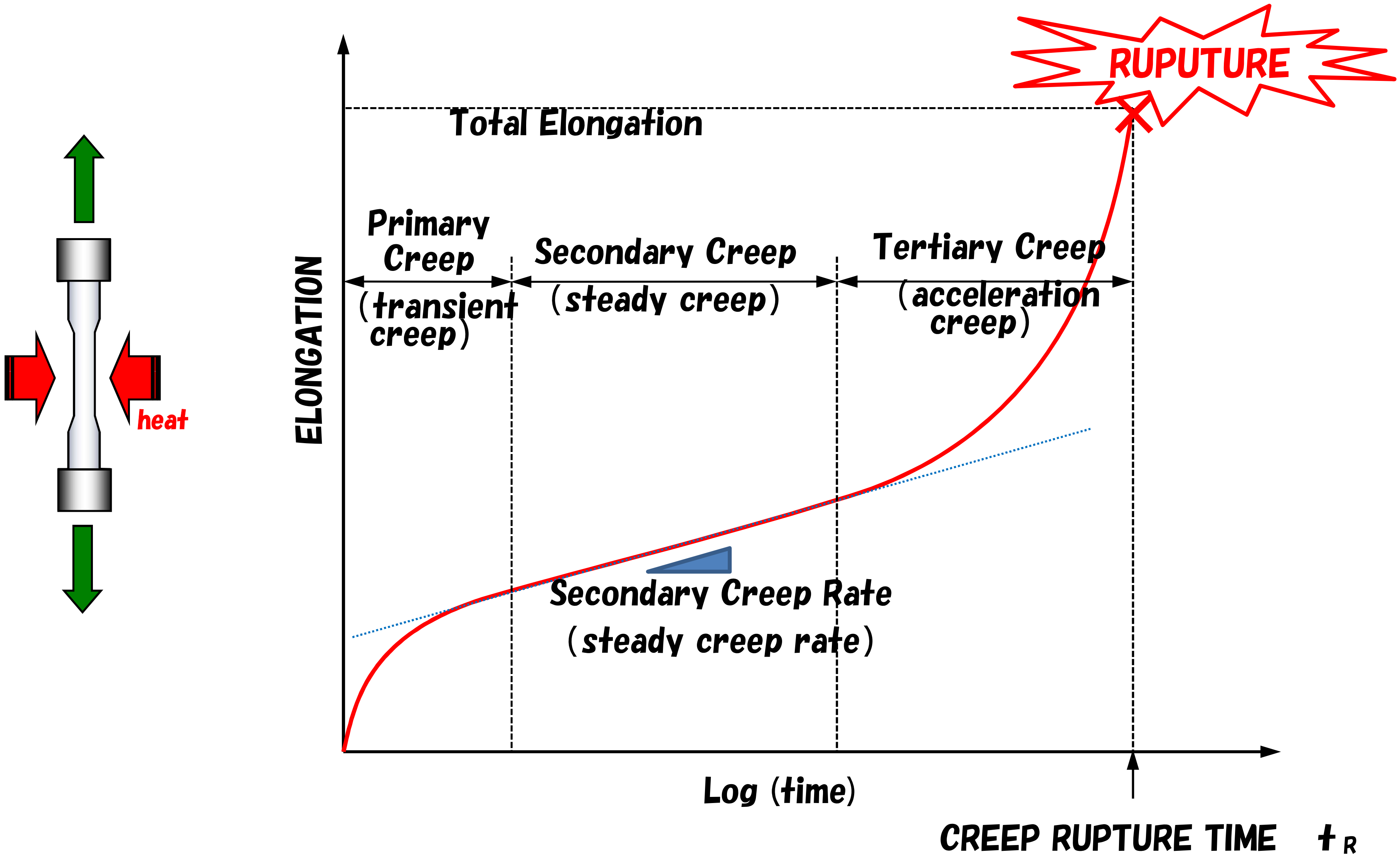
Ductile Fracture and Brittle Fracture



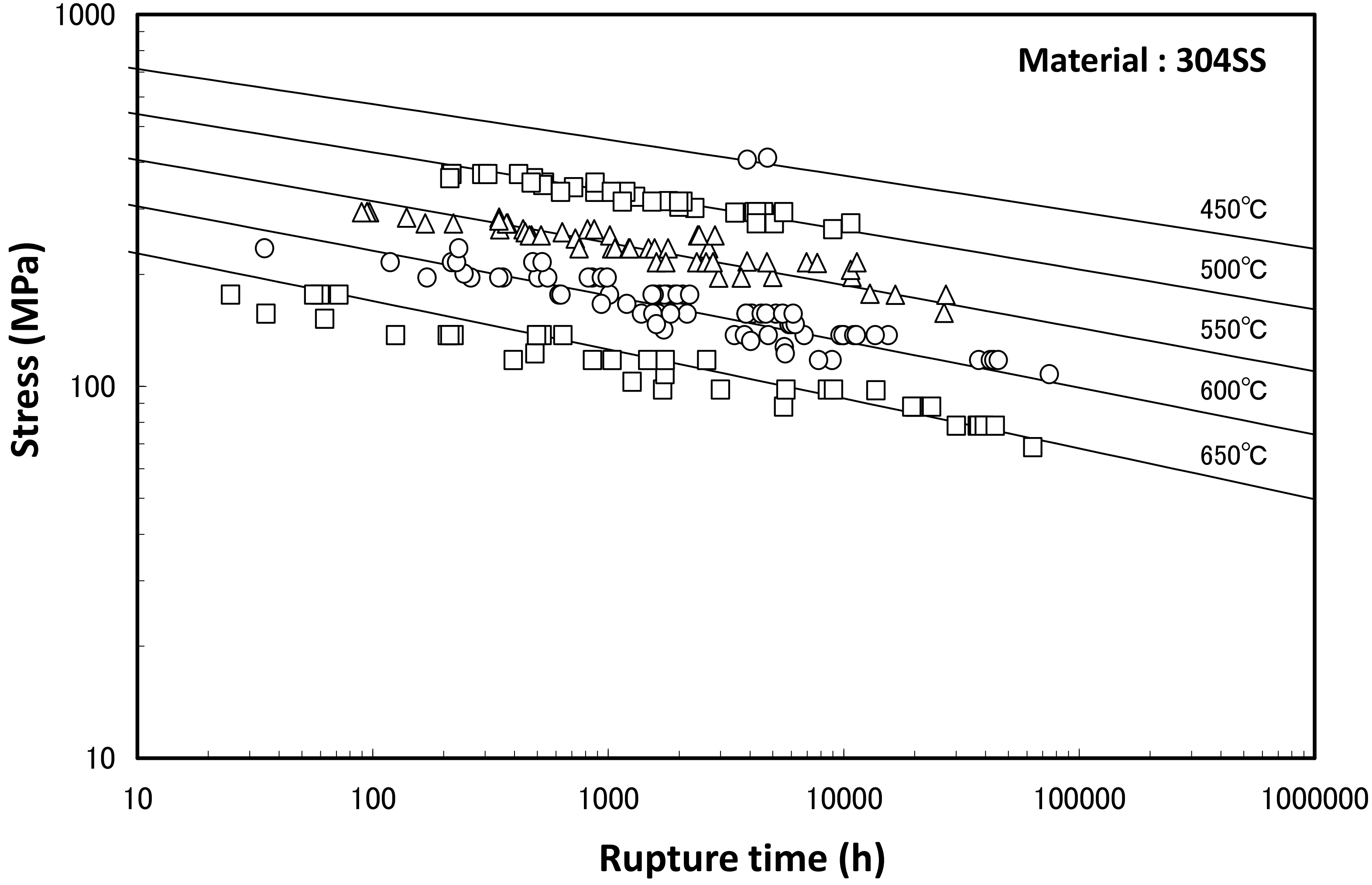
Tensile Test Machine



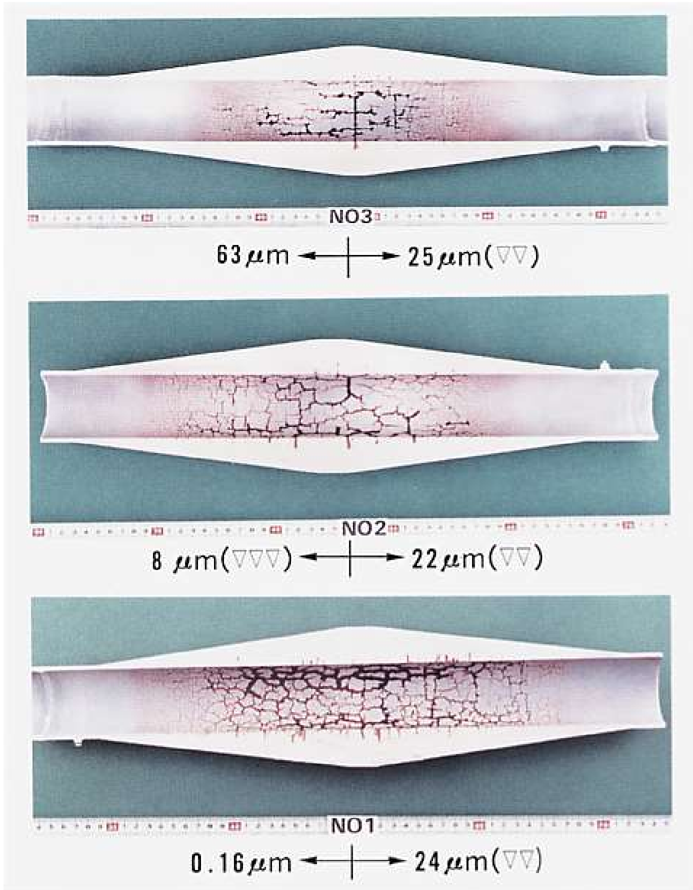
CREEP

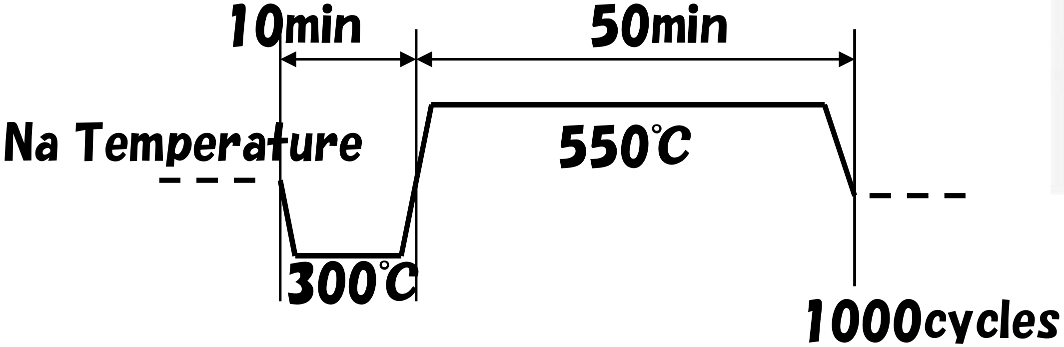

RUPUTURE
Total Elongation
Primary Creep
(transient creep)
Secondary Creep
(steady creep)
Tertiary Creep
(acceleration creep)
ELONGATION
heat
Secondary Creep Rate
(steady creep rate)
Log (time)
CREEP RUPTURE TIME t_R

Relationship between creep rupture time and temperature/stress

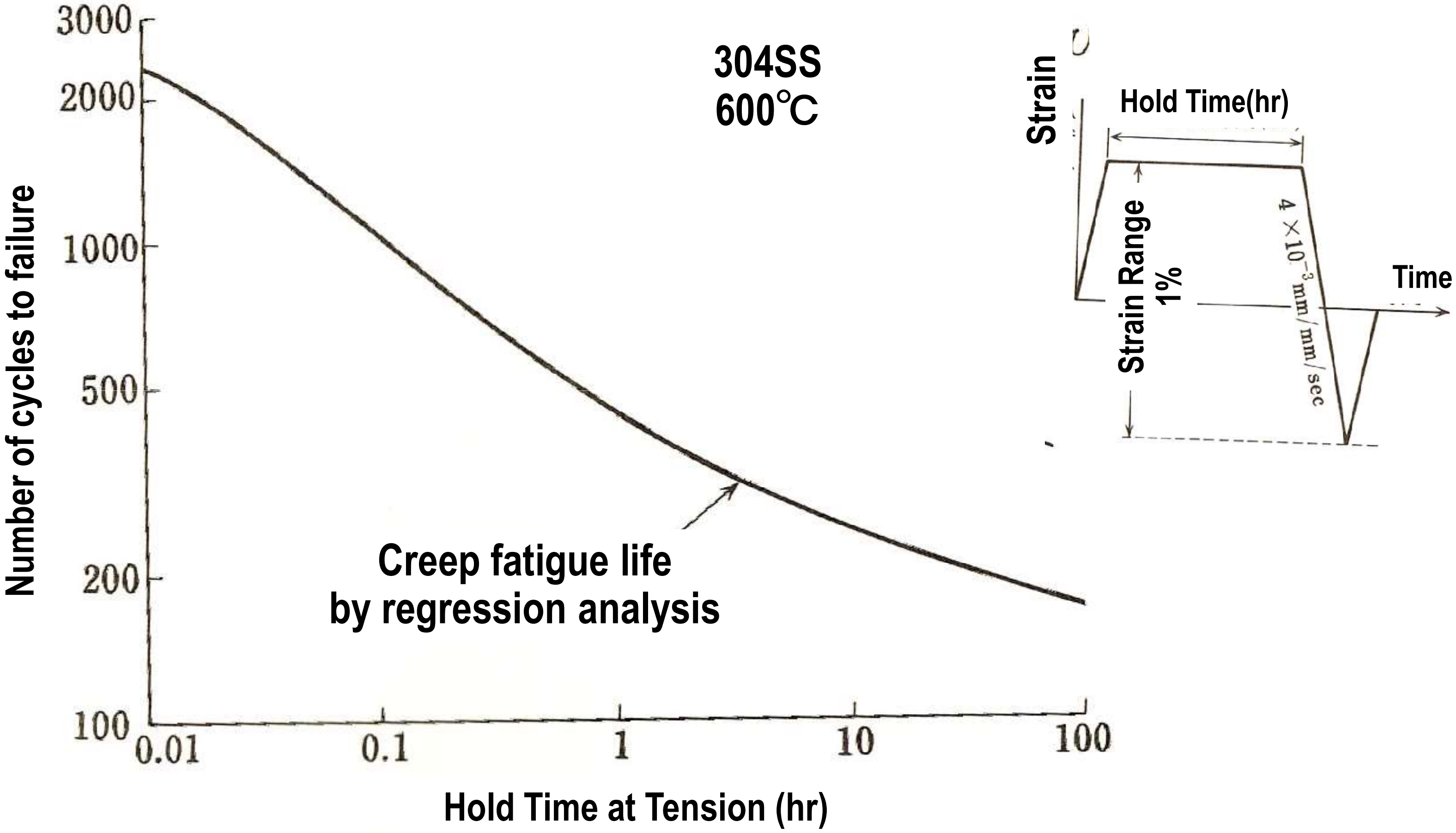


Creep-Fatigue Crack observed in the structure subject to repeated temperature change



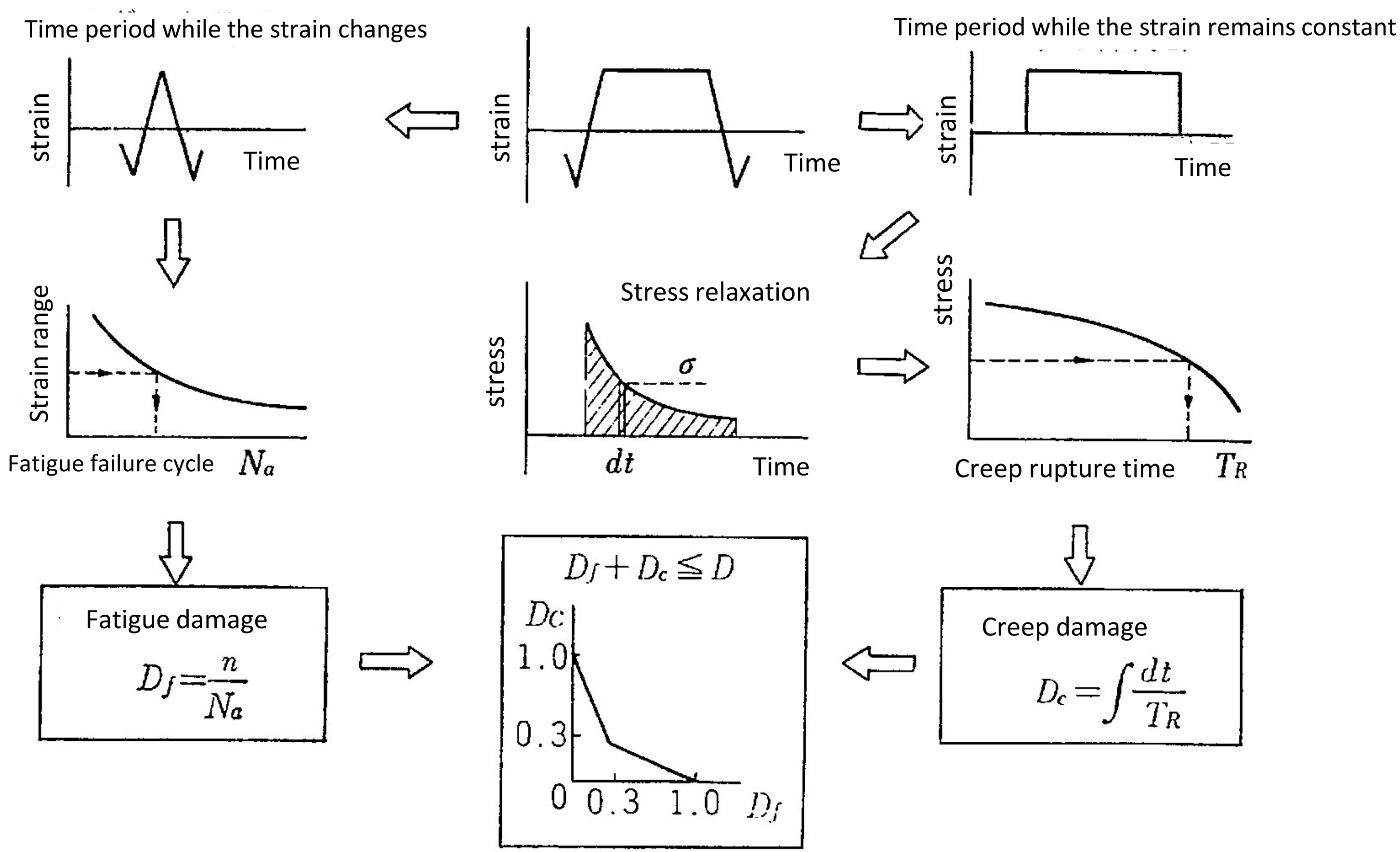


Creep-Fatigue Life



Limits for creep fatigue damage

The prevention of the creep fatigue failure is achieved according to the linear cumulative damage rule that limits the sum of the following calculated values : i) usage factor Df, and ii) creep damage factor Dc.



Expected failure modes of Reactor Vessels

Thermal load

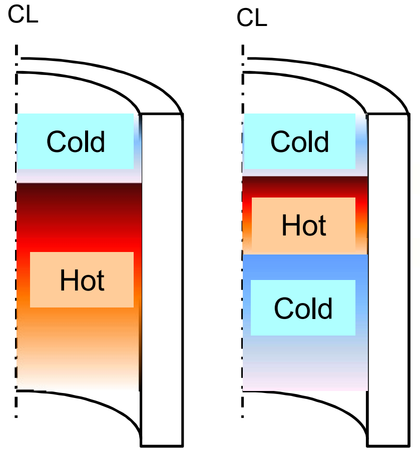
The dominant load is thermal stress caused by the change in fluid temperature during plant startup/shutdown

Structural response

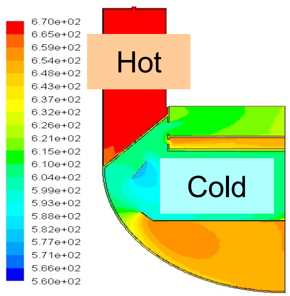
Elastic plastic creep response of structure due to operation at high temperatures

Failure

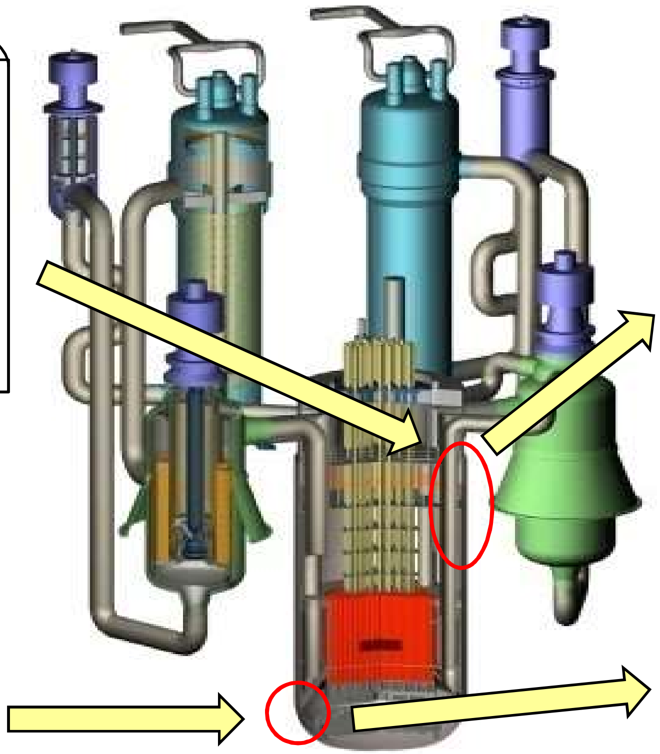
Failure mode due to cyclic loading during lifetime

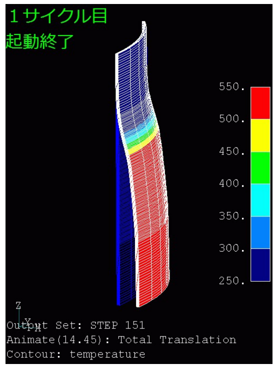


Startup Shutdown

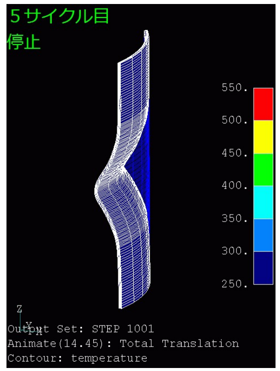


Shutdown

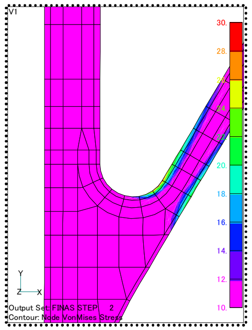




Residual strain



Excessive deformation due to ratcheting strain



Strain concentration

Creep fatigue crack

Ref: Fast Reactor System Design, Naoto Kasahara Ed., Springer.

Neutron Irradiation Effect

① Atoms on the metal crystal lattice are knocked out by collision with neutron to produce a disturbance of the crystal lattice(i.e., lattice defect)

⇒ Fast neutron （E>0.1MeV）

⇒ These defect hinder the distortion movement and lead to a reduction in ductility due to hardening.

② Thermal neutrons convert minute impurities in steel into He.

⇒ Thermal neutron （E<0.4eV）

⇒ The generated He atoms enhance the aggregation of vacancy to the grain boundary, etc., a reduction in ductility and creep strength results.