The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

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Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors

27 June - 1 July, 2011

INTRO TO MATERIALS AND CHEMISTRY

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IAEA – SCWR

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(SC22) Intro to materials and chemistry

Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy, 27 June - 1 July 2011

CONTENTS OF SC22

1. General about BWR and PWR development
2. PWR and BWR main components and materials / SCWR
3. Water chemistry characteristics and comparison
4. Main components and materials selection
5. Bimetallic material welding
6. Aging mechanisms

   Irradiation effects

   Corrosion types

7. Fuel cladding requirements and materials

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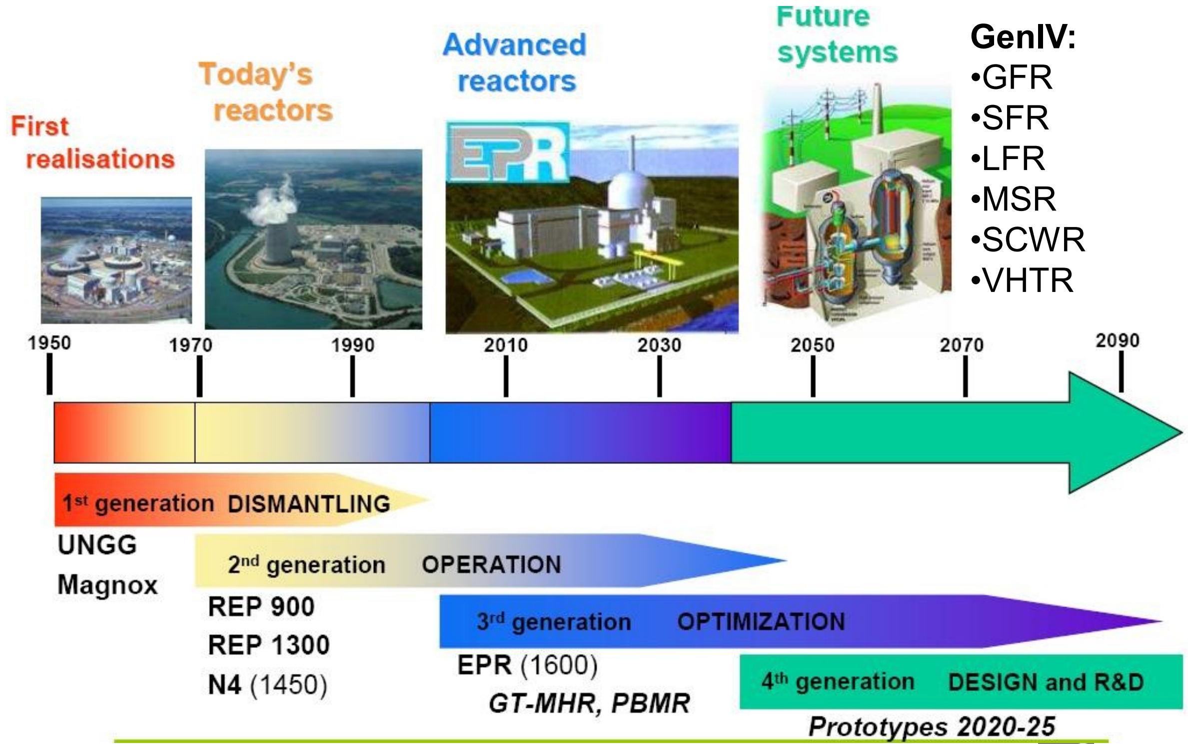
EVOLUTION OF FISSION REACTORS

- RPV size and power output increase
- safety improvements
- fuel improvements
- structural materials development and operational experiences
- water chemistry
- operational experiences

> longer lifetime
> better operability
> higher safety



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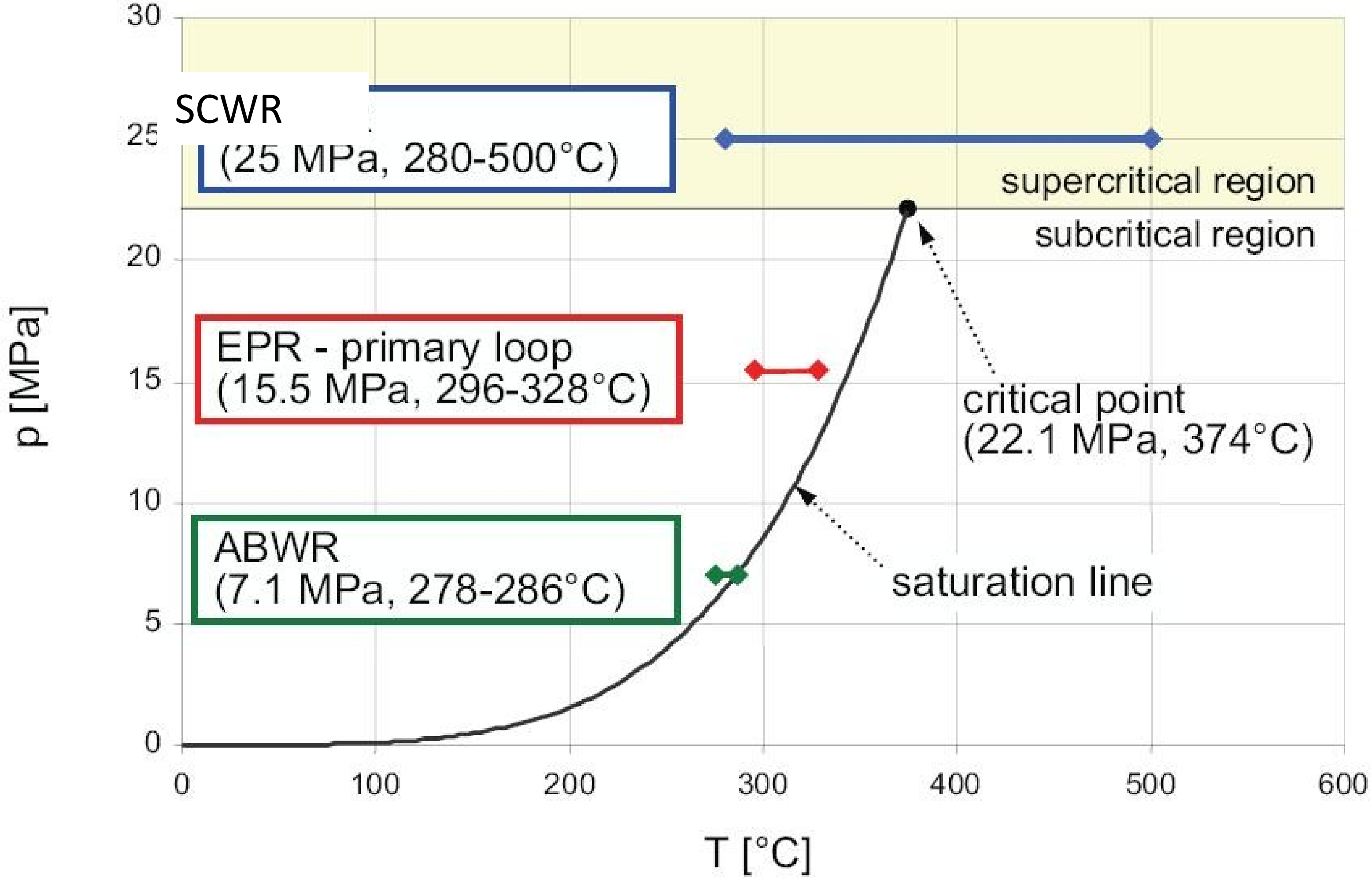
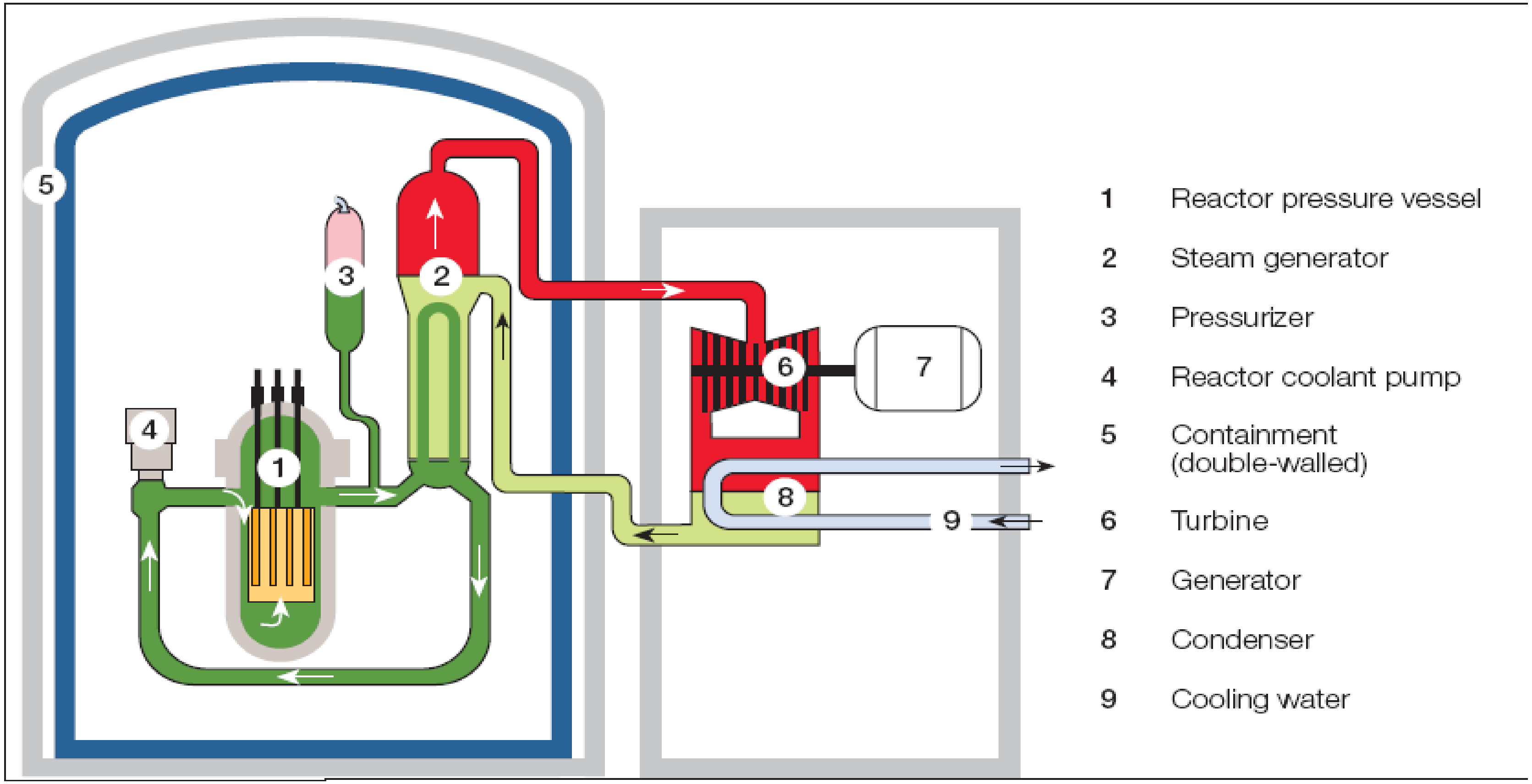
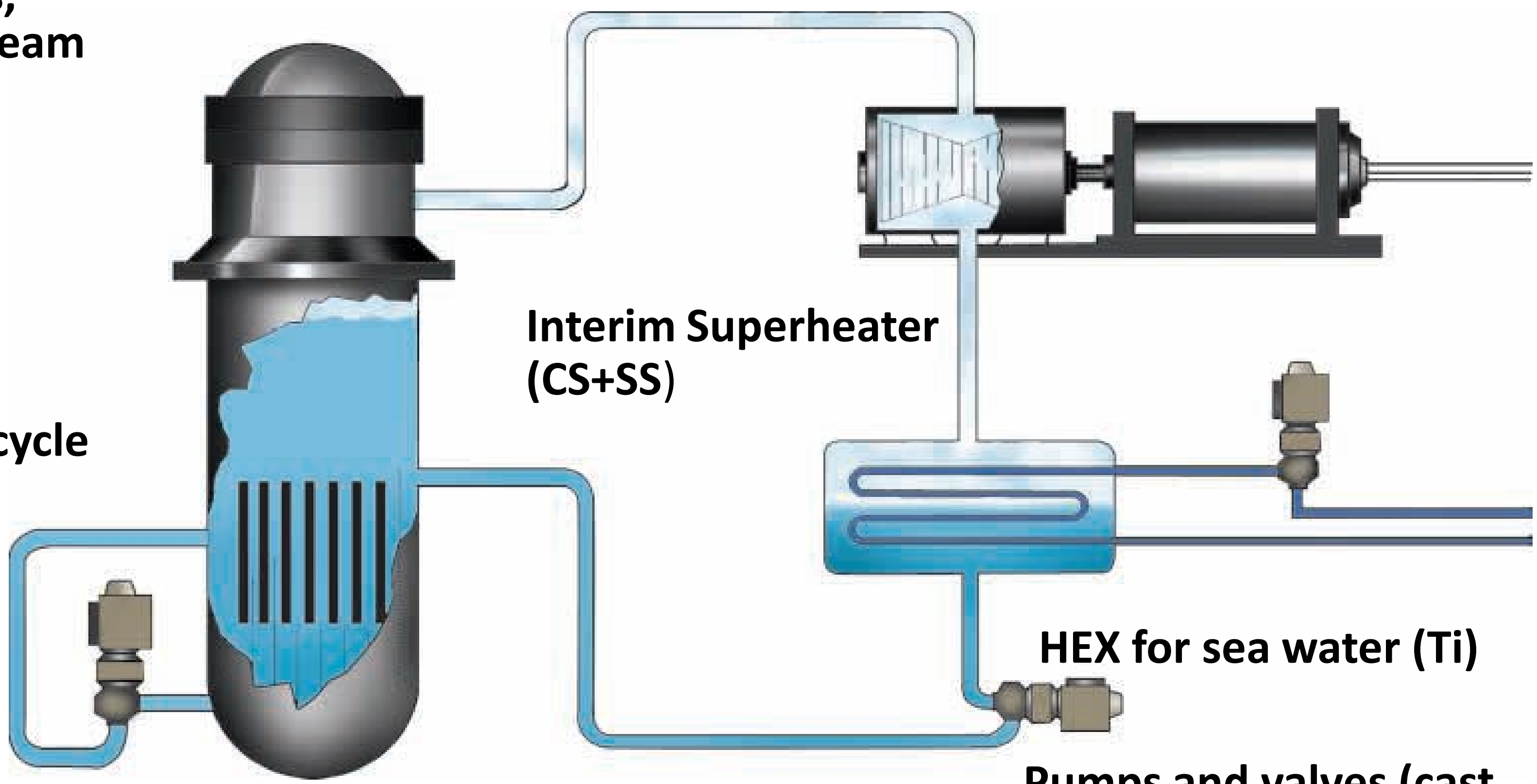
PRESSURE – TEMPERATURE REGIMES OF MODERN BWR AND PWR REACTORS AND SCWR CONCEPT



PWR PRIMARY AND SECONDARY CIRCUITS



BWR MAIN COMPONENTS (MATERIAL TYPE)



COMPARISON OF BWR/PWR SERVICE PARAMETERS AND WATER CHEMISTRY

Requirement	Property	BWR	PWR
Thermal efficiency	**Temperature**	**288 ºC**	**327 /293 ºC (EPR /VVER)**
Radiolysis and corrosion control	**Coolant Water**	**High purity Water**	**B, LiOH or KOH (VVER)** **Hydrogen added 30 ...50 cc/kg**
	Water pH_T	**~5.6**	**6.9 – 7.4**
	Water conductivityµS/cm	**0.01 – 0.02**	**~25 µS/cm**
	Oxygen content	**200 ppb (oxidasing)**	**~0 (reducing)**
Thermal efficieny	**Operational pressure**	**8.0 MPa**	**15.5/12.0 MPa (EPR /VVER)**

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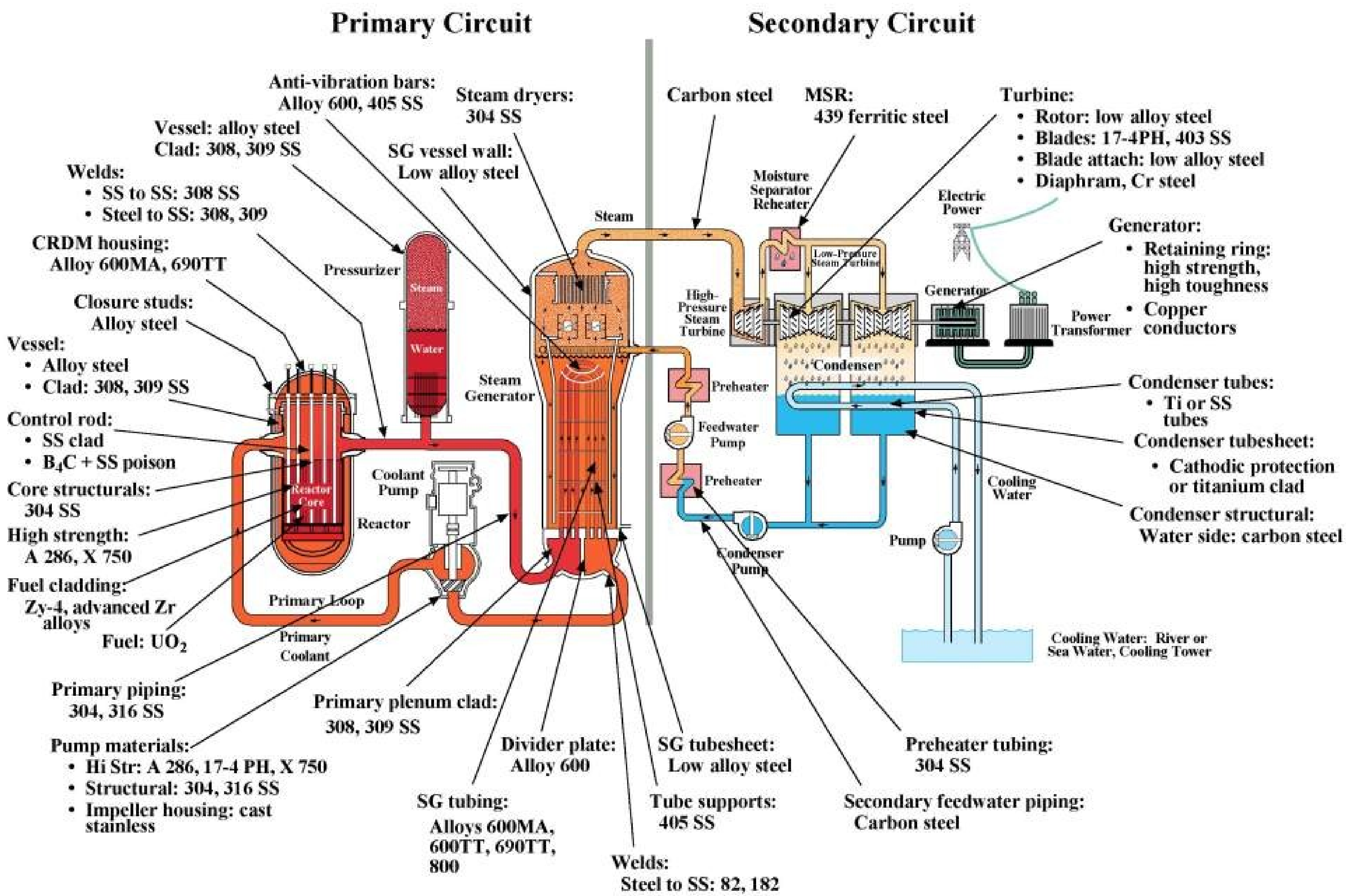
PWR- materials



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Materials in BWRs

Steam separator and dryer:
- components, 304
- welds 308L

Steam outlet nozzle:
- carbon steel

Closure studs:
- alloy steel

Steam piping:
- carbon steel

Turbine:
- rotor, low alloy steel
- blades, alloy steel
- attachments, low alloy steel

Vessel plates:
- low alloy steel;
- clad: 309 SS

Fuel supports:
- wrought or cast SS

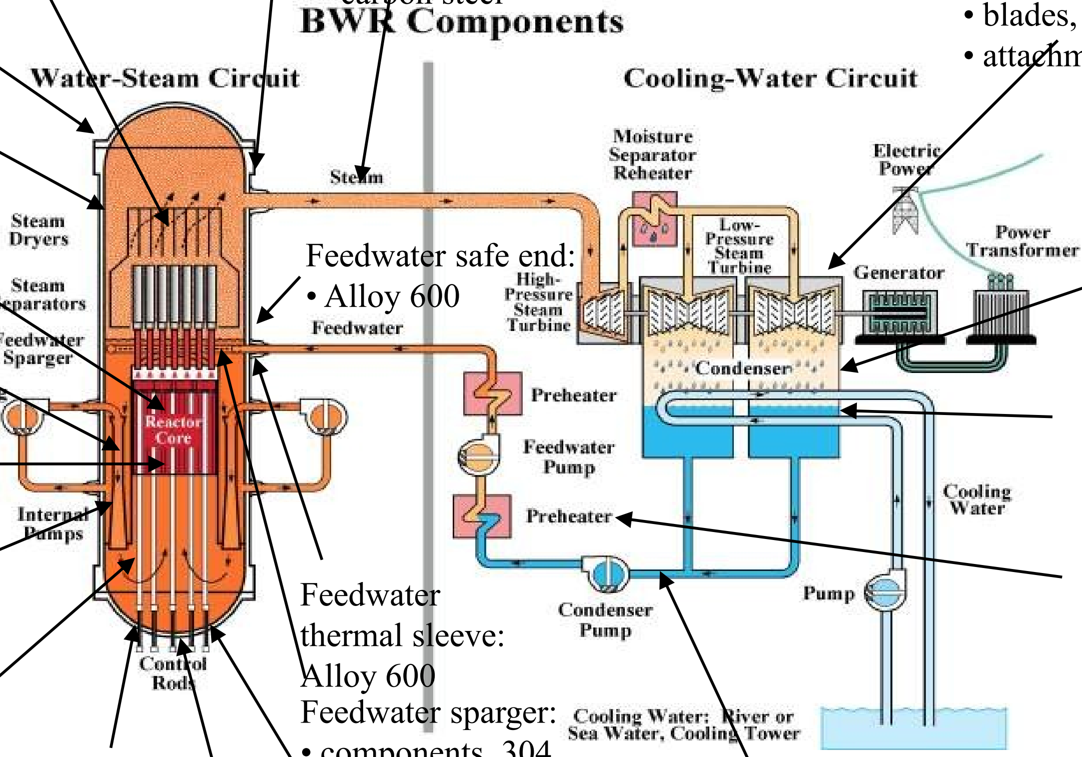
Core shroud:
- plates, 304 SS
- plate welds, 308/308L
- springs, alloy 750X

Core support structure:
- 304 SS

Fuel:
- Cladding, Zr-2
- Fuel, UO_2

Jet pumps:
- piping, 304 SS
- welds, 308L
- hold down bar: 750X

Control rods:
- blades, 304/316 SS
- poison, B_4C



Feedwater safe end:
- Alloy 600

Condenser structure:
- carbon steel

Condenser tubing:
- Ti or SS

Preheater tubing:
- SS

Feedwater thermal sleeve: Alloy 600

Feedwater sparger:
- components, 304
- welds, 308L

CRD safe ends:
- 316 SS

Feedwater piping: carbon steel

CRD stub tubes:
- Alloy 600
- upper weld, 182
- Inconel to Inconel 182

Dissimilar metal welds
- Safe ends: 182/82

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Material types for RPV and internals

RPV steels

SA 508 cl 2 forgings, SA 533 Gr. B levyt (1.35% Mn, 0.8%Ni and 0.5%,Mo)
S <0.010 %, Cu < 0.05 %, C 0.14 -0.25 %

Stainless steels

AISI 304 and 304L.. 19%Cr, 9%Ni; 0.08 tai 0.03%C_{MAX}
AISI 316 and 316L.. 18%Cr, 10%Ni, 2% Mo, 0.08 tai 0.03%CMAX
AISI 316 NG………. 18% Cr, 10%Ni, 2% Mo, 0.020 % C_{MAX}+N
AISI 347 and 348… 18%r, 10 %Ni, Nb =10 x % C,
AISI 321 348 18%Cr, 10%Ni, Ti =5 x % C,
Annealed state, hardness max Rockwell B 92 (~ 200 HV)

Inconel Alloy 600: 16%Cr, 8%Fe, Bal. Ni, annealed at ~ 620 C
Inconel Alloy 182 welding alloy: **15%Cr**, 7%Fe, 6%Mn, 1.7%Nb, 0.3%Ti, 0.05%C,…balance Ni

Inconel Alloy 82 weld : **20%Cr**, 2.7%Nb, 0.4%Ti, 3%Mn, 0.4%Fe, 0.04%C,…Bal. Ni
Inconel Alloy X-750, springs: 16 % Cr, %Fe, 2.5 %Ti, 1%(Nb+Ta), 70% Ni, precipitation hardened

Material choices and conditions for RPV and internals

- Operational T = 20-288°C
- High gamma and beta irradiation, up to 2 Mgray/h (irradiation embrittlement studies need data for irradiation history)
- Neutron flux $1x10^{13}$ n/s

- Radiolysis produces H_2, O_2 , ja H_2O_2, to optimise the water chemistry oxidasing conditions have to be controlled (BWR)
- pH is not favorable in preventing corrosion (BWR)

- Mechanical loadings:
  - tensile stresses
  - residual stresses in welded joints
  - vibrations ans cyclic stresses due to temperature changes and transients
  - fatigue/corrosion fatigue
  - pressure and temperature shocks, transients

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RPV: MAIN REACTOR COMPONENT MANY MANUFACTURING STAGES

Steel:

SA 508 cl 2: 0.14 -0.25%C, 1.35%Mn, 0.8%Ni, 0.5% Mo; S, P, CU, Sn impurities, content limited

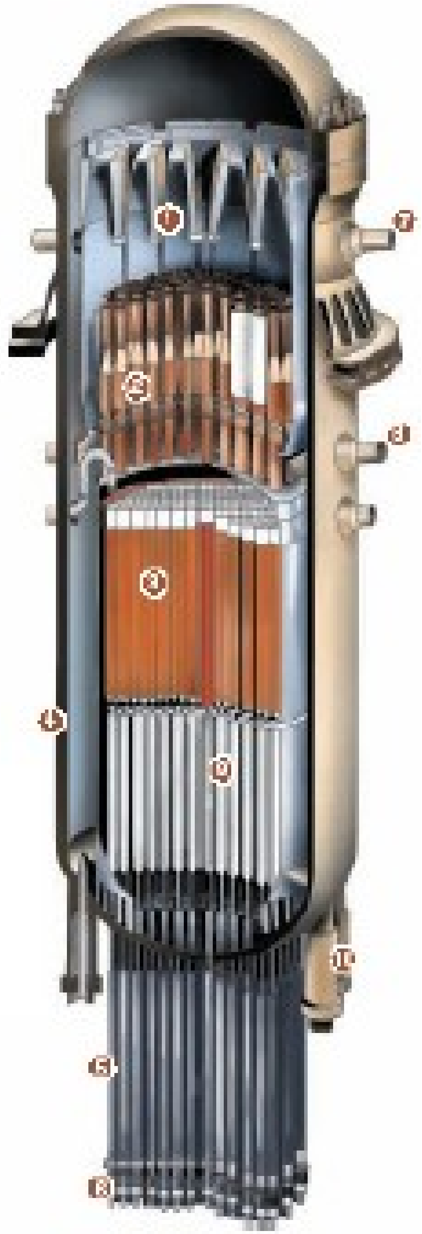
Manufacturing process:

Casting =>
Hot forging 1200°C =>
Quenching from anneal at 900°C in water => annealing 580°C=>
Forged rings are assembled using welding =>
Cladding SS using welding =>
Annealing at 530°C (residual stress relieving)

Main criteria for the RPV material:

Weldability, charpy-V toughness, irradiation embrittlement resistance – mainly controlled by alloying of the steel and by special steel making processes.

RPV steel is ferritic/bainitic microstructure, no martensite in the final stage.



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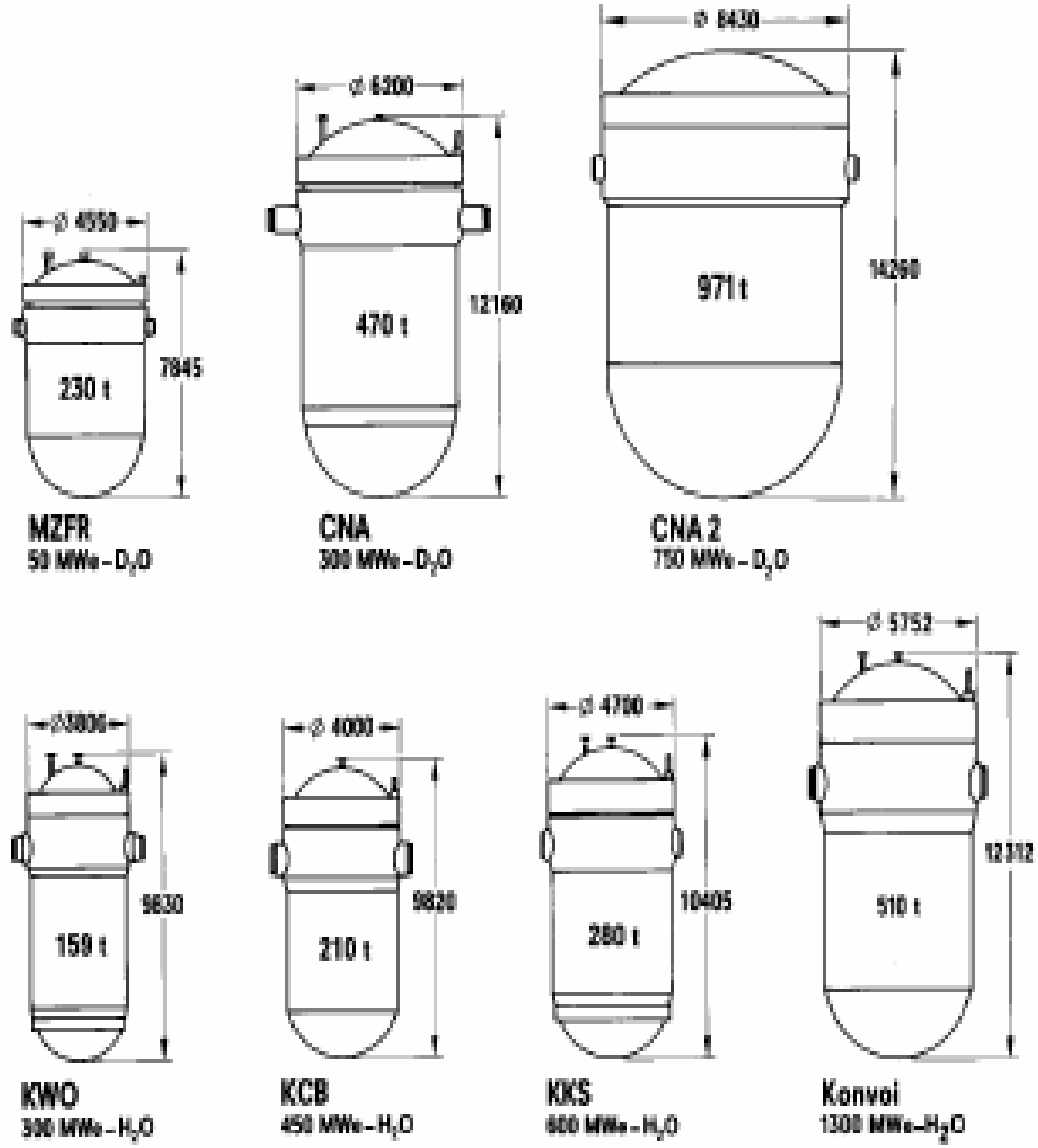
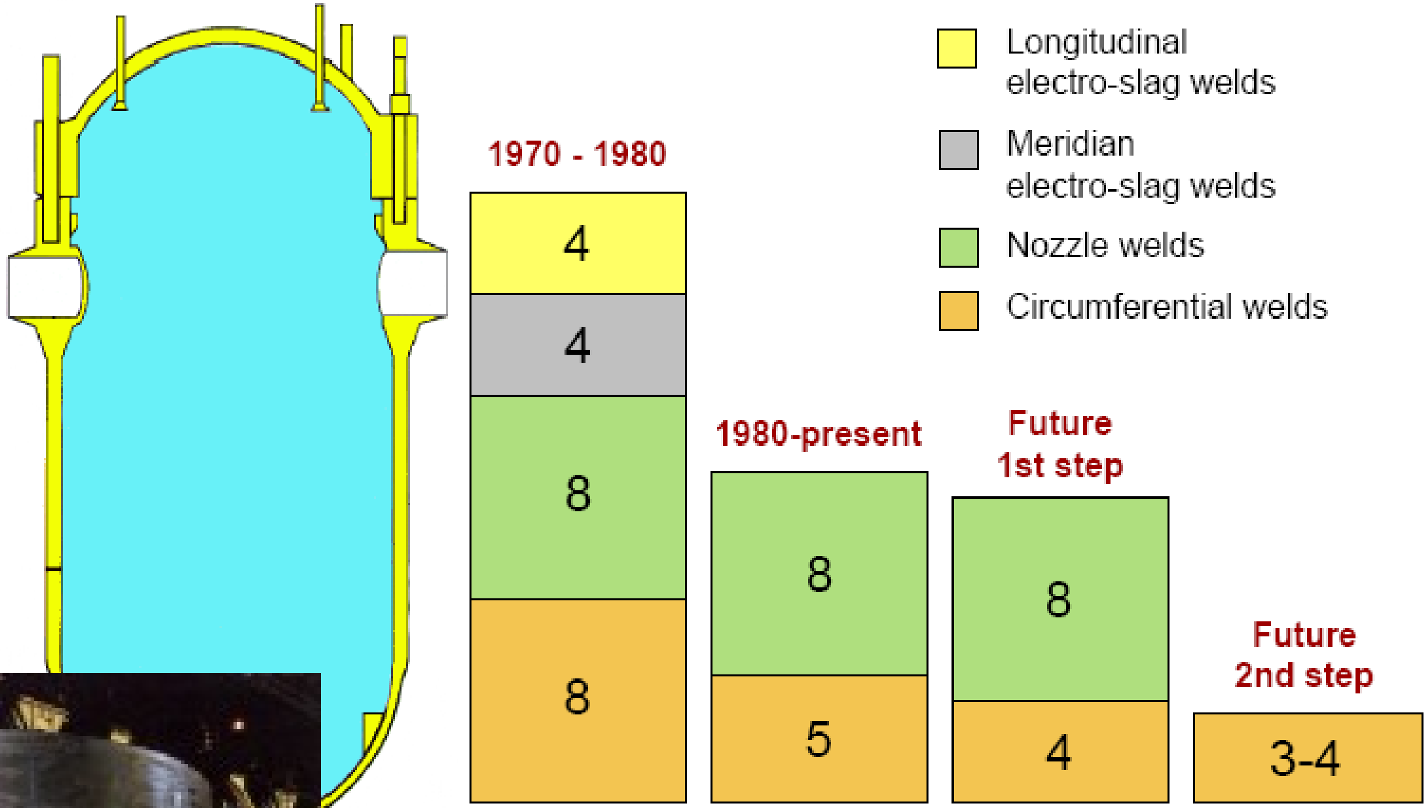
TRENDS in RPV vessels:

- RPV size growth
- Less welded seams
- Material composition has been optimised
- The irradiation dose has been limited with new designs
- Eg. Loviisa 1 the circular weldment of RPV has been annealed to improve the toughness in 1996.



Reactor Pressure Vessel 1300 MWe
Comparison Numbers and Types of Welds



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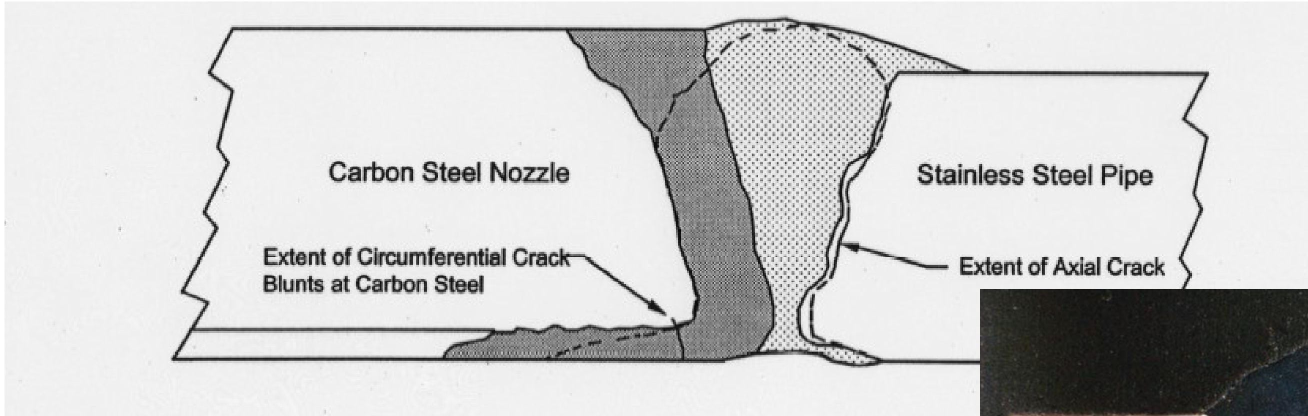
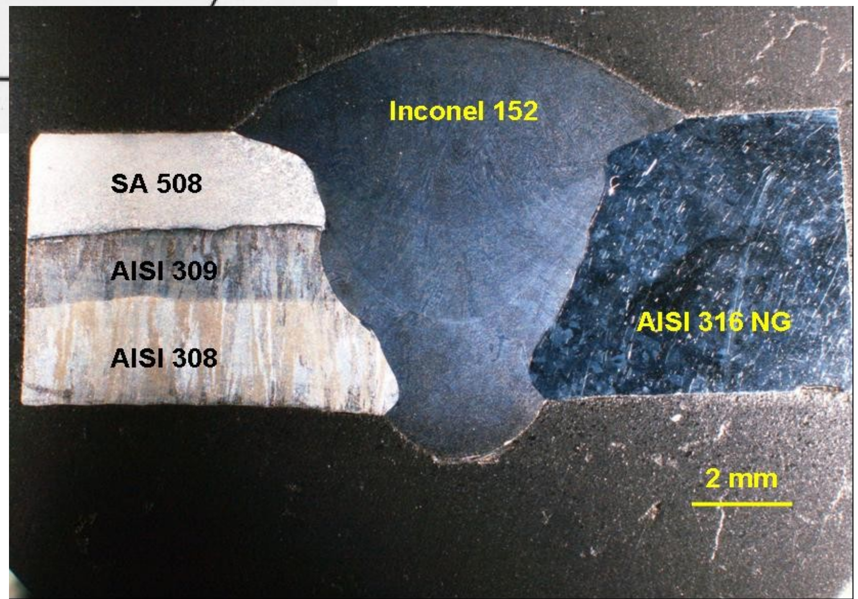
RPV / SG JOINT STRUCTURE WITH A FERRITIC/SS WELDMENT

Welding before heat treatment – dissimilar metal joint, not avoidable in modern RPV assemblies:

- I600 + I82 buffer / I182 weldment
- SS + I 52 weldment





An example of dissimilar material welding research for main assemblies in RPV

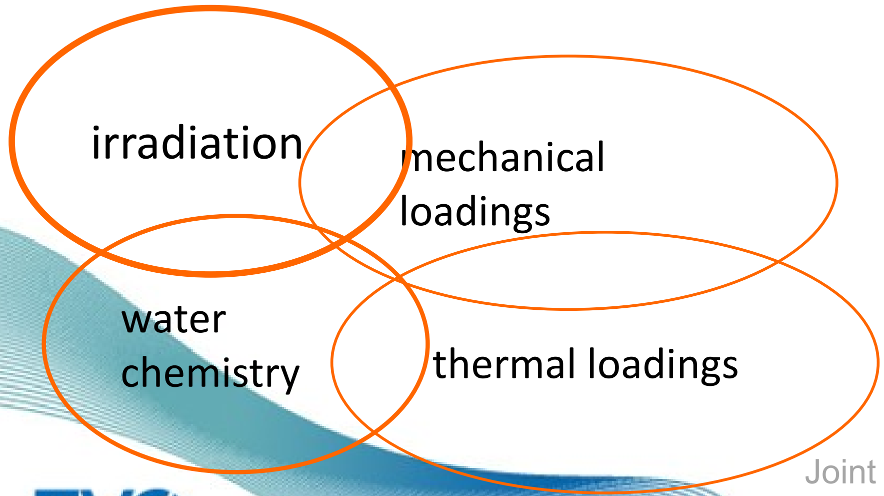
RPV AGING MECHANISMS

Main aging mechanisms:

- irradiation embrittlement
- fatigue
- thermal fatigue
- Stress Corrosion Cracking (SCC)

Control:

- RPV surveillance testing programmes
- In Service Inspections (ISI)
- Control and monitoring of loads (mechanical and process)
- Monitoring of temperatures
- Fatigue analyses
- Analyses of embrittlement > fracture mechanics studies and analyses



LIFETIME of RPV = LIFETIME of PLANT?

MATERIAL CHALLENGES RELATED TO A HIGH OPERATION TEMPERATURE TOWARDS GENIV

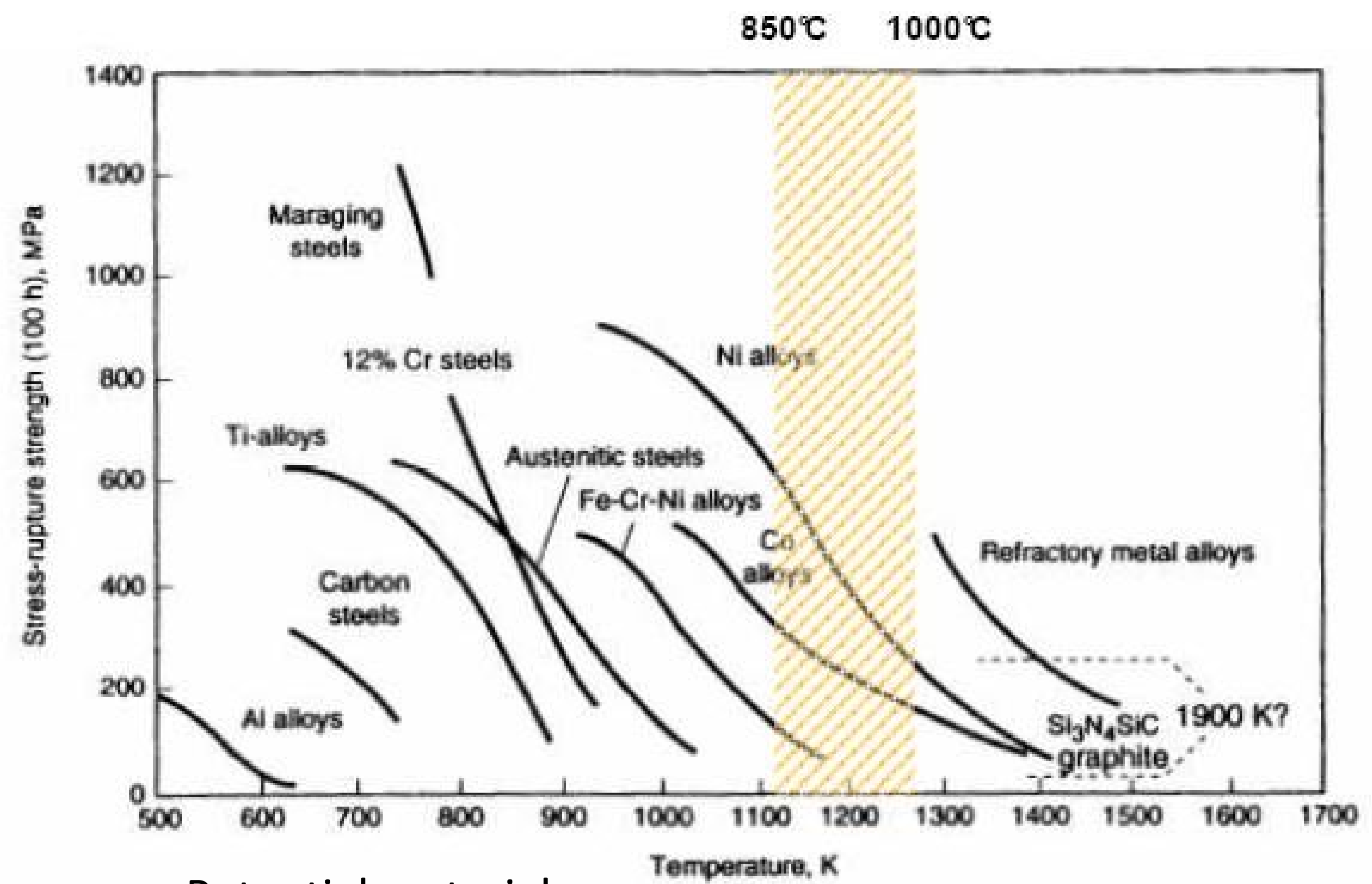
- Decrease of the mechanical strength of metals with temperature (316L limited to 550°C)

- Corrosion issues in gas atmosphere increases with temperature (increase in the kinetic rate of reaction)

- Microstructure changes at elevated temperatures → risk of strength drop

- High thermal stresses → problem of differential expansions in case of thermal gradient in walls

Temperature capability of construction materials



Potential materials:

- nickel alloys
- ceramics or composites
- (refractory alloys → too brittle and difficult to process)

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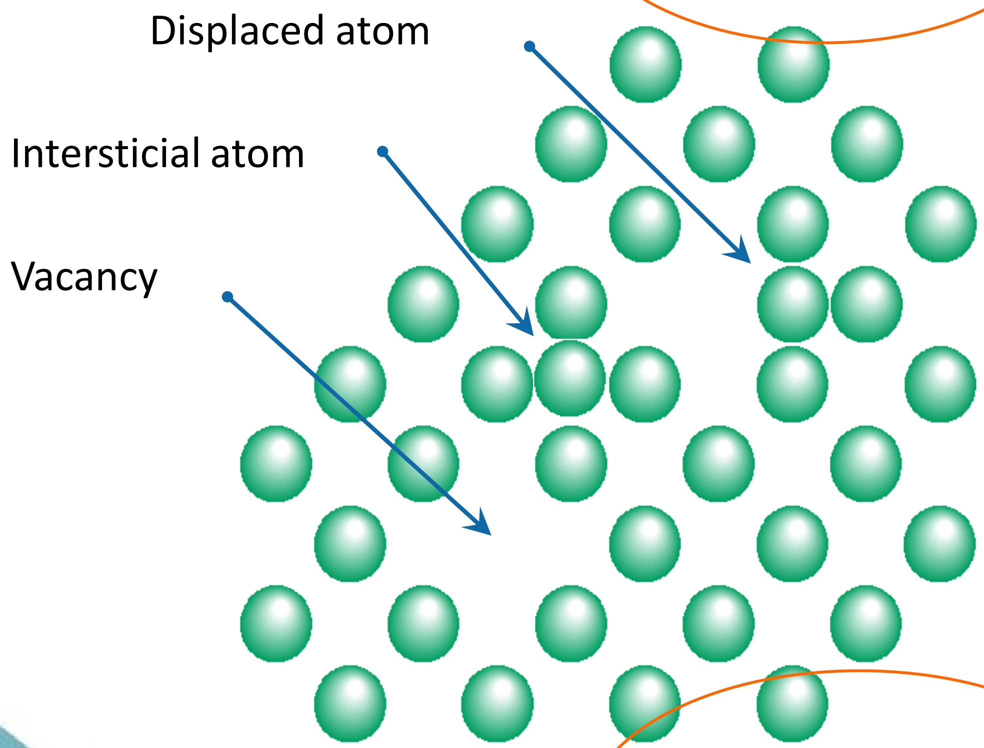
Irradiation embrittlement, mechanism:

Neutrons hit lattice atoms

lattice changes and defects



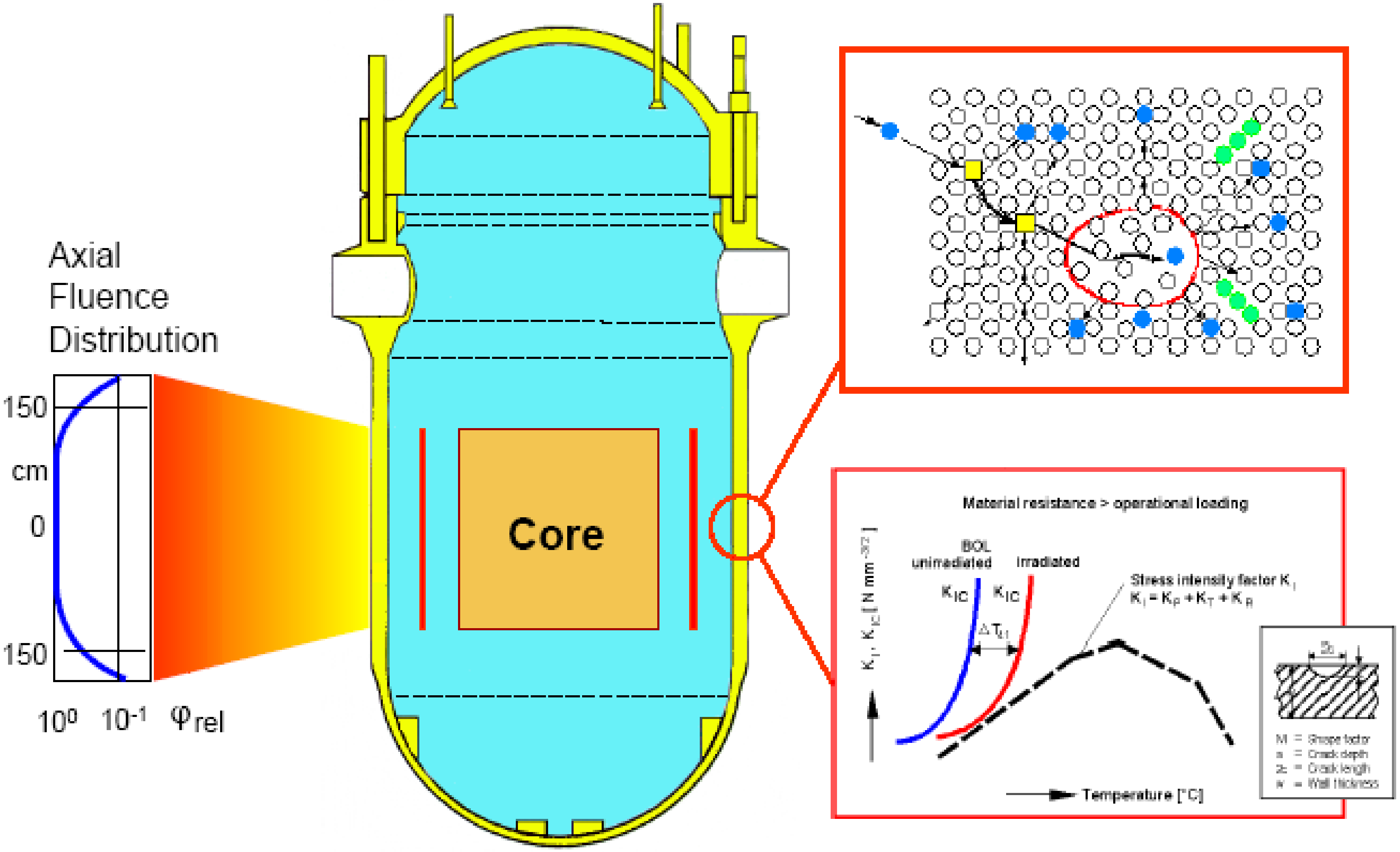
- Point defects
- Defect cascades
- Dislocation loops
- Defect clusters
- Precipitation

Hardening
Reduced ductility
IASCC

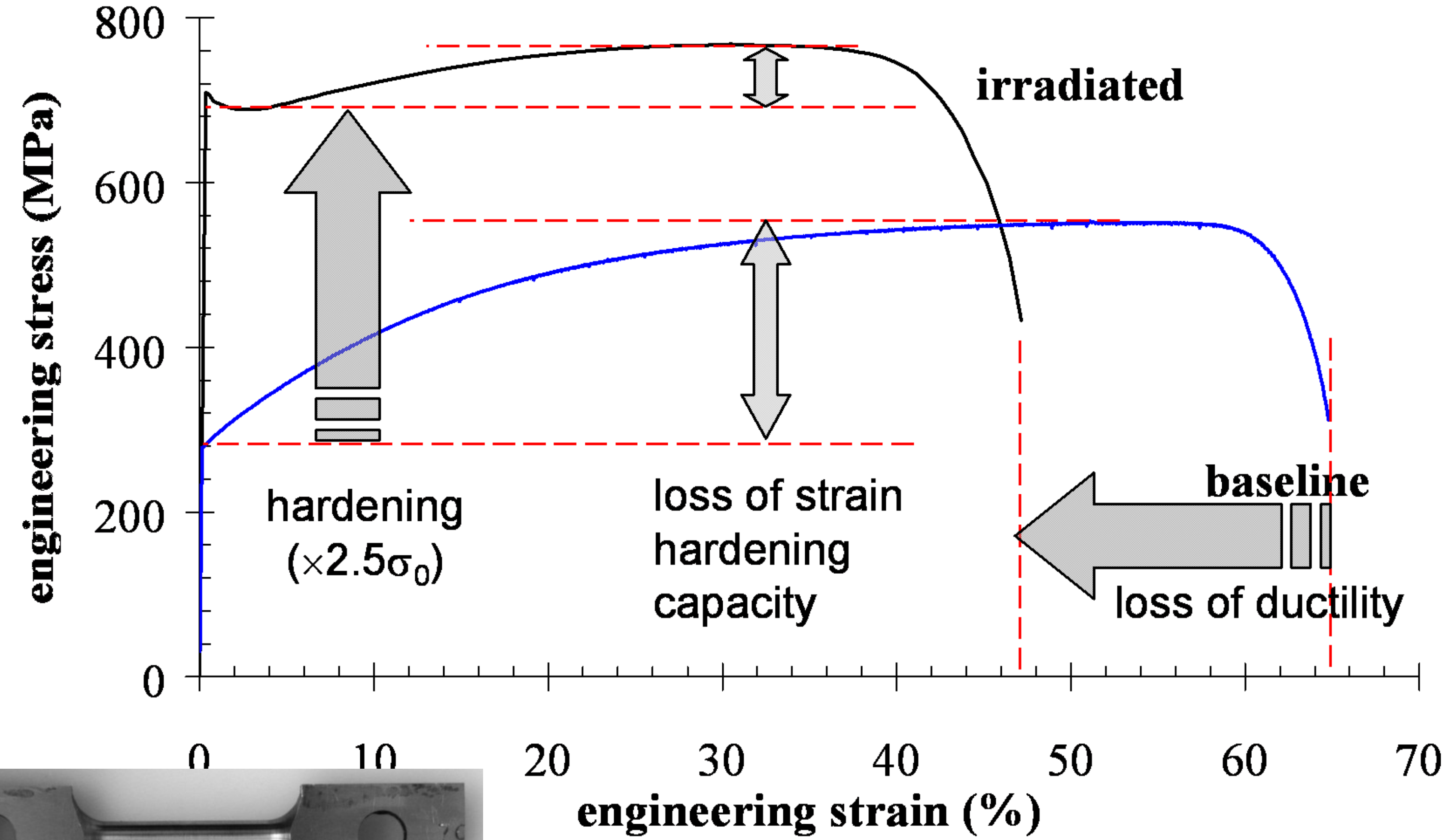
Thermochemical changes

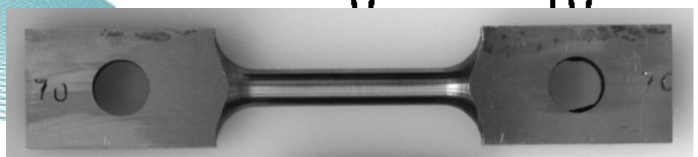
- Impurity segregation
- Enhanced diffusion (RIS)

Irradiation Embrittlement

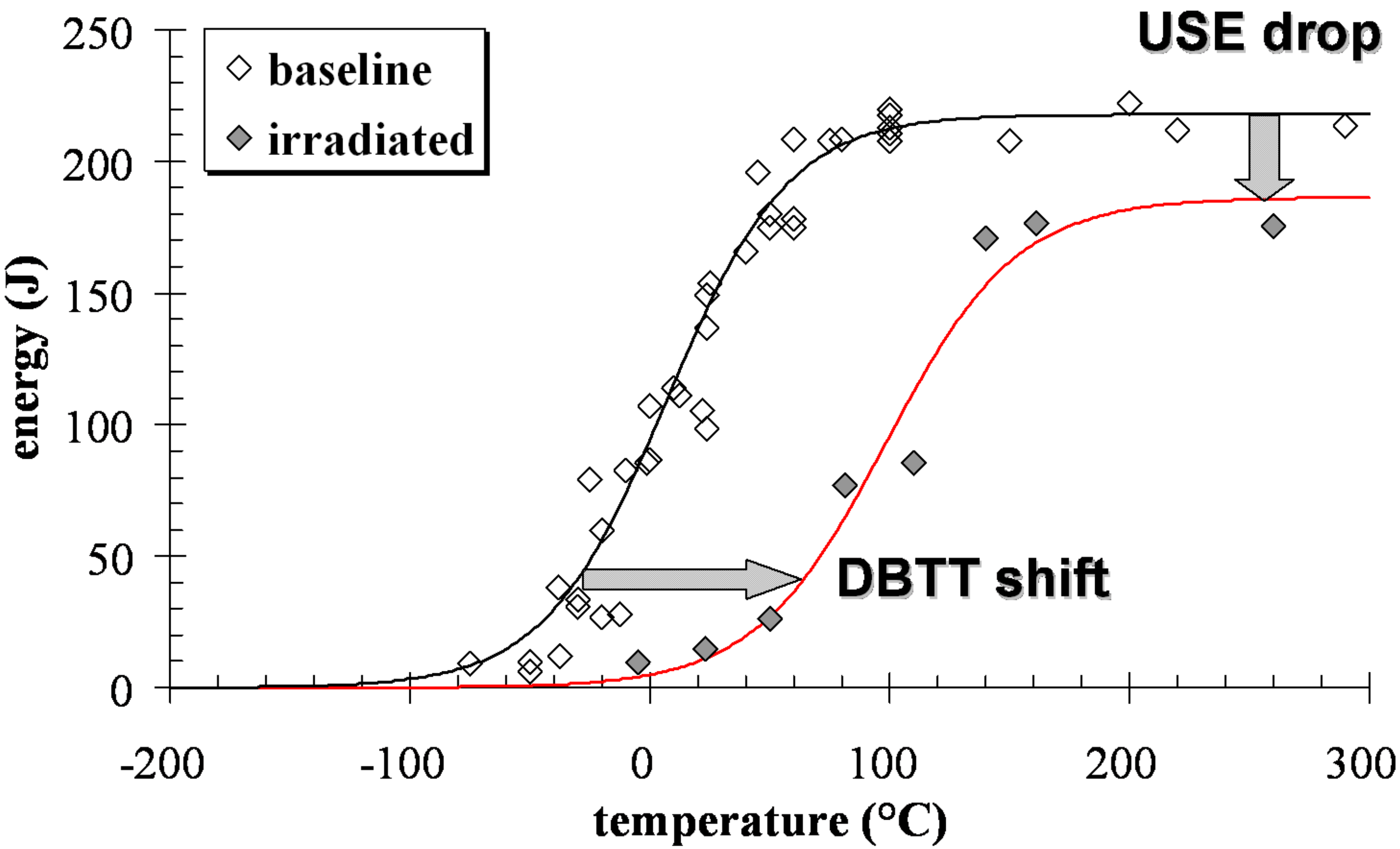


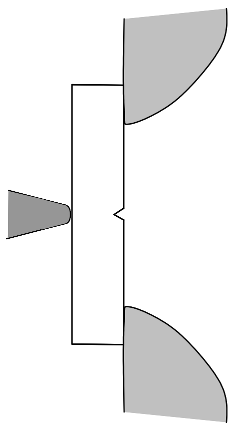
IRRADIATION DUE TO THE NEUTRON FLUX





IRRADIATION EMBRITTLEMENT
CHARPY-V TOUGHNESS



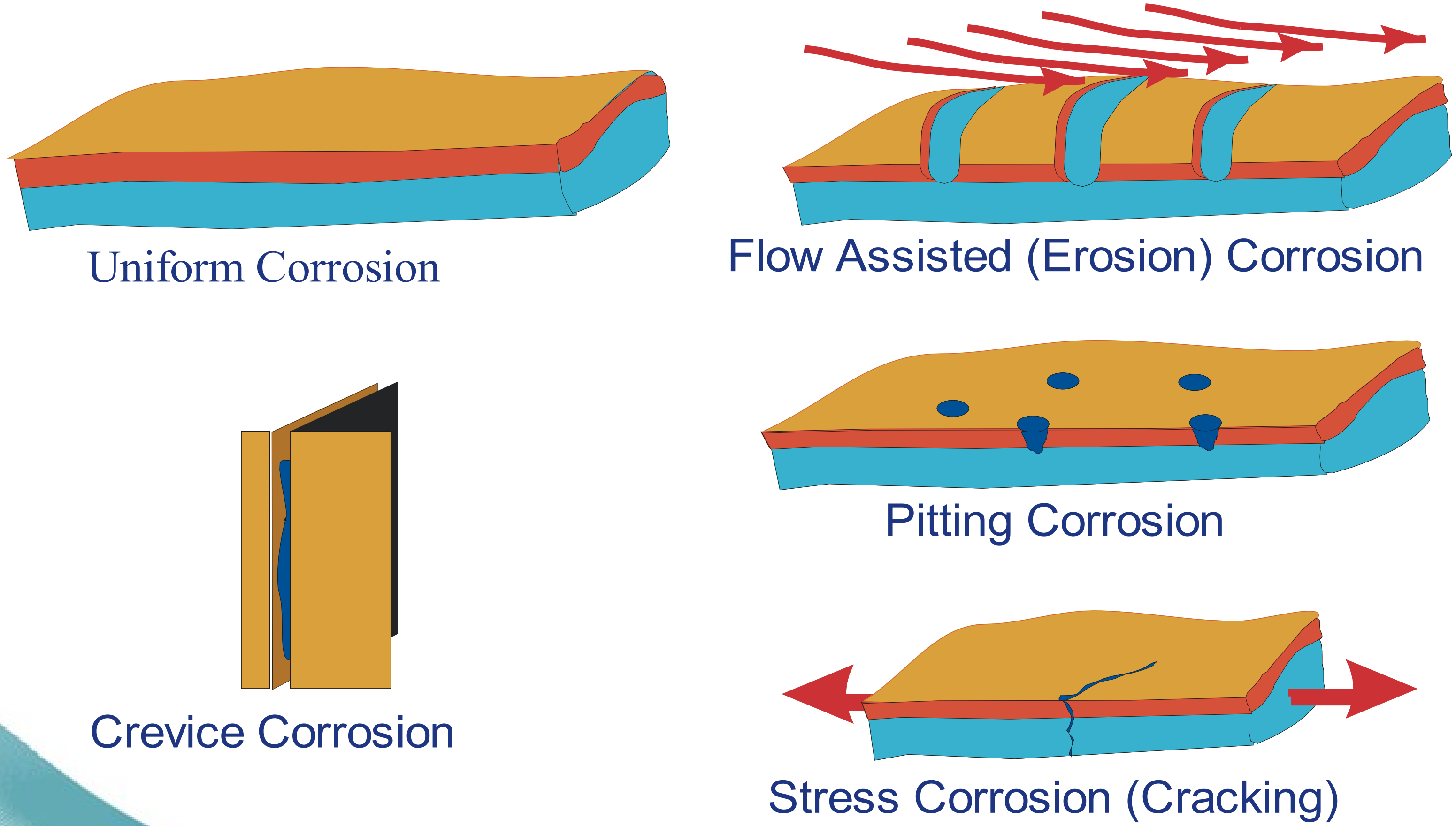


CORROSION TYPES IN REACTORS

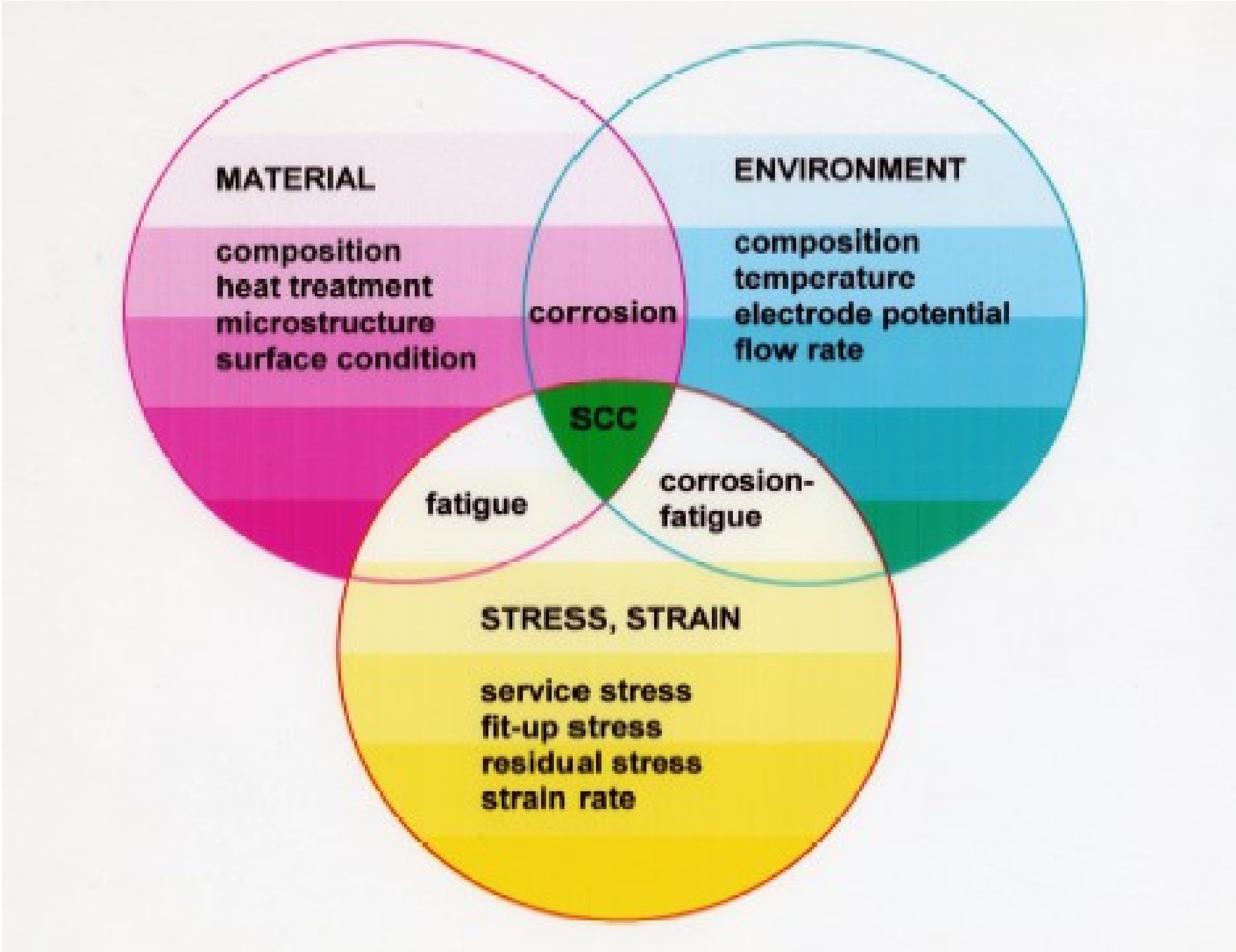
- Stress Corrosion Cracking, SCC
- Irradiation Assisted SCC, IASCC
- Intergranular SCC, IGSCC
- Transgranular SCC, TGSCC

- Crevice corrosion
- Erosion Corrosion
- Corrosion Fatigue, CF
- Pitting Corrosion

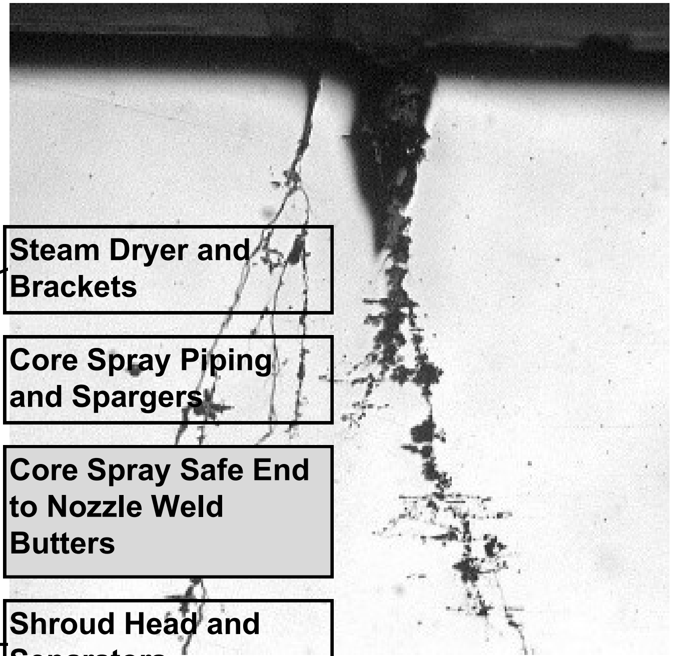
CORROSION MODES IN REACTOR CIRCUIT

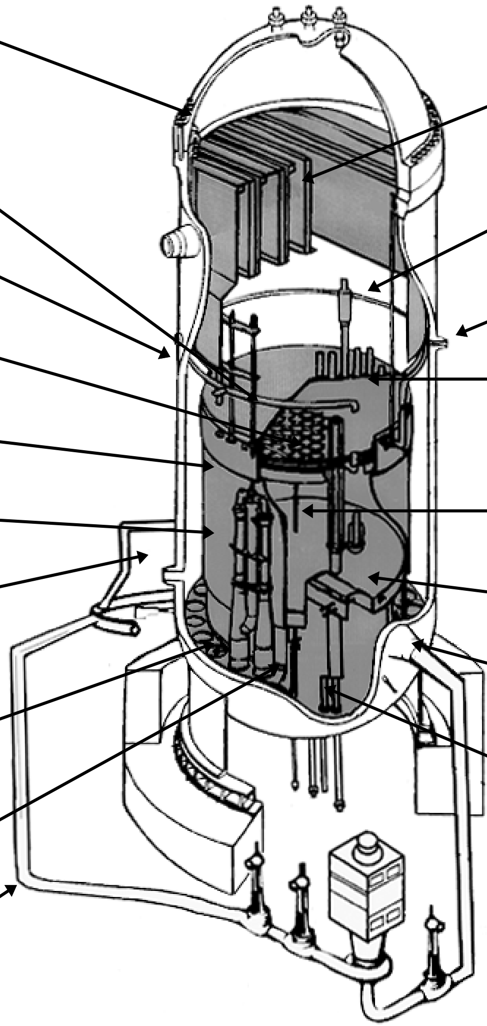


LOCAL CORROSION MODES



BWR plant data about IGSCC cases





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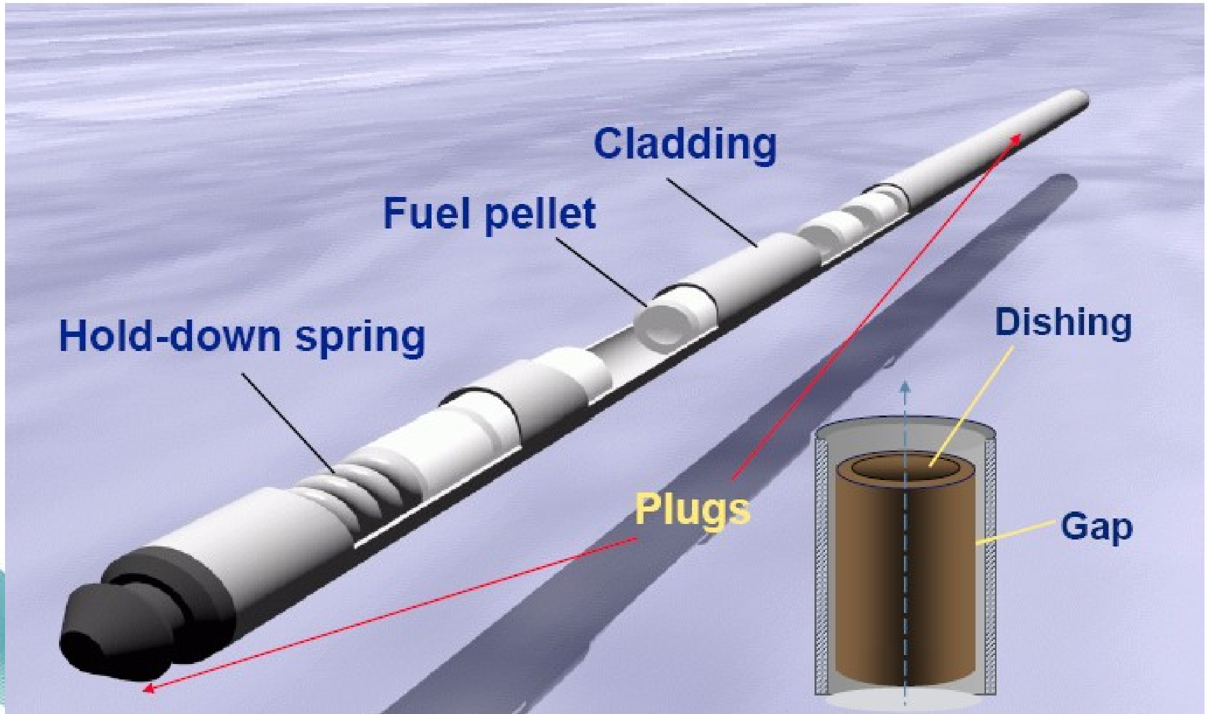
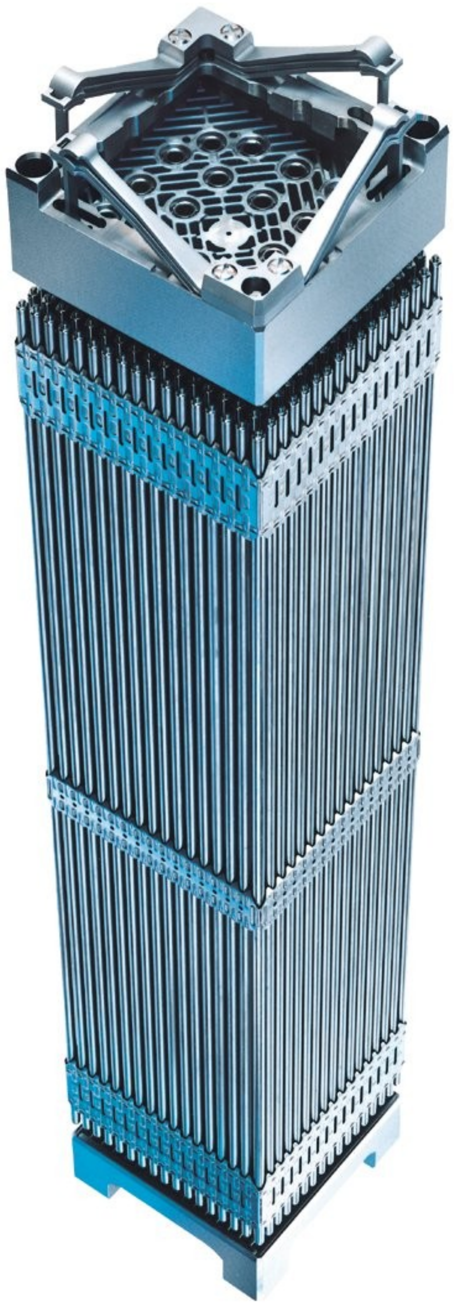
FUEL CLADDING MATERIALS GENERAL REGUIREMENTS

Poor absorbant for thermal neutron flux – transparency
Good stability under irradiation
High melting temperature
Low activation
Good chemical stability at high temperatures
Good corrosion resistance (local and general)
Good deformability in manufacturing
Good dimensional stability (thermal stability)
”manufacturability, weldability and availability” reasonable costs

NEW EPR FUEL

In EPR there will be 241 fuel assemblies
Each fuel rod includes about 2 kg U.
The fuel assembly Uranium weight is 535 kgU.





SUMMARY

Material choices

- plant type
- component type
- manufacturing and manufacturing effects
- assembly and repair
- activation
- stability
- long term performance…

Aging mechanisms and operational stresses

- Irradiation
- temperature
- water chemistry
- transients
- cyclic loads
- combined effects
- towards higher temperatures…

THANK YOU