The influence of irradiation on Reactor Pressure Vessel materials

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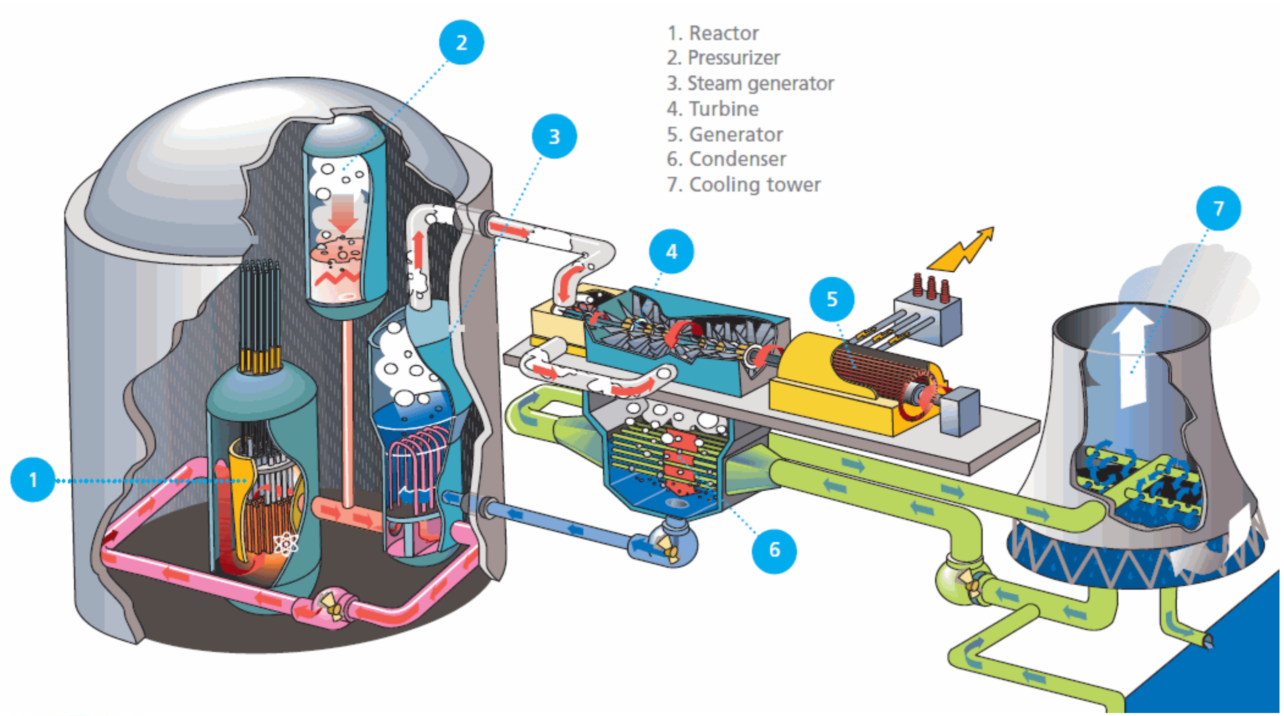
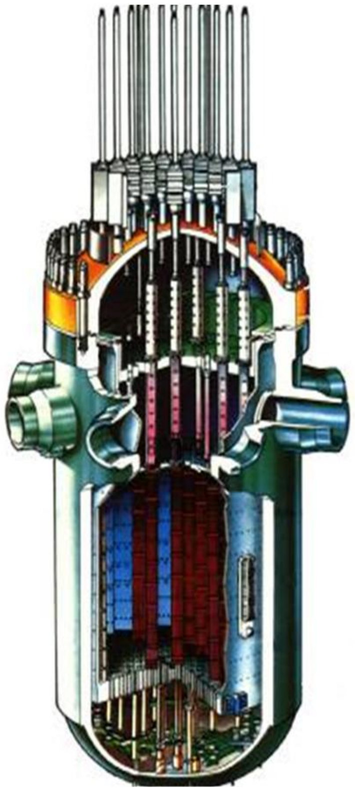
Introduction

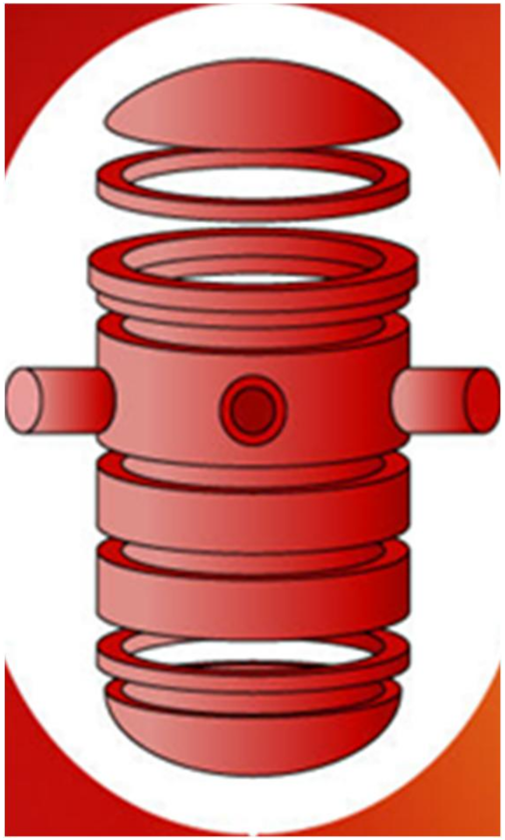
Nuclear Power Plant





Reactor Pressure Vessel

- Operating pressure: 155 bar
- Design pressure: 171 bar
- Design temperature: 343°C
- Height: 10-15m
- Diameter: ±5m
- Wall thickness: 20-30cm
- Weight: 330 ton
- Material: carbon steel
- Fluence after 40 years: ± 6.10^{19}n/cm²



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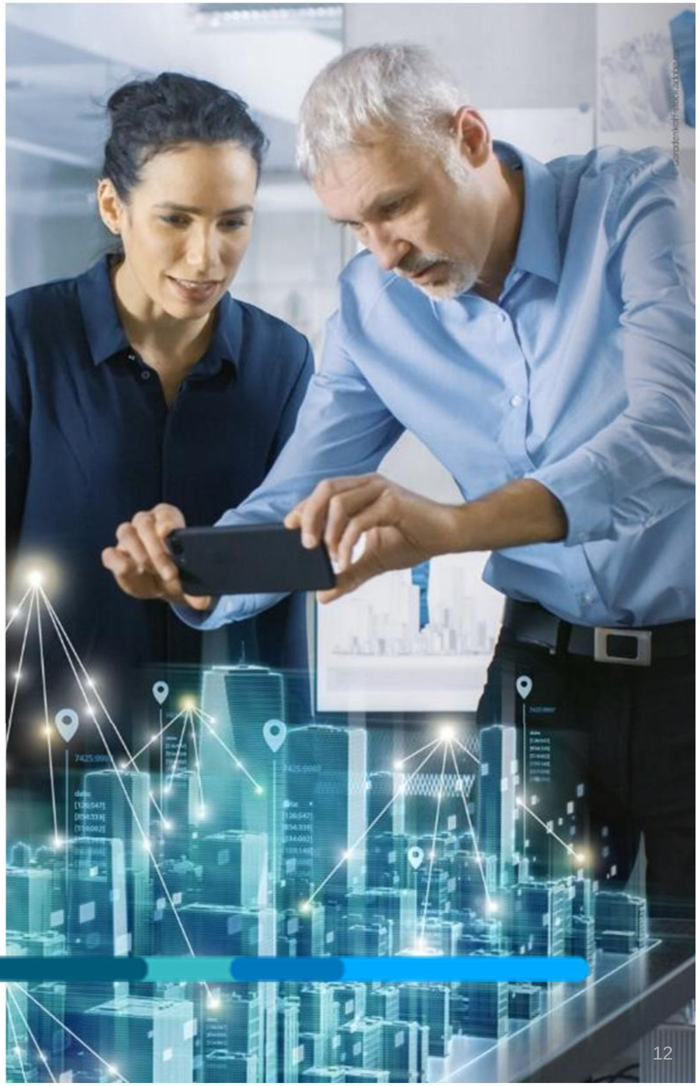
Mechanism of irradiation ageing



Primary damage

Neutron irradiation causes primary damage in two phases:

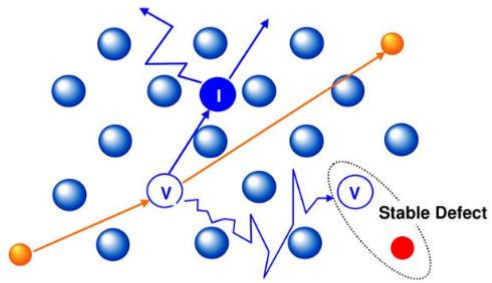
Phase 1: Collision phase (few tenths of a pico second):

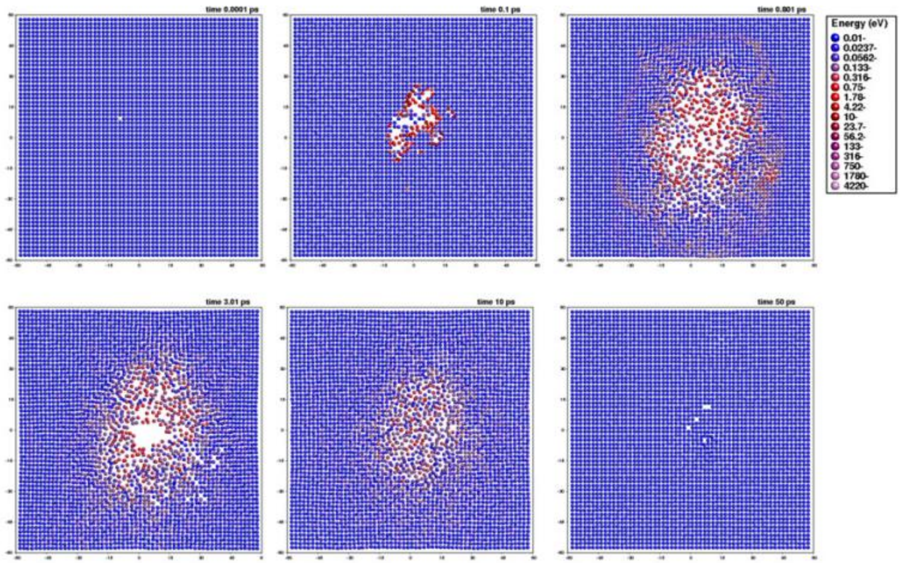
- Neutrons hit lattice atoms which can be knocked out of their lattice sites
- These Primary Knock-on Atoms (PKA's) collide with other atoms, which can collide with other atoms etc. till all PKA energy is dissipated
- This results in a displacement cascade, creating vacancies and self-interstitial atoms (SIA's).

Phase 2: Recombination phase (some pico seconds):

- Most of the vacancies and SIA's annihilate each other
- Only some surviving point defects form the primary defects

Vacancies and interstitials migrate, either recombine (~90%) or migrate and form stable defects (Frenkel pair)



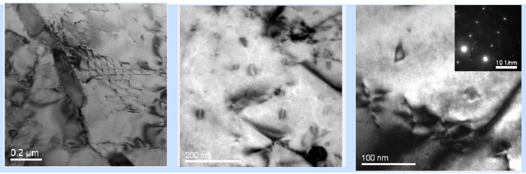
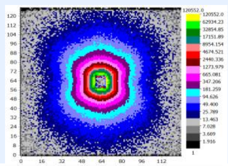
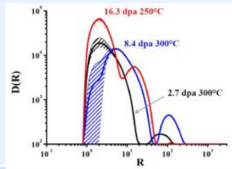
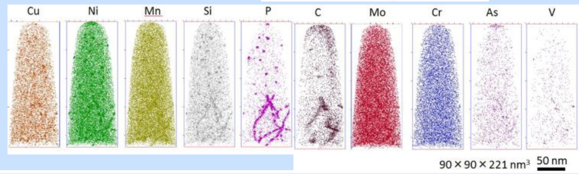
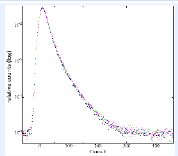
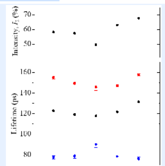


Secondary damage

- Primary damage creates an excess of vacancies
- This induces radiation enhanced diffusion (RED)
- This creates the irradiation induced secondary defects
- Two families of irradiation induced defects:
  - Precipitates
  - Stable matrix features (SMF)

Type		Size (nm)	Number density (m^{-3})	Composition
Precipitates	CRPs	0.5-1.5	Some 10^{24}	Cu(>50%)-Mn-Ni-Si
	MNPs	0.5-1.5	Some 10^{24}	Mn-Ni-Si (>50%) - Cu
SMFs	Dilute solute atmospheres	< 2nm	< 10^{24}	Fe-Cu-Mn-Ni-Si
	Vacancy-solute clusters	<0.5-1.5nm	< 10^{24}	Vacancies – Cu-Mn-Ni-Si
	Nanovoids	<0.5nm	< 10^{24}	Vacancies – Cu-Mn-Ni-Si
	SIA clusters	<0.3nm	Some 10^{24}	-
	SIA dislocation loops	<0.8nm	Some 10^{24}	-

Characterization methods

Technique	Use	Examples
Transmission Electron Microscopy (TEM)	Observations and identifications on nm scale of precipitates, dislocations, etc.	
Small Angle Neutron Scattering (SANS)	Detection of neutron induced defects (shape and size)	 
Atom Probe Spectroscopy (APS)	3D compositional and structural analysis at the atomic and near-atomic scale	
Positron Anihilation Spectroscopy (PAS)	Presence of irradiation-induced vacancy related damage	 

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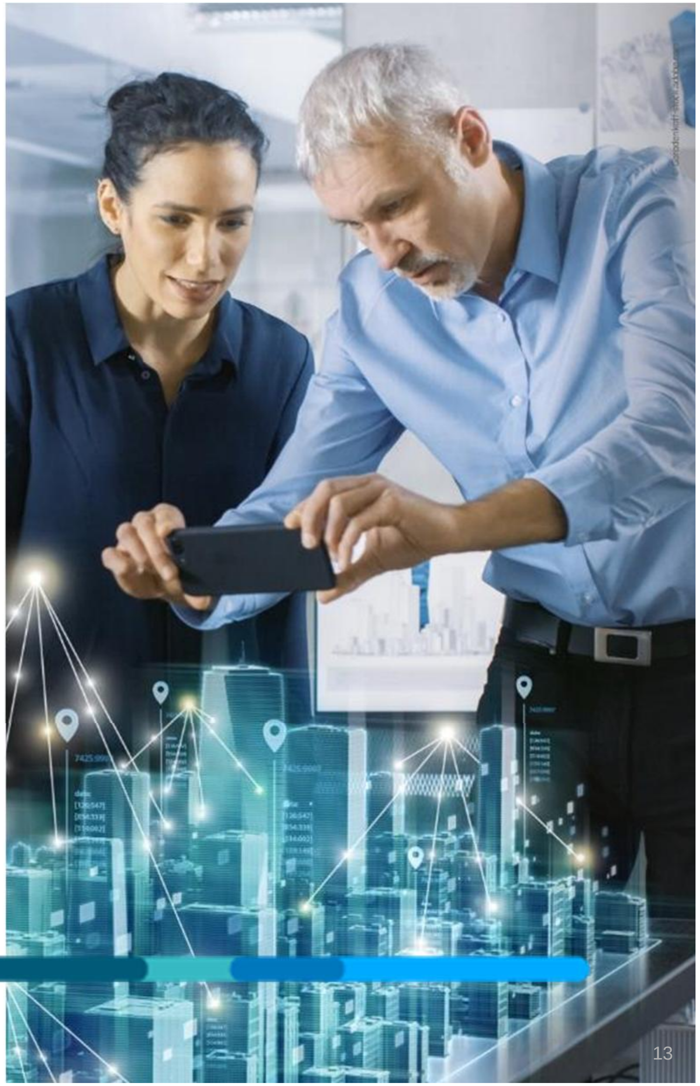
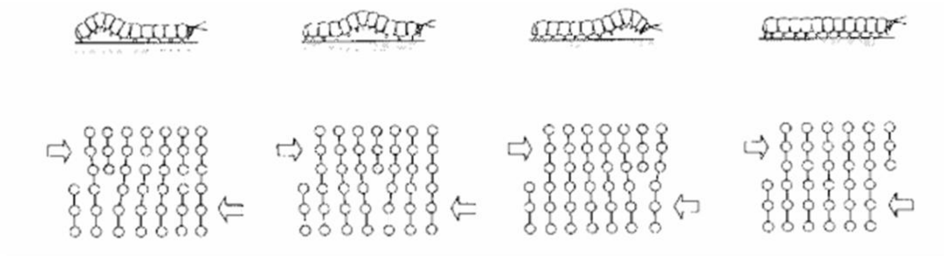
Impact of irradiation on material properties

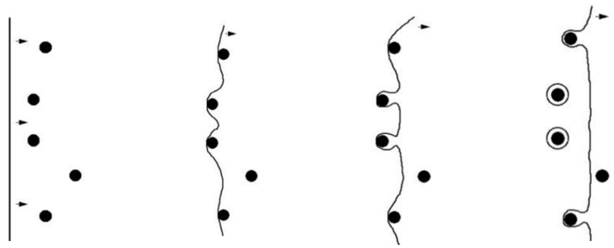


Hardening embrittlement under irradiation

- Deformation of steel takes place due to movement of dislocations.



- Irradiation-induced defects form obstacles to the gliding of dislocations and hence harden RPV steels.



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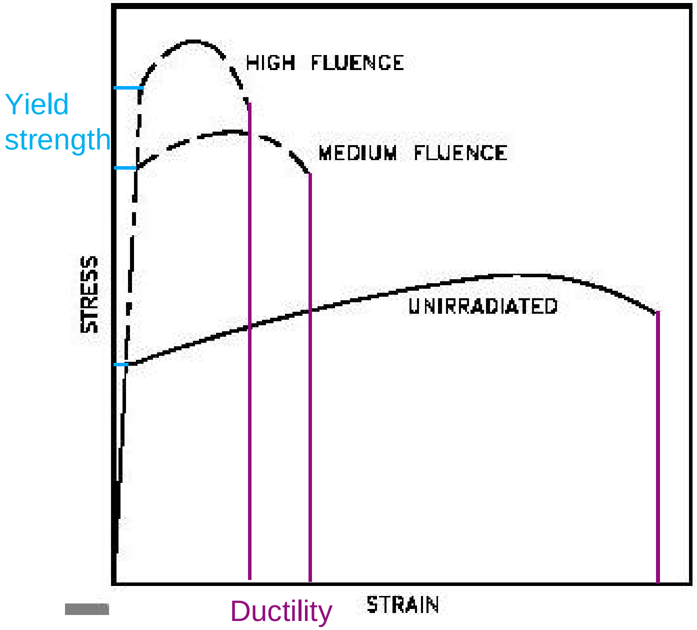
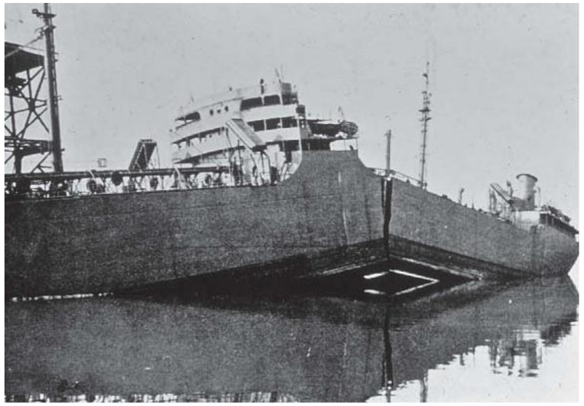
Hardening embrittlement under irradiation

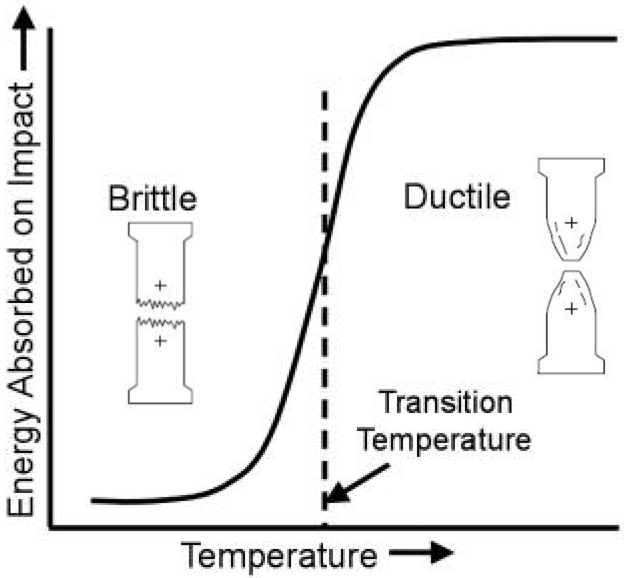
- This hardening makes it more difficult to permanently deform the material
- This results in an increase in yield strength and decrease in ductility

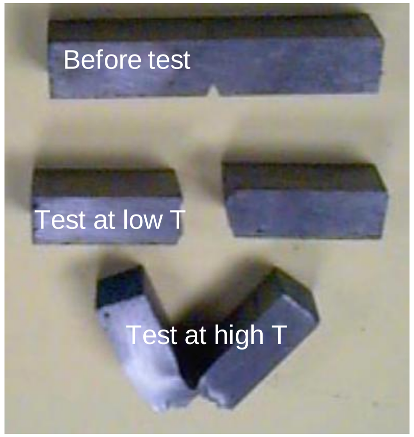


Hardening embrittlement under irradiation

- Below a certain temperature, a carbon steel becomes brittle (cfr. cracks in ships in ice water).
- This temperature is called the ductile to brittle transition temperature.

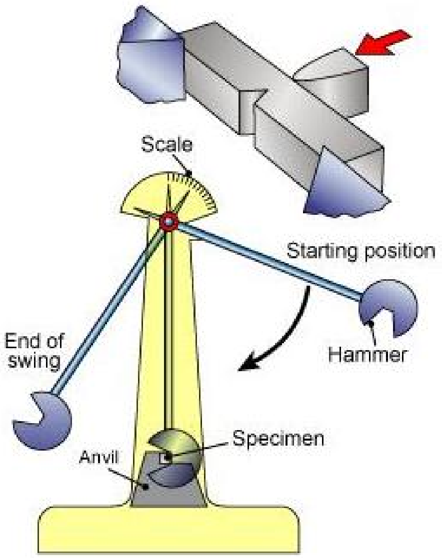


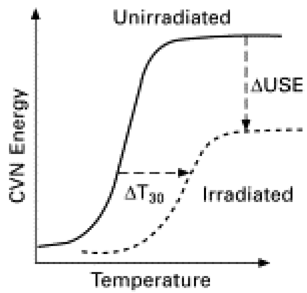


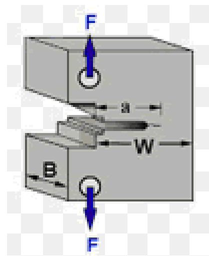


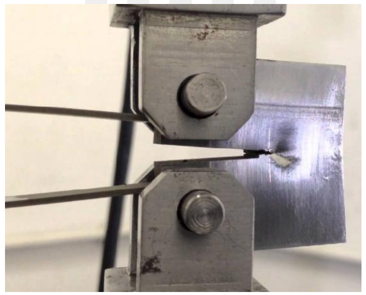
Hardening embrittlement under irradiation

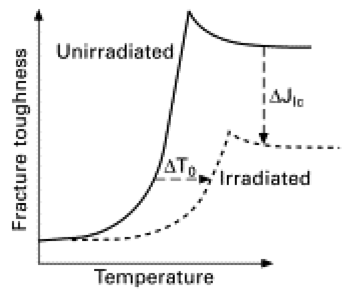
- Increase in yield strength due to irradiation, in turn, reduces the fracture toughness.
- This leads to an increase in the Ductile to Brittle Transformation Temperature.





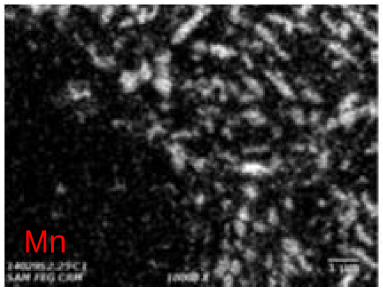


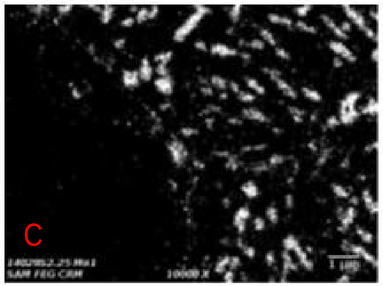


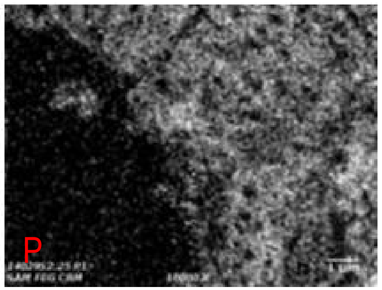


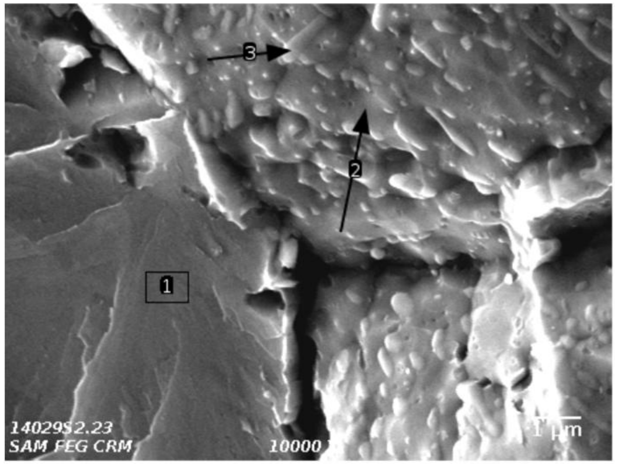
Non-hardening embrittlement

- Embrittlement without corresponding yield strength increase.
- Less well understood.
- Main reported mechanism: Grain boundary (GB) embrittlement by irradiation enhanced diffusion of impurities (mainly P) to GB's.







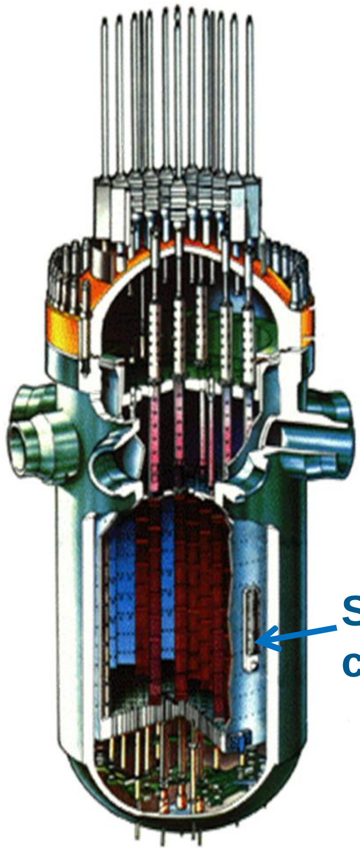


04

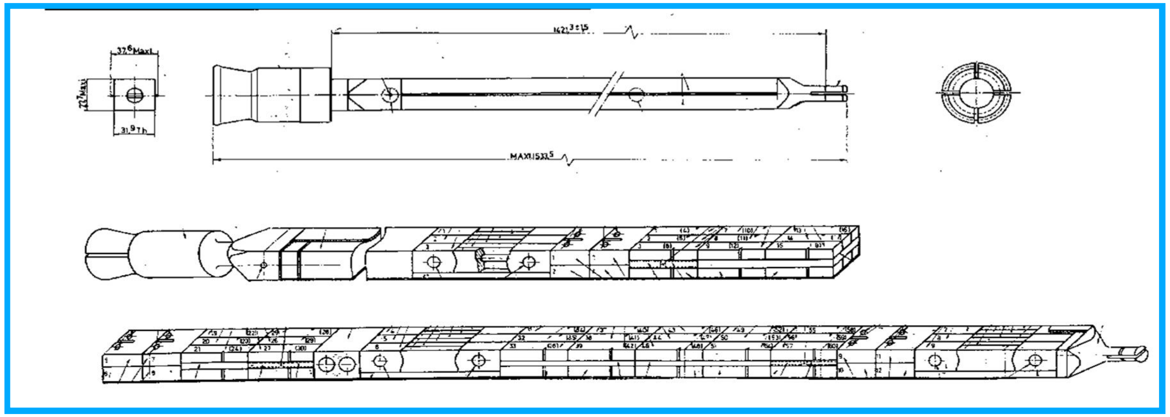
Prediction and follow-up of irradiation ageing

Principle of surveillance samples

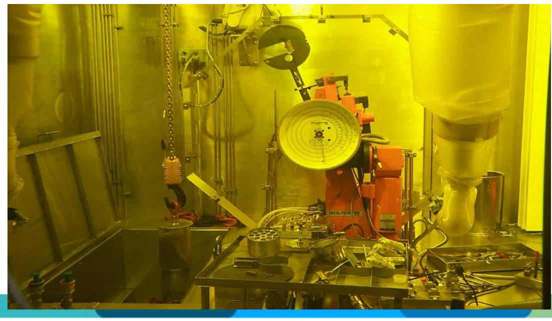
- RPV irradiation embrittlement is monitored by means of surveillance capsules containing the RPV beltline materials that are inserted in the RPV before the start of operation.
- These capsules are placed at locations in which they receive a higher neutron flux than the vessel wall by a factor on the order of two to three.
- They are regularly retrieved and tested to evaluate RPV irradiation embrittlement according to specific regulatory procedures and standards to guarantee the safe operation of the RPV throughout its lifetime.

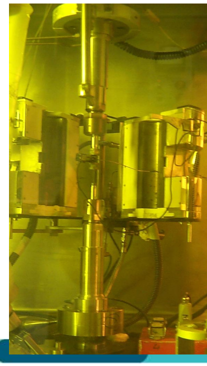


Surveillance capsules



Tests in hot cells at SCK.CEN





Embrittlement trend curves

- Embritllement trend curves are used to predict RPV embrittlement based on chemical composition (P, Cu, Ni) and neutron fluence (F in 10^{19}n/cm²).
- Test results of surveillance samples are compared to these trend curves to confirm that they are conservative.
- Some examples of trend curves:
  - French FIS formula used for Tihange 1, Tihange 3, Doel 4

$$DRT_{NDT} = \quad 8 + [24 + 1537(P-0.008) + 238\ (Cu-0.08) + 191\ Cu \cdot Ni^2] \cdot F^{0.35}$$

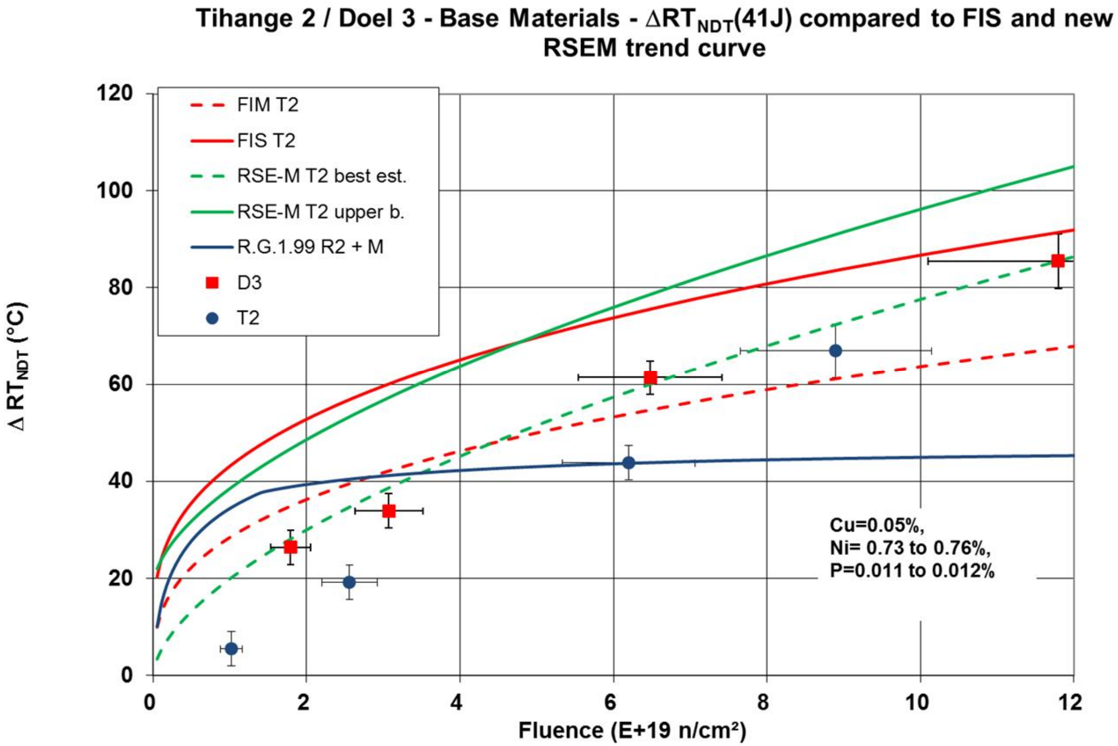
  - RSEM trend curve used for Doel 3 – Tihange 2

$$DRT_{NDT} = A\ [1 + 35.7(P-0.008) + 6.6(Cu-0.08) + 5.8Ni^2Cu] \cdot F^{0.59}$$

A = 15.4 (base metal) or 15.8 (weld)

(P-0.008)=0 if P<0.008%; (Cu-0.008)=0 if Cu<0.008%;

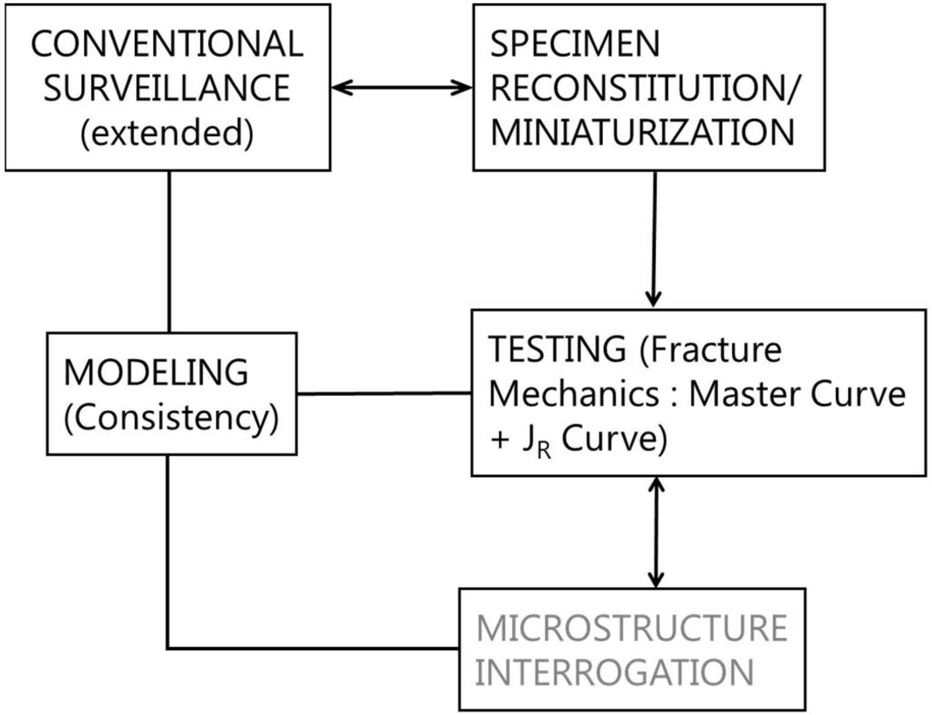
Embrittlement trend curves - Example



RPV surveillance for LTO (beyond 40)

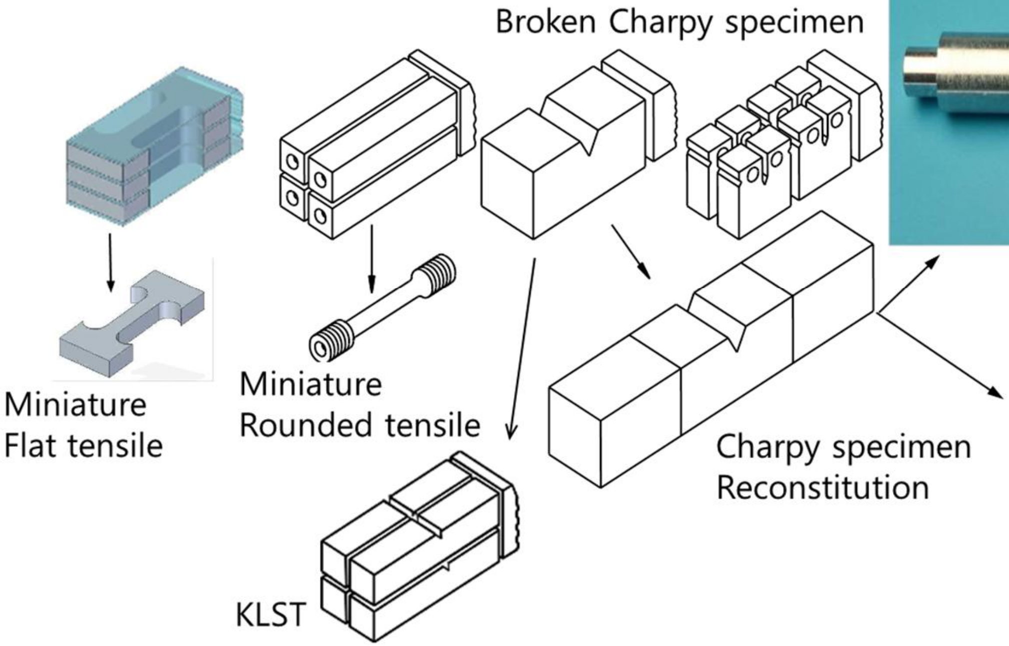
- Legal context:
  - LTO only authorized for Doel 1-2 and Tihange 1 (from 40 to 50 years)
  - Tihange 2, Doel 3, Tihange 3, Doel 4 supposed to shut down after 40 years (unless…)
- Tihange 1: results available for fluence > 50 years; two capsules remain in reactor, fluence levels comparable to existing results but used to confirm fluence evaluations.
- Doel 1-2: results available for fluence > 50 years, no capsules left in reactor but ex-vessel dosimetry implemented since the eighties can be used to confirm fluence evaluations.
- Other units: results available for fluence > 60 years, two spare capsules inserted some years ago (2004 to 2011) to provide follow-up in LTO period (if any).

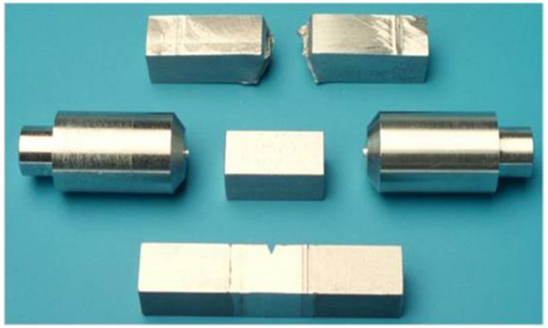
Enhanced surveillance strategy



R.Chaoudi, R.Gérard, “An Effective Surveillance Strategy for Reactor Pressure Vessel Assessment in the Long Term Operation Perspective”; Fontevraud 8 - Contribution of Materials Investigations and Operating Experience to LWRs’ Safety, Performance and Reliability
France, Avignon – 2014, September 14-18

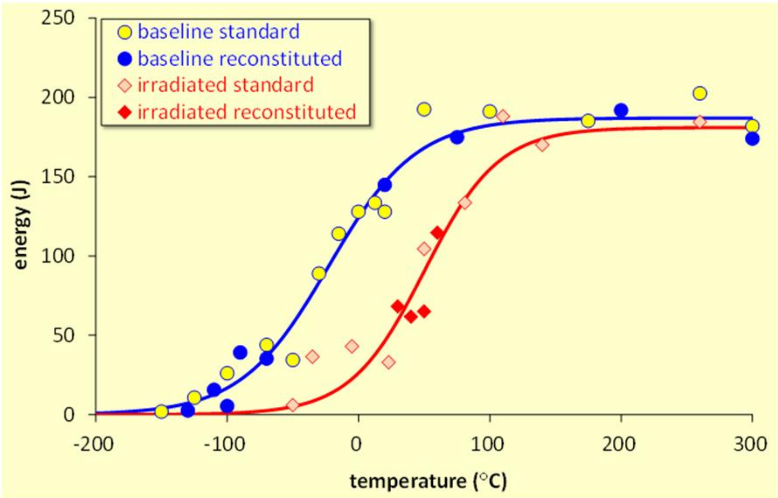
Specimen reconstitution - miniaturization



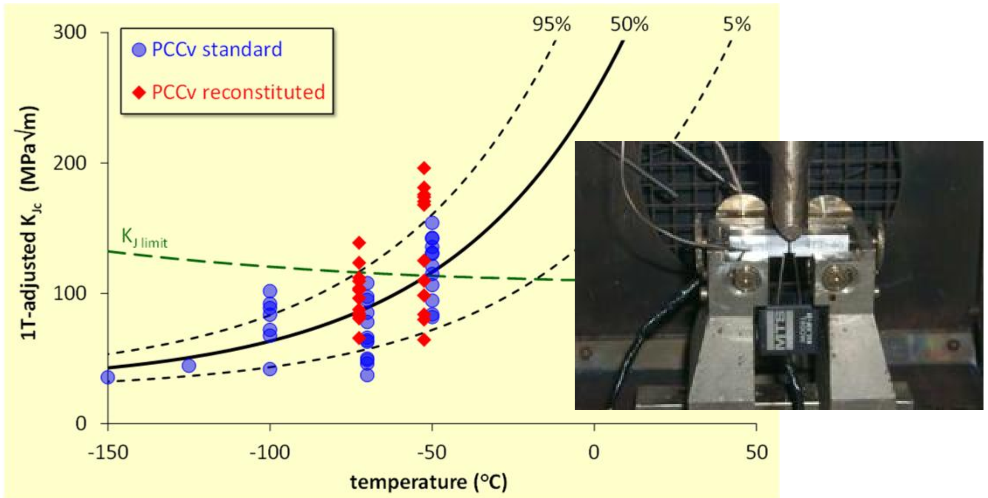


Specimen reconstitution

Charpy impact



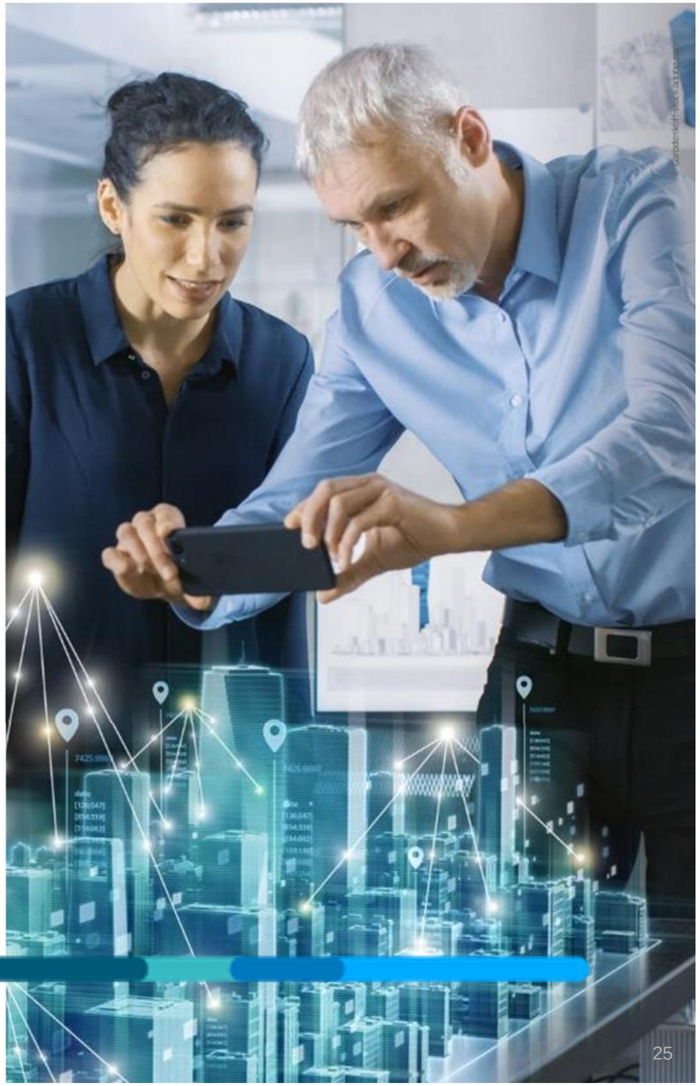
Master Curve



Reconstitution of Charpy-size specimens either for additional Cv tests or for Master Curve (after pre-cracking and test in three point bending)

05

Summary



Summary

- Neutron irradiation causes irradiation induced defects in the RPV material.
- These defects cause irradiation embrittlement over time due to irradiation hardening.
- Surveillance samples, placed in areas with high neutron flux, are used to follow-up irradiation ageing of RPV's.
- Enhanced surveillance strategy for long term operation.