RPV SURVEILLANCE PROGRAMMES AND INTEGRITY ASSESSMENT

H. Hein

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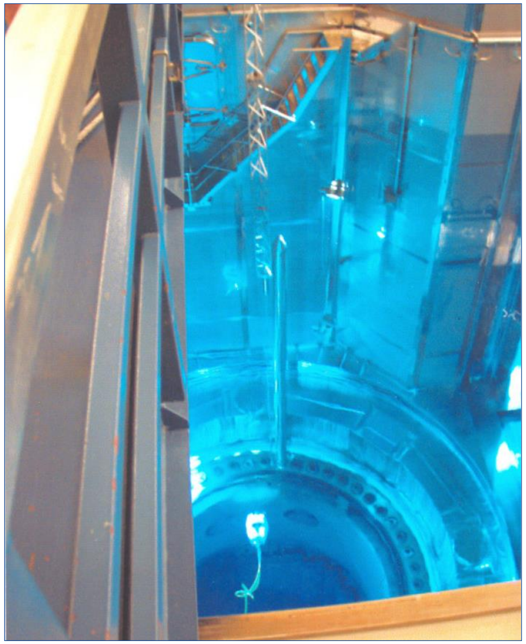
Contents



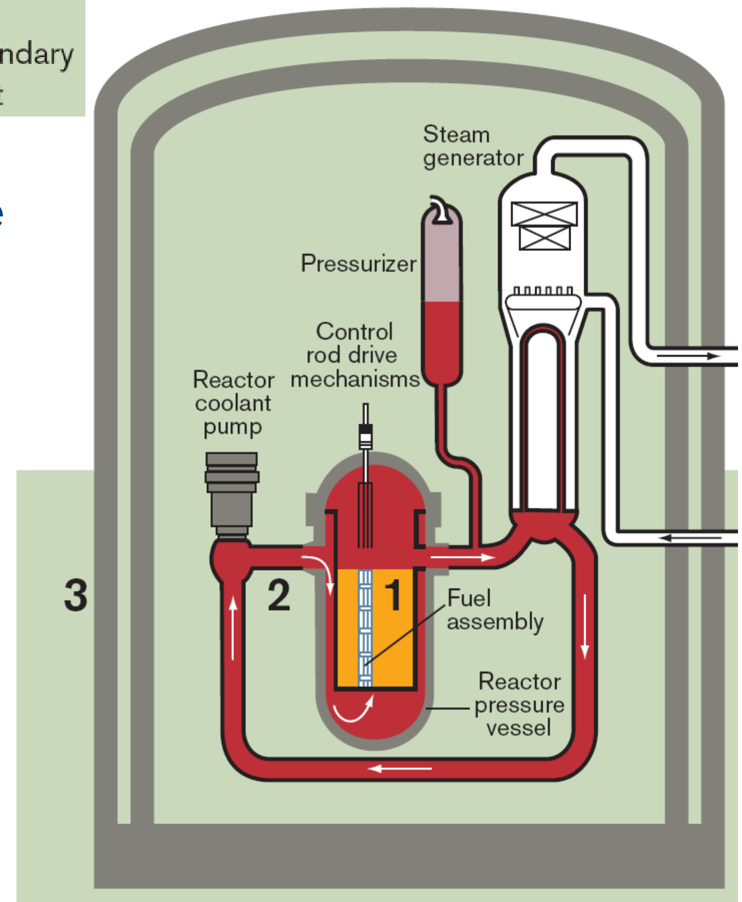
INTRODUCTION

Introduction

- Reactor Pressure Vessel (RPV) is very important for reactor operation and safe inclusion of fission products
  - Fuel elements (core)
  - Physical barrier
  - Core cooling function

The three protective barriers

1 Fuel cladding
2 Reactor coolant boundary
3 Reactor containment



- RPV is almost impossible to replace

EPR™ (European Pressurized Water Reactor)

Installation of the EPR™ RPV in NPP Olkiluoto 3 2010

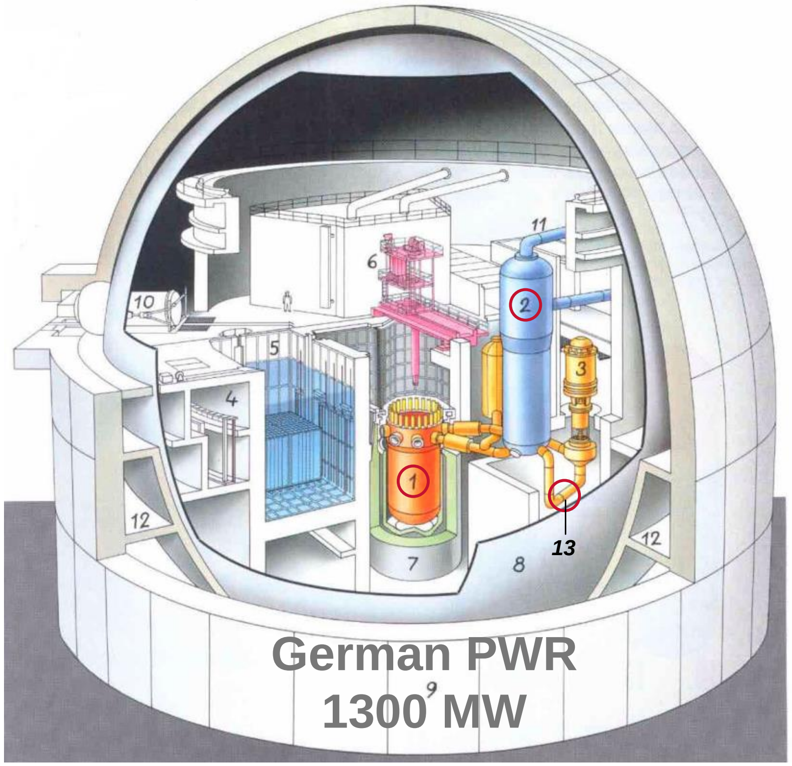
Introduction

- RPV integrity is a design principle for safe inclusion of the activity inventory
  - to be maintained during operation
- Requirement of both RPV monitoring and structural mechanical analyses

1 **RPV**

2 *Steam generator heat tubes*

13 *Main coolant lines*

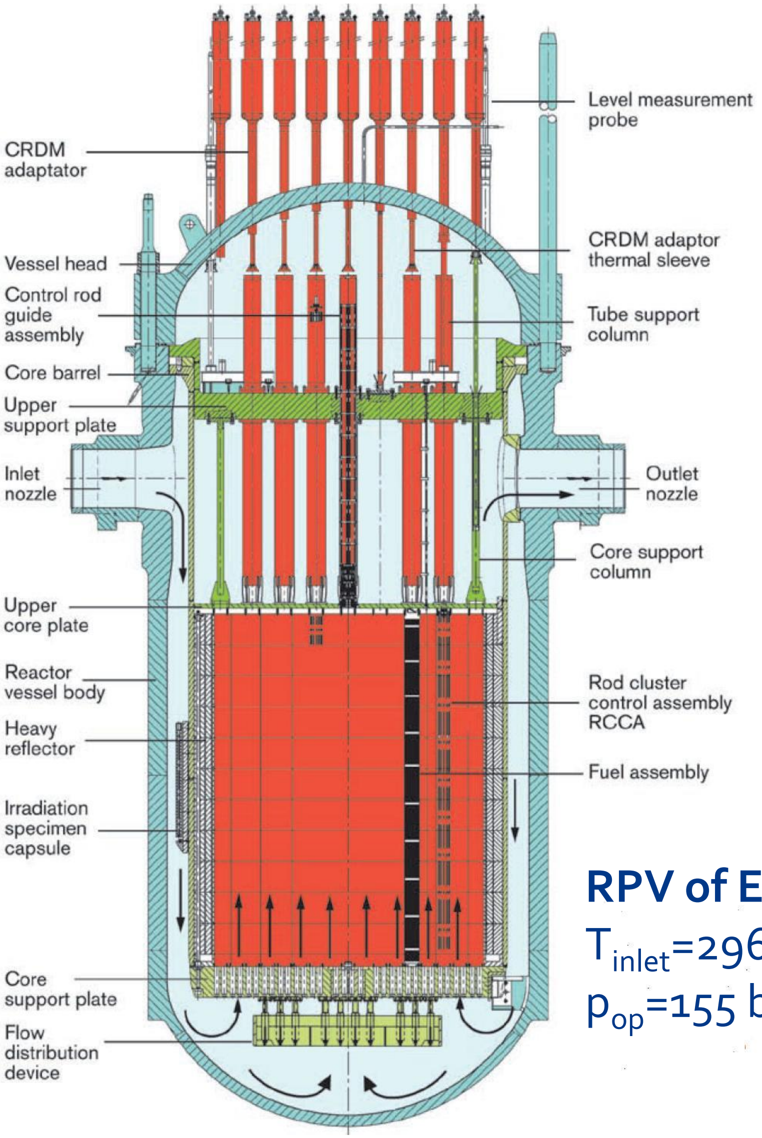


[1]

RPV AGEING MECHANISMS

RPV Ageing Mechanisms

- Influencing factors
  - Irradiation by fast neutrons
    - Neutron generation in the core
    - Impact on RPV beltline
  - Gamma irradiation
  - Thermal loading by hot coolant
  - Some hydrogen by radiolysis and water chemistry regime



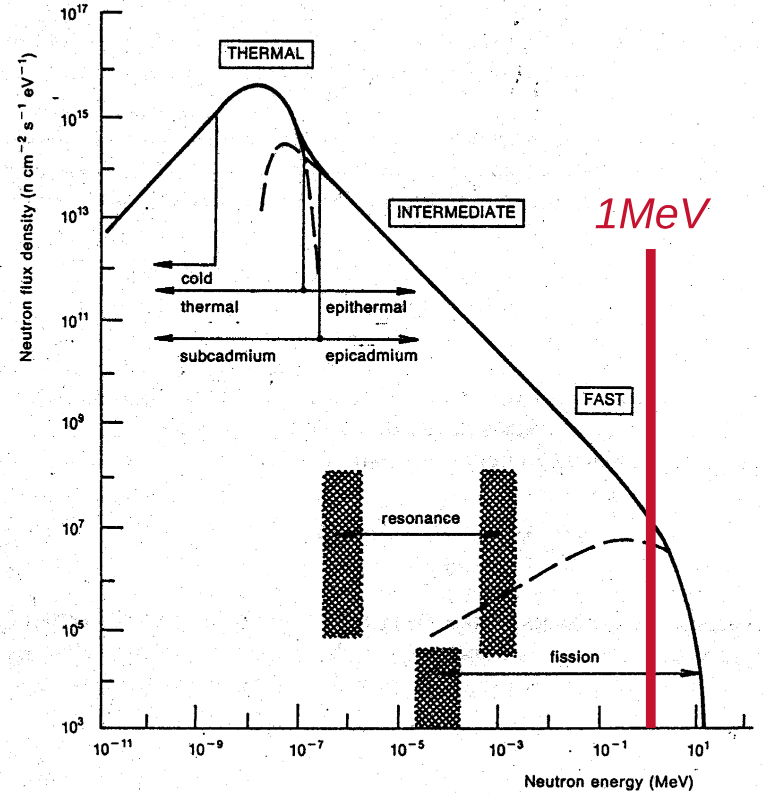
RPV of EPR™ [2]

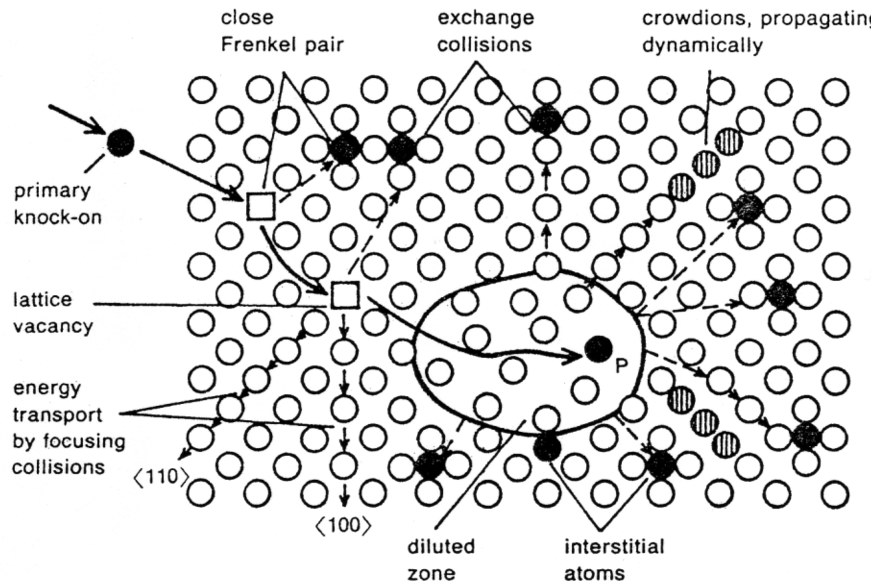
T_{inlet}=296 °C

p_{op}=155 bar

RPV Ageing Mechanisms

- Irradiation by fast neutrons
  - Formation of microstructural lattice defects

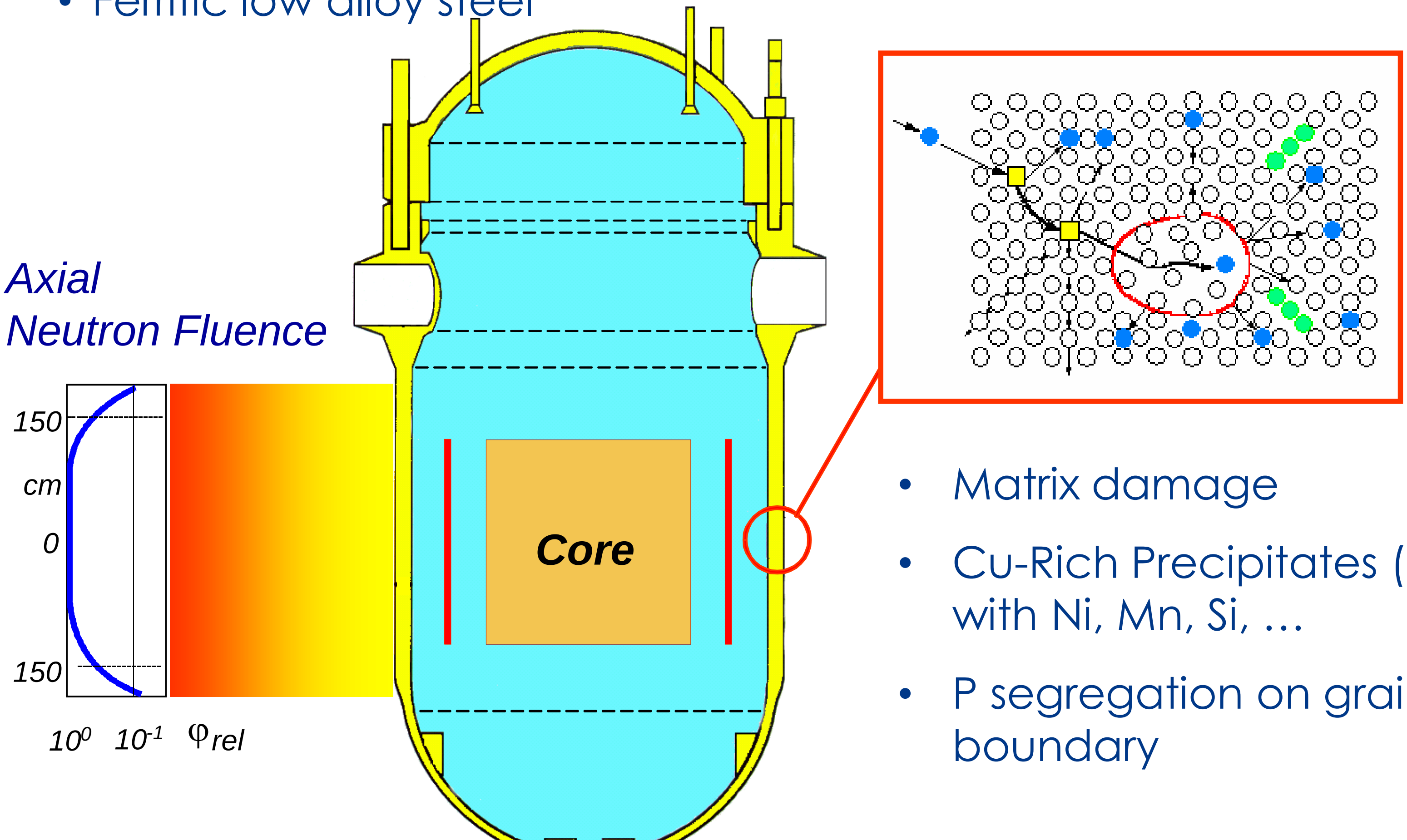




Model concept according to Alfred Seeger [3]

RPV Ageing Mechanisms

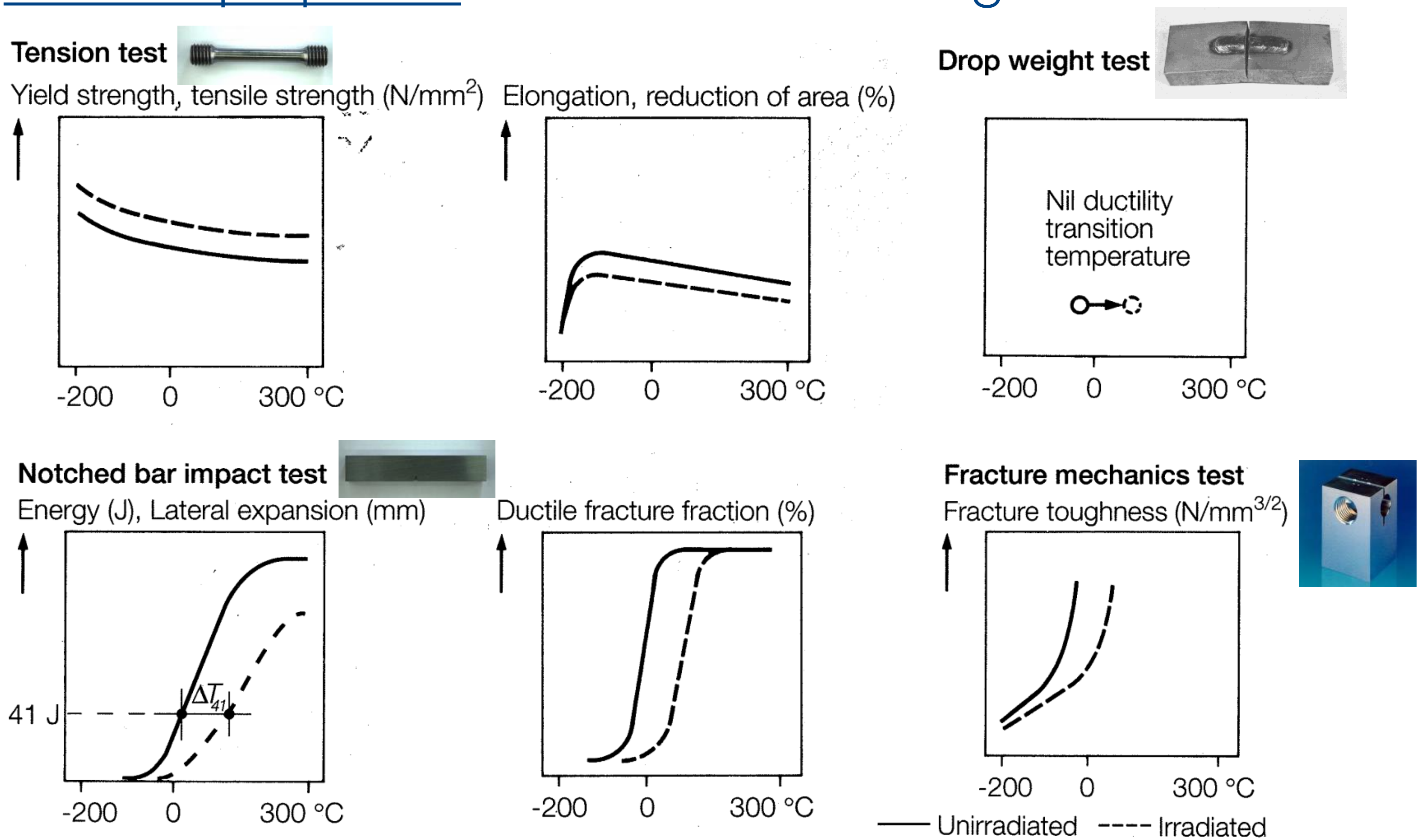
- ❑ Impact of irradiation by fast neutrons (E > 1 MeV) on the <u>microstructure</u> in the RPV beltline region
  - Ferritic low alloy steel



- Matrix damage
- Cu-Rich Precipitates (CRP) with Ni, Mn, Si, …
- P segregation on grain boundary

RPV Ageing Mechanisms

- Impact of fast neutron fluence (>10^{17} n/cm^2) on the material properties in the RPV beltline region



RPV Ageing Mechanisms

❑ Thermal Ageing of RPV Materials

- For western RPV steels with Cu ≤ 0.25% thermal ageing is not observed for T ≤ 325°C for long operating times, however some recent indications found for Ni ≥ 1.2 %
- No thermal ageing in LWR RPV steels with Cu < 0.35% and T < 300 °C
- Some significance in Magnox type reactors (UK) in C-Mn RPV steels with 360 °C exposure temperature

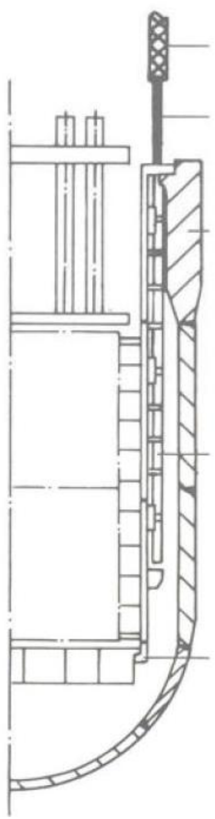
❑ Other Influencing Factors

- Hydrogen: no effect under operating conditions (embrittlement of ferritic RPV material by hydrogen no more detectable at 250°C)
- Gamma irradiation: not significant at LWR operating temperatures due to strong annealing effects
  - No indications of γ-irradiation effect on change of material properties of ferritic RPV materials under operating conditions
  - If any g effect would exist it is limited on the surface of inner RPV wall because the attenuation for γ is higher than for neutrons

RPV IRRADIATION SURVEILLANCE PROGRAMMES

RPV Irradiation Surveillance Programmes

Management of RPV Irradiation Behavior



Assessment

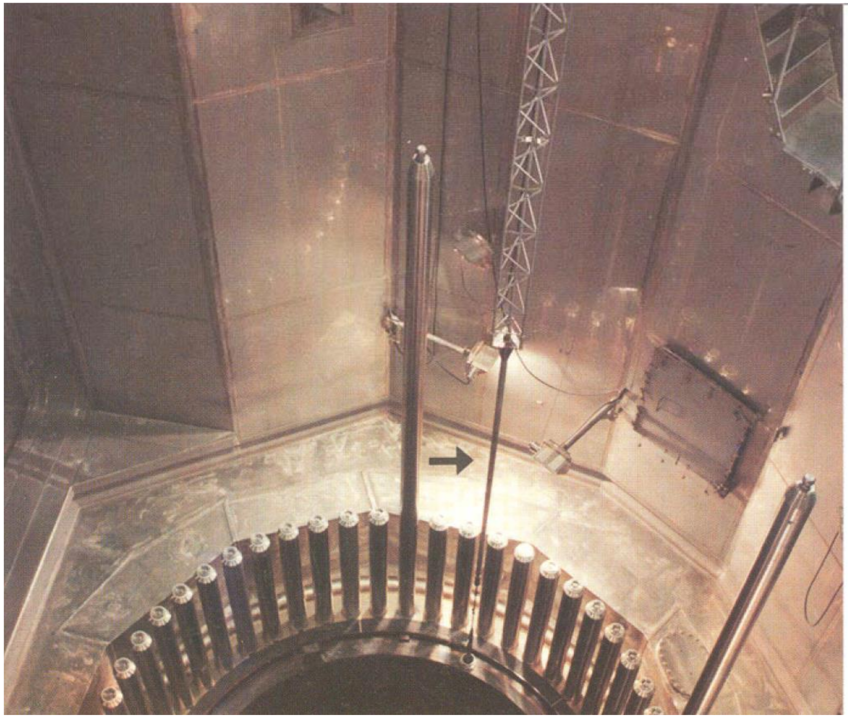
- ***Irradiation Surveillance Programs***
  - ✓ *Monitoring material changes depending on neutron fluence*
- ***RPV Integrity Assessment***
  - ✓ *Fracture mechanics based PTS analysis*
  - ✓ *p-T curves, in-service pressure tests*

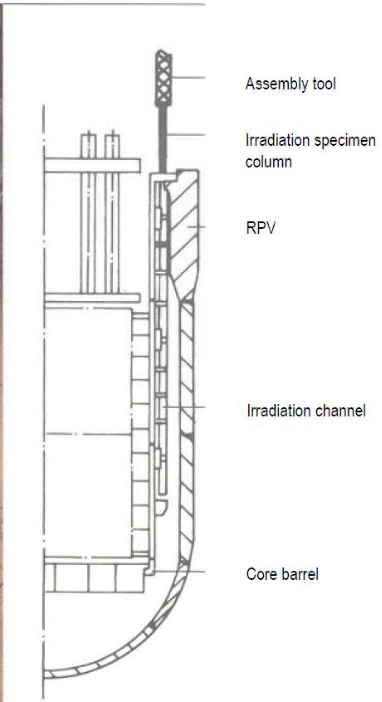
Countermeasures

- ***Core Loading Management***
  - ✓ *Low leakage*
- ***RPV Neutron Shielding***
  - ✓ *Dummy assemblies*
  - ✓ *Internals replacement*
- ***Thermal Annealing***
  - ✓ *Recovery heat treatment*

RPV Irradiation Surveillance Programmes

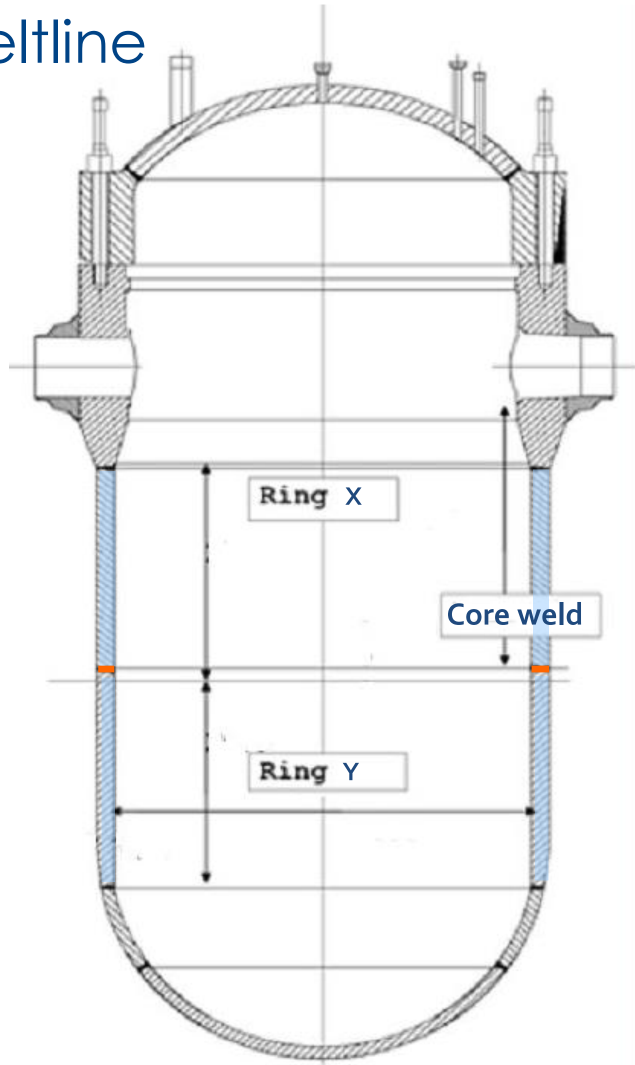
- Objective
  - Measurement of strength and toughness properties of materials in the RPV core beltline region as a function of neutron irradiation by accelerated irradiation specimen capsules (position nearer to the core)

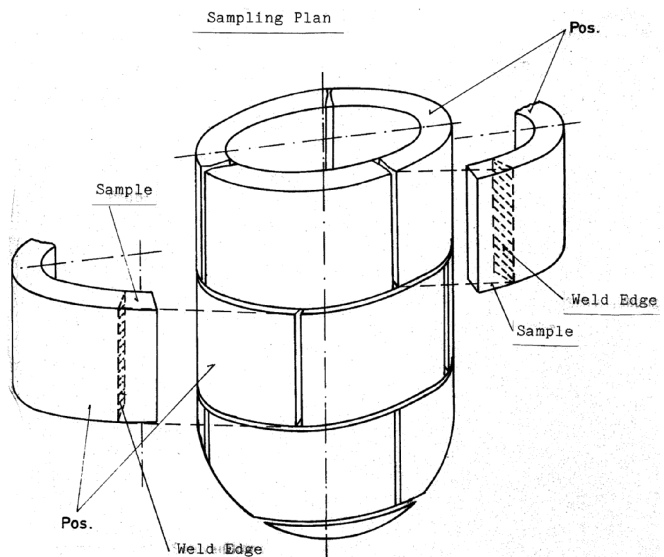




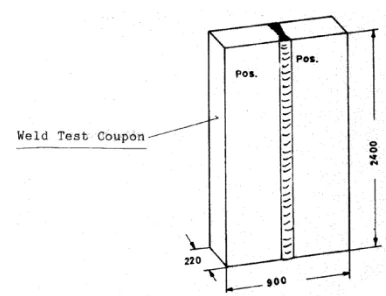
RPV Irradiation Surveillance Programmes

- Base and weld materials are monitored in the RPV core beltline



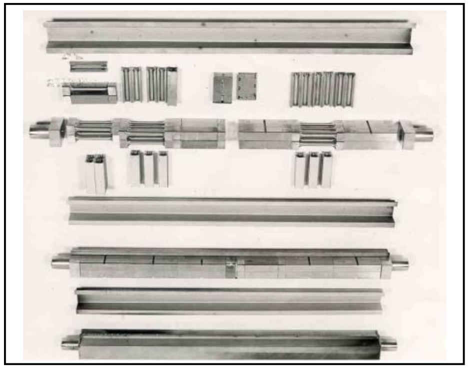


Sampling

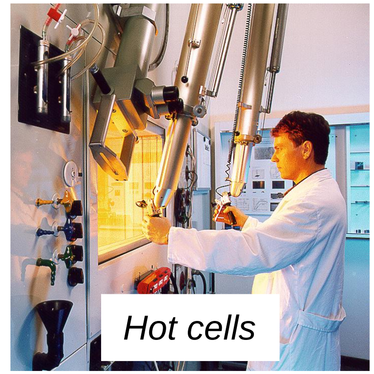


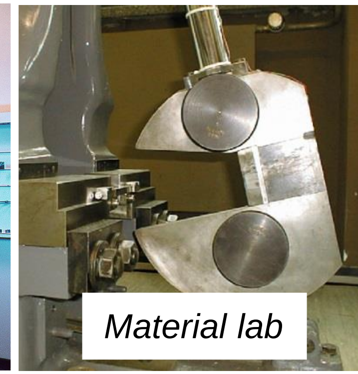
RPV Irradiation Surveillance Programmes

Design and Manufacture

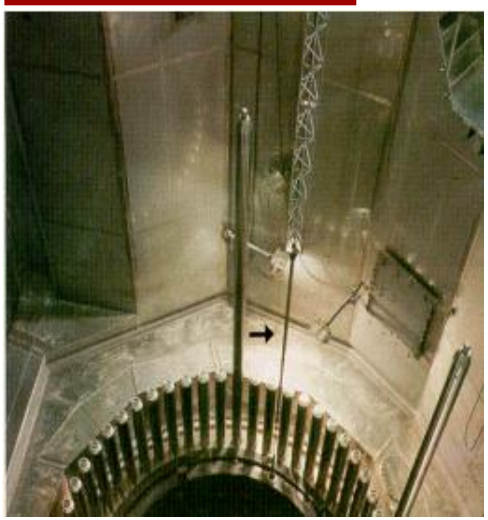


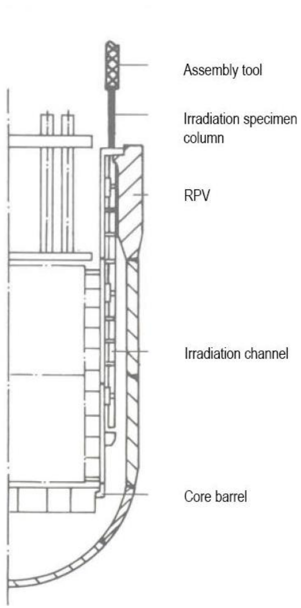
Pre & post examination



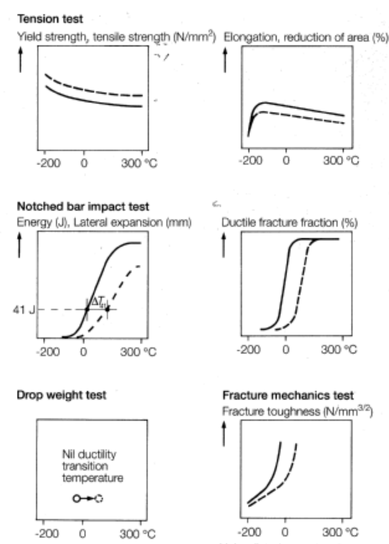


Implementation





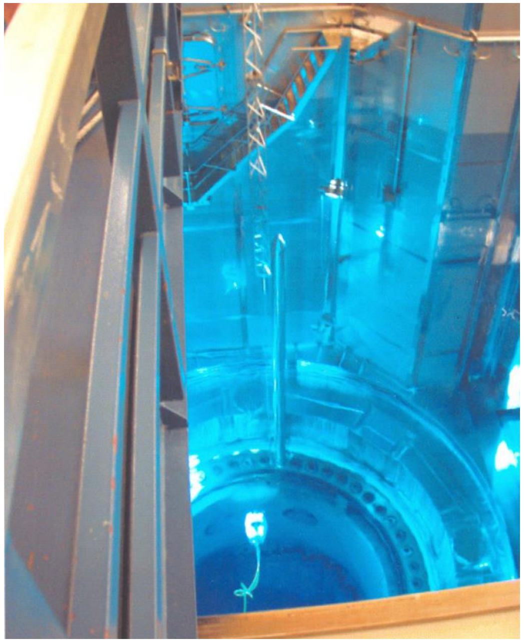
Assessment of irradiation behaviour



RPV Irradiation Surveillance Programmes

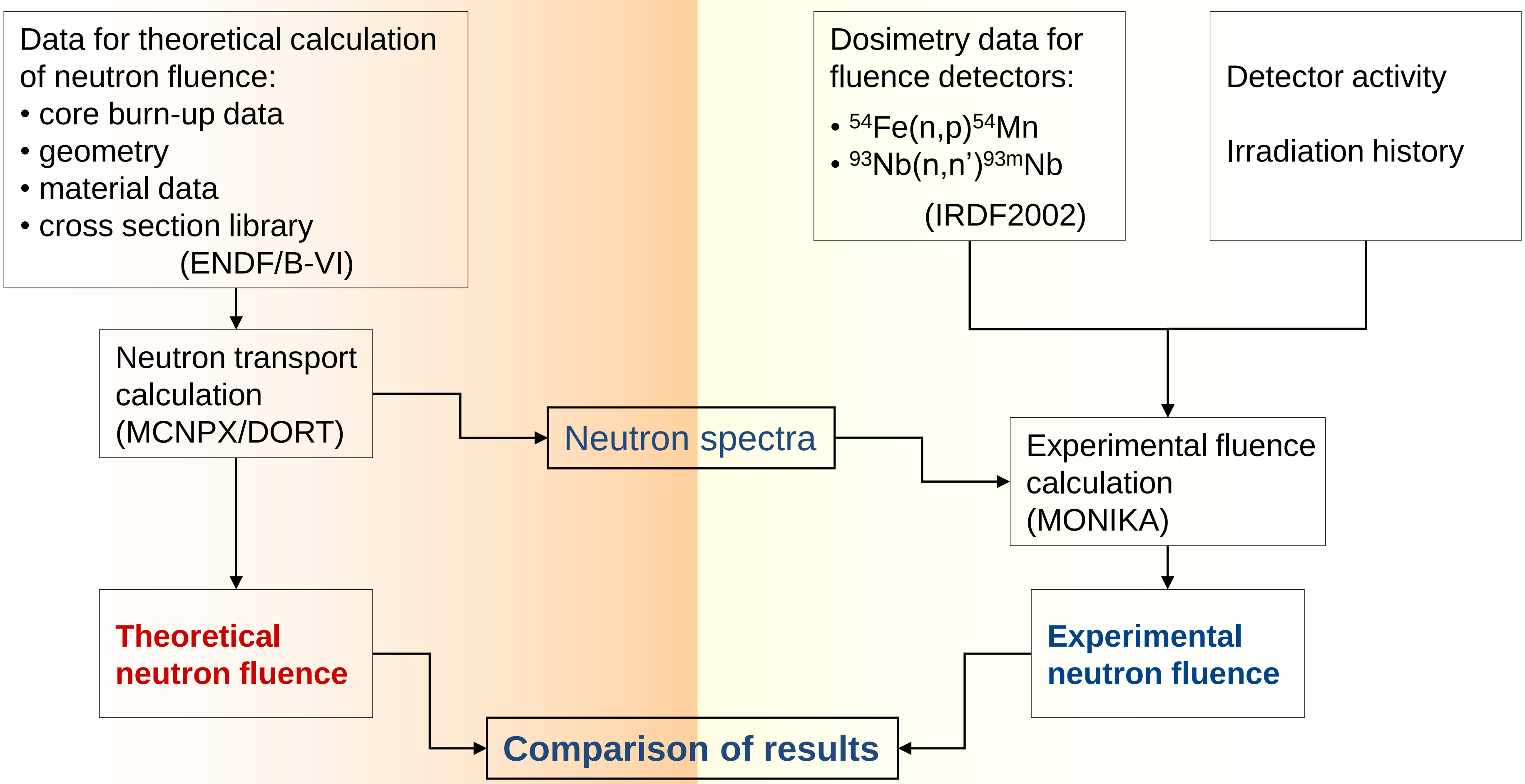
Main steps

- Manufacture of specimens, fluence dosimeters, temperature monitors, and capsules
- Insertion, irradiation and take out of capsules
- Transportation services
- Radiochemical examinations and activity determination of neutron dosimeters
- Neutron fluence calculations for specimens and RPV wall (Dosimetry)
- Mechanical testing in the „Hot Cells“ laboratory (tensile, Charpy-V, fracture mechanical)
- Evaluation of the results and RPV safety assessment according to regulatory requirements



RPV Irradiation Surveillance Programmes

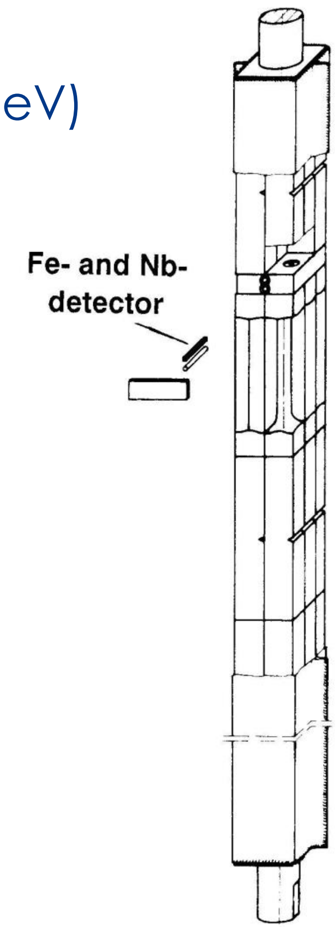
❑ Dosimetry - Dual concept of fast neutron fluence calculation



- ***Benchmarking of theoretical calculations***
- ***Verification of theoretical approach***

RPV Irradiation Surveillance Programmes

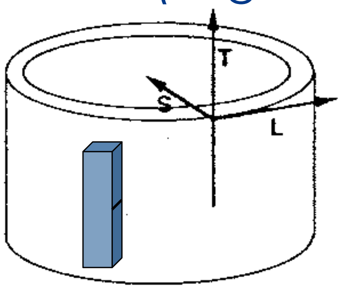
- Dosimetry
  - Determination of fast neutron fluence (E > 1 MeV)
    - at dosimeter positions
    - in RPV wall
  - Dosimeters
    - Internal dosimeters (inside RPV)
    - External dosimeters (outside RPV)
  - RPV scraping samples
    - Taken from cladding



RPV Irradiation Surveillance Programmes

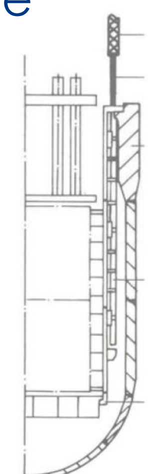
❑ What else is important to know?

- Take out position and orientation of specimens taken from the (original) material blocks
  - Tension, Charpy and fracture toughness specimens shall be removed from 1⁄4-T or 3⁄4-T locations (base metal)
  - Transverse specimens (T-L, longitudinal axis transverse to the main direction of forming)



cylindrical rings

- Lead factor - the ratio of the peak neutron fluence (E > 1 MeV) of the specimens in a surveillance capsule to the peak neutron fluence (E > 1 MeV) at the reactor pressure vessel inside surface
  - $1.5 \leq LF \leq 12$ (Germany)
  - $1.5 < LF < 5$ (USA)
- Number of the capsules and take out schedule
  - Usually 2 to 6 capsules covering the reactor life



RPV Irradiation Surveillance Programmes

- How to use surveillance data for RPV integrity assessment?

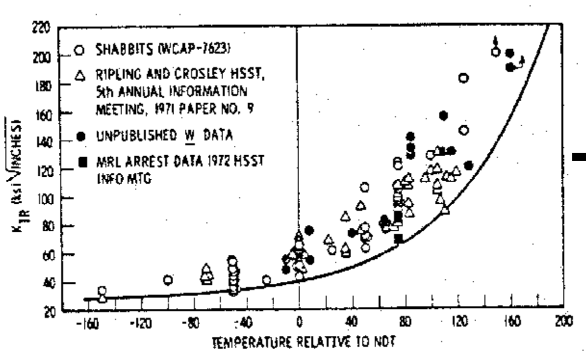


Fig. A1-1—Derivation of curve of reference stress intensity factor (K_{IR})

ASME K_{IC} Curve [5]

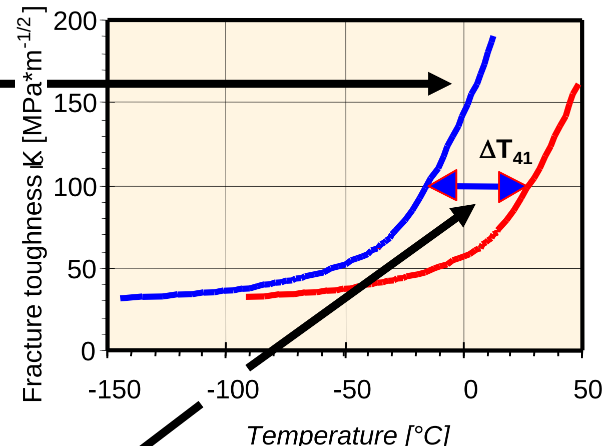
RT_{NDT} concept:

$RT_{NDTj} = RT_{NDT} + \Delta T_{41}$

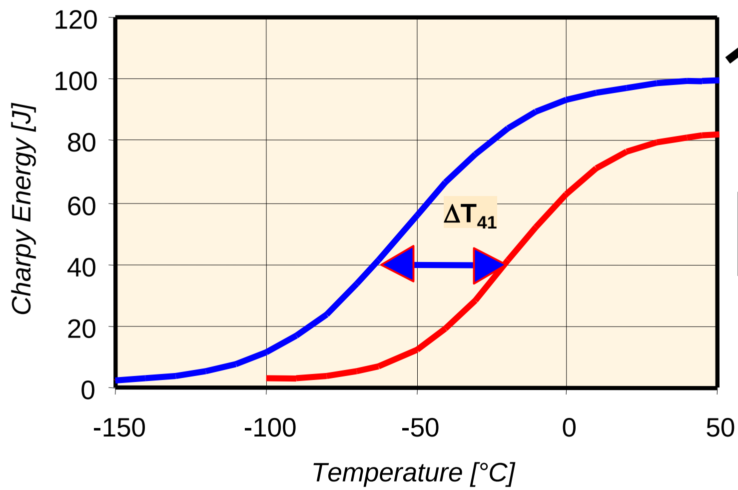
unirradiated adjusted versus RT_{NDT}

irradiated adjusted versus $RT_{NDTj} = RT_{NDT} + \Delta T_{41}$

plant spec. K_{IC} - Curve



acc. to [4]



plant spec. C_v Energy -T - Curve

RPV Irradiation Surveillance Programmes

- How to use surveillance data for RPV integrity assessment?

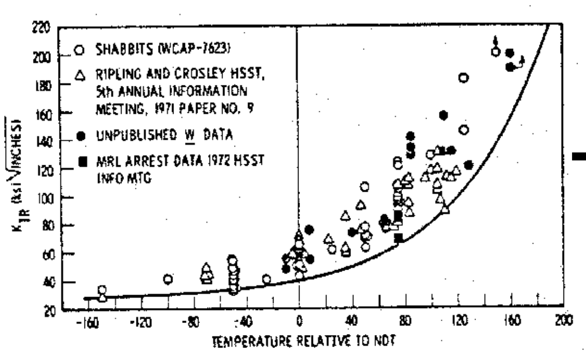


Fig. A1-1—Derivation of curve of reference stress intensity factor (K_{IR})

ASME K_{IC} Curve [5]

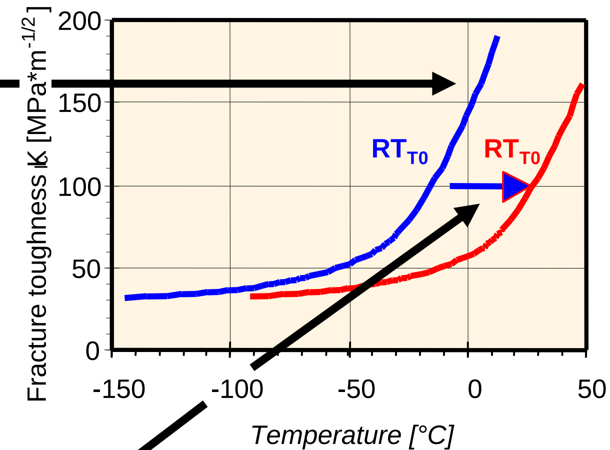
RT_{T0} concept

$RT_{T0} = T_0 + 19.4$ K

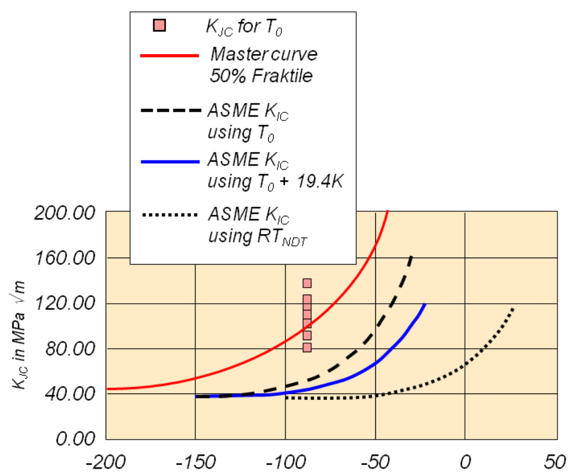
unirradiated adjusted versus RT_{T0}

irradiated adjusted versus RT_{T0} irradiated

plant spec. K_{IC} - Curve



Master Curve based on direct fracture toughness measurement acc. to[4], [7]

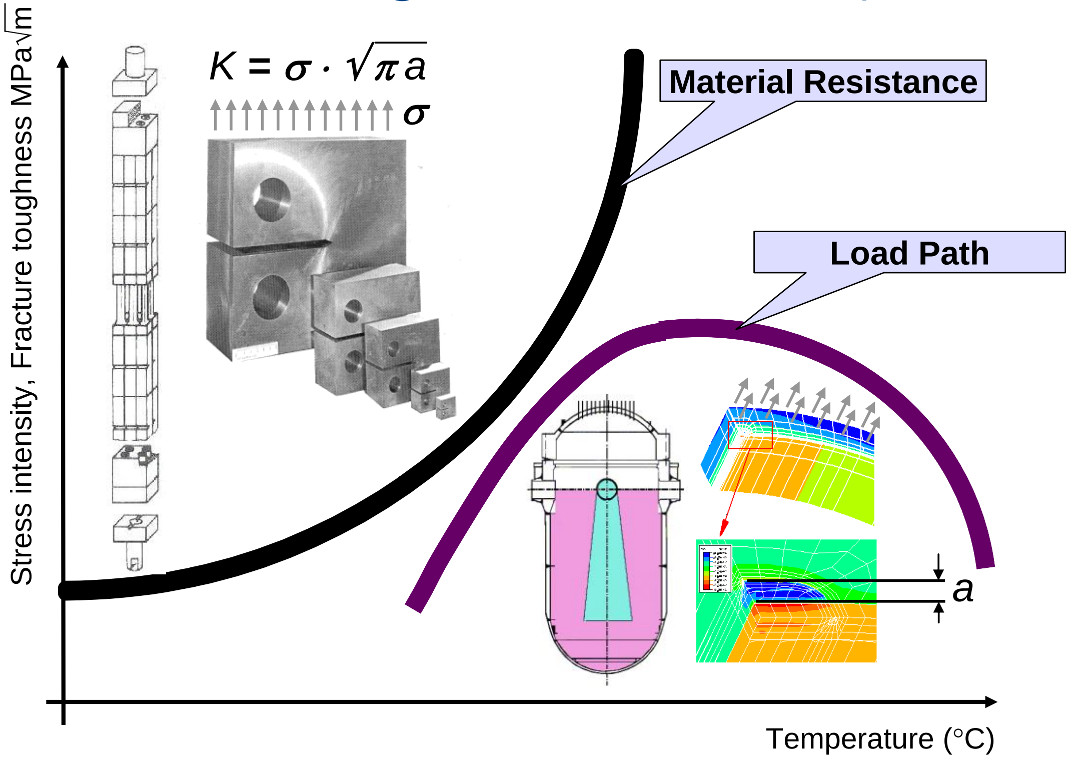


plant spec. K_{Jc}-T curve: T_0 at 100 MPa$\sqrt{m}$

RPV INTEGRITY CONCEPTS

RPV Integrity Concepts

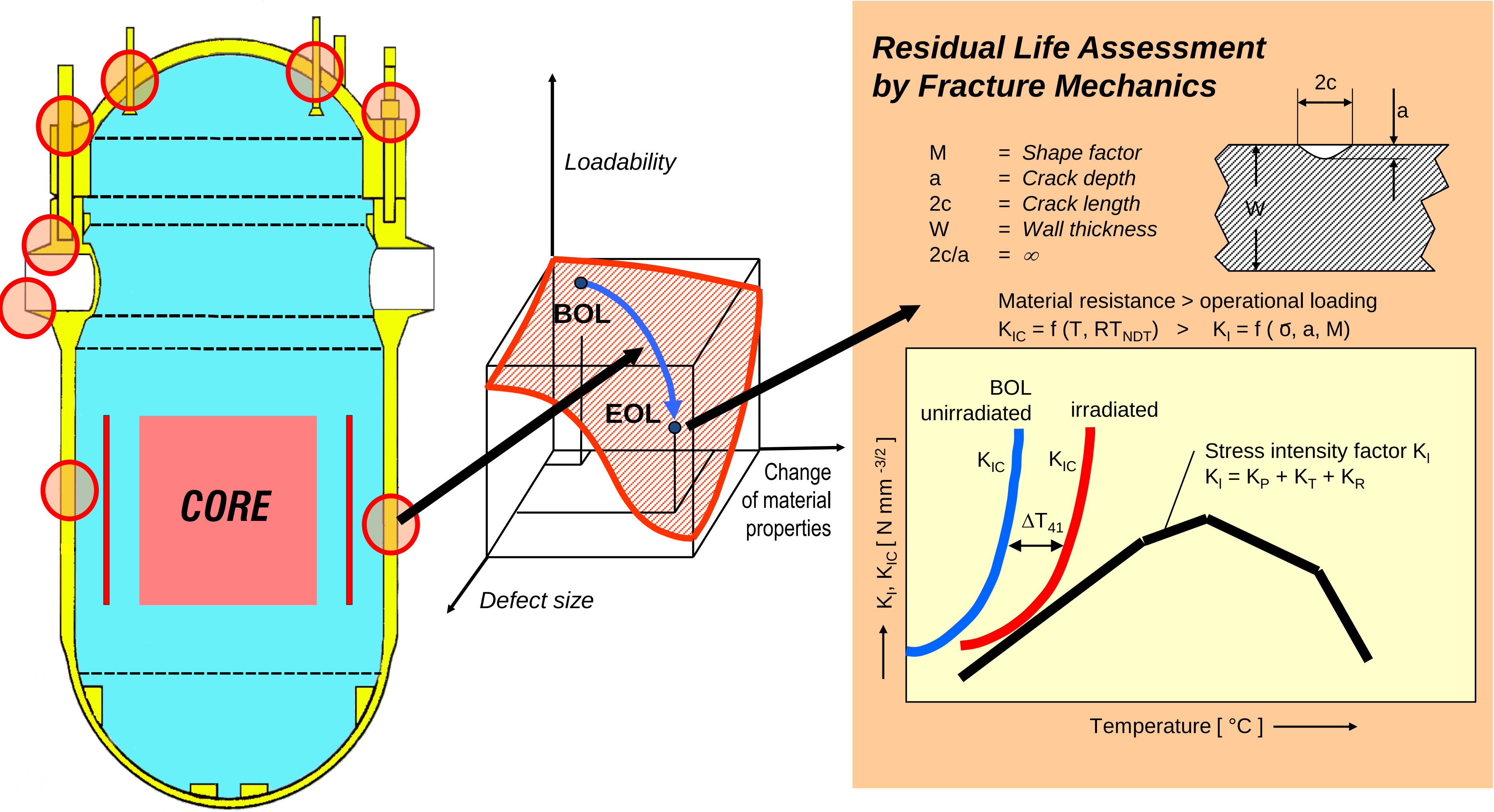
- Objective: Proof of safety against brittle fracture of the RPV
- The reference temperature (e.g. RT_{NDTj} or RT_{T0}[5]) governs the material resistance
- Transients and LOCA govern the load path



acc. to [4]

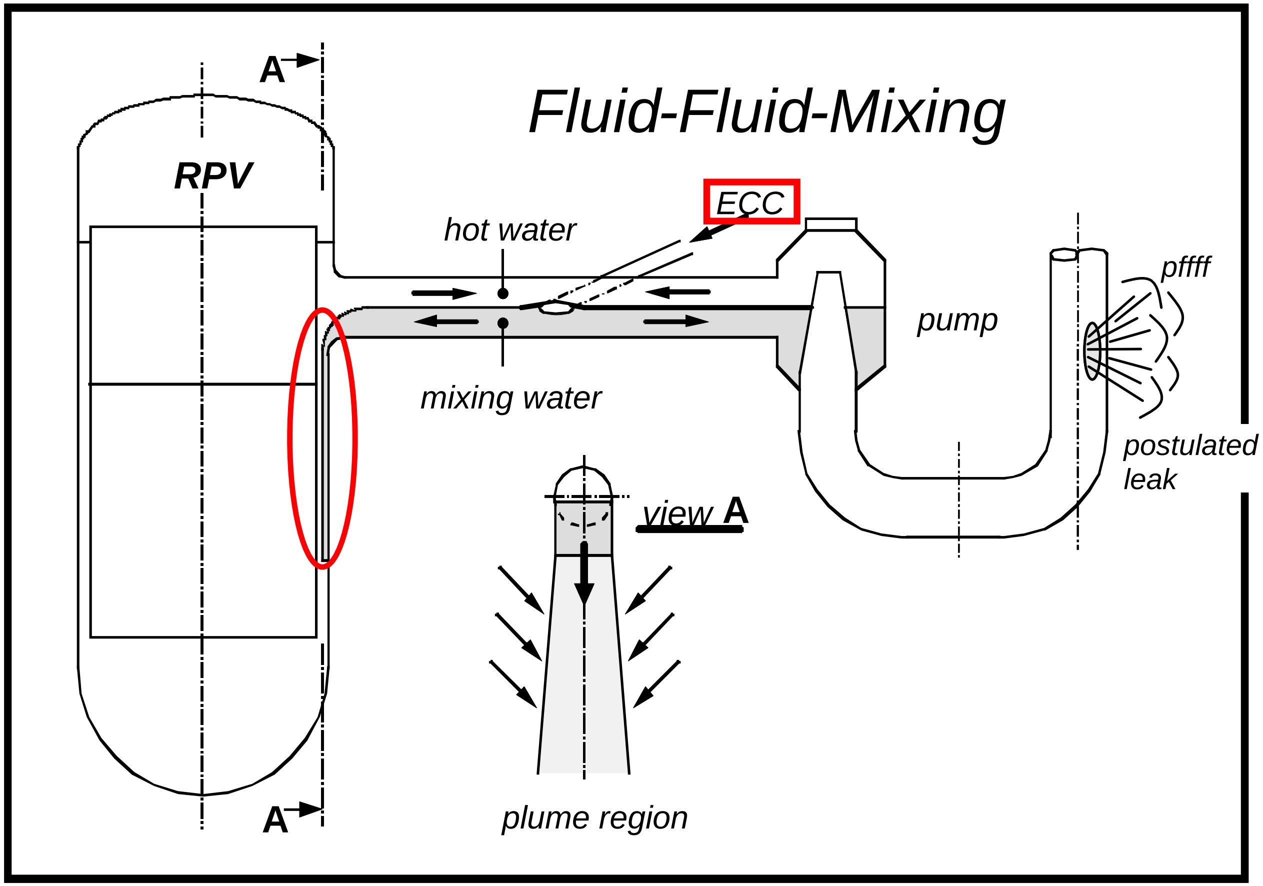
RPV Integrity Concepts

- Areas of postulated flaws of the RPV [4]



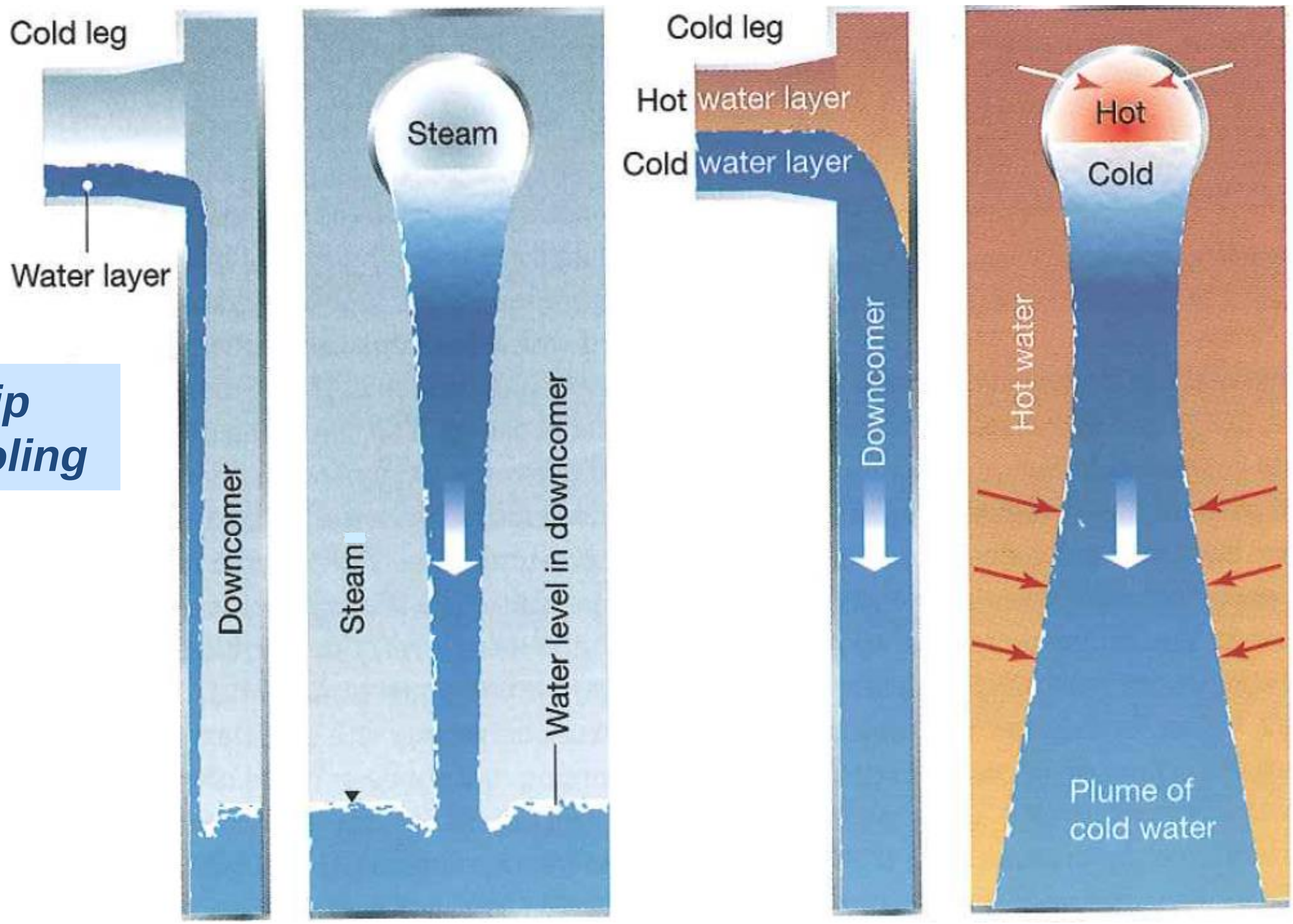
RPV Integrity Concepts

- Pressurized Thermal Shock (PTS) by Loss Of Coolant Accident (LOCA) [4]



- Thermal hydraulics at PTS [4], [6]

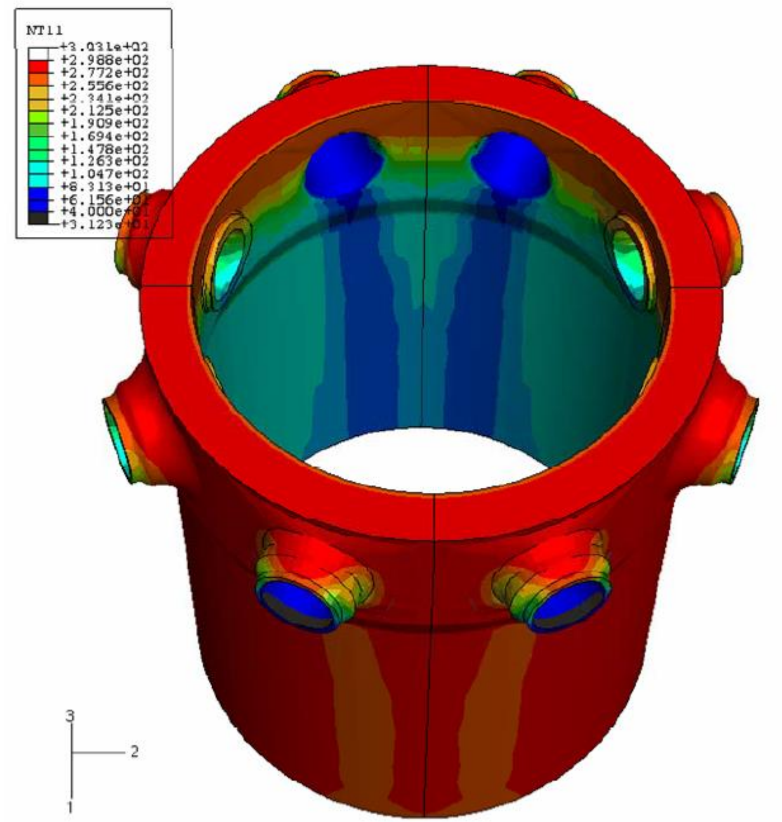
Strip cooling

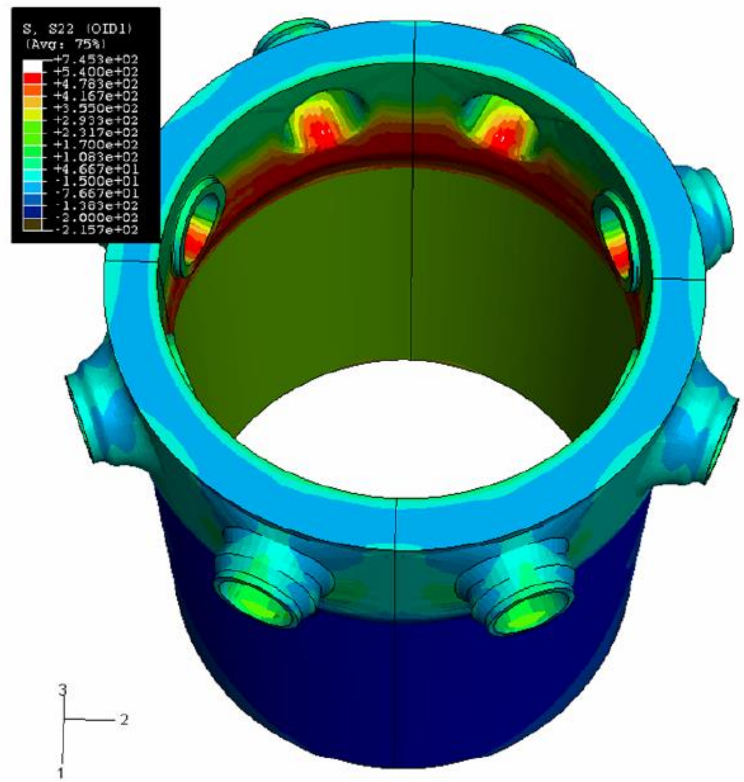


Plume cooling

RPV Integrity Concepts

- Thermal hydraulic and mechanical analyses at PTS by FEM [4], [8]

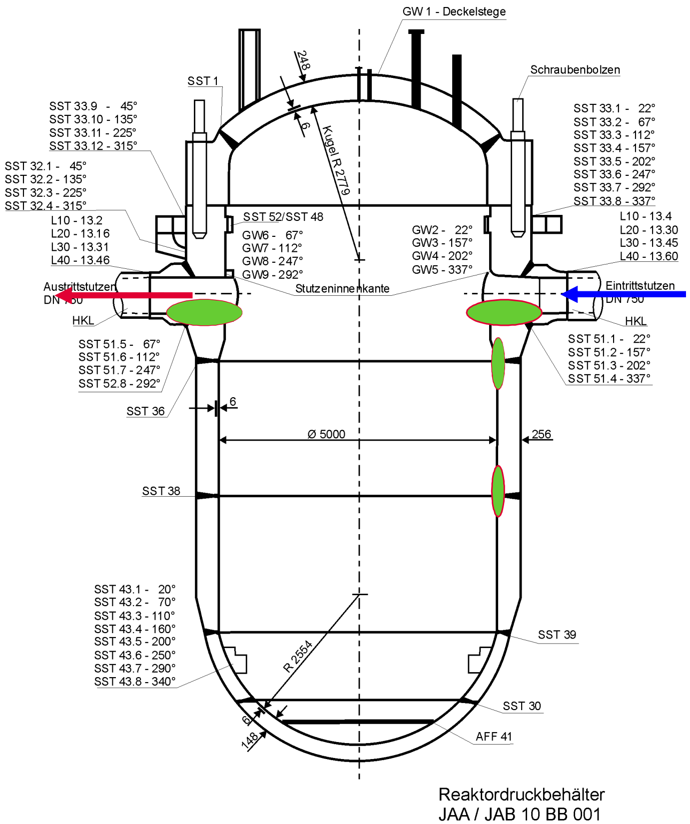


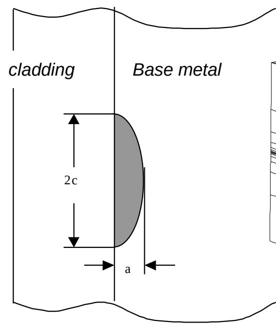


RPV Integrity Concepts

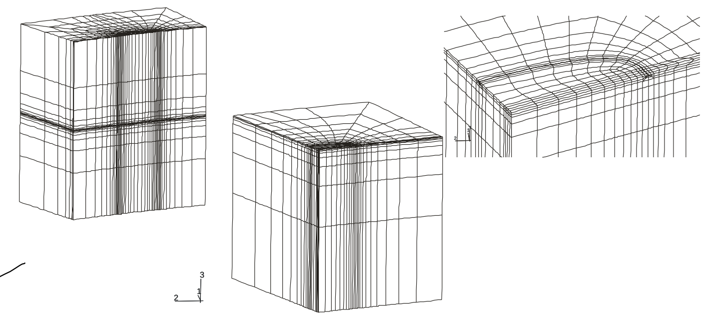
- Mechanical analysis of postulated flaws at PTS by FEM [4]

RPV Areas under consideration

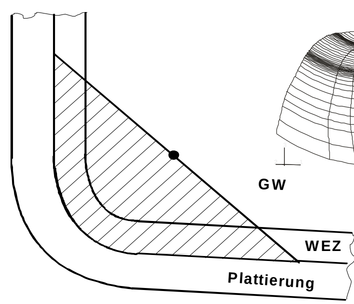




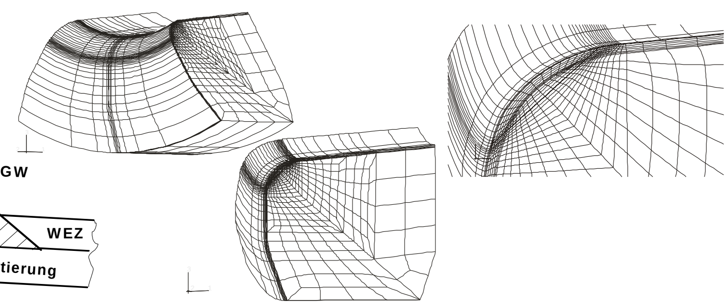
Example of crack geometry



Hot leg leak 200 cm², Submodel for crack in cylindrical region, flaw depth 20 mm



Example of crack geometry

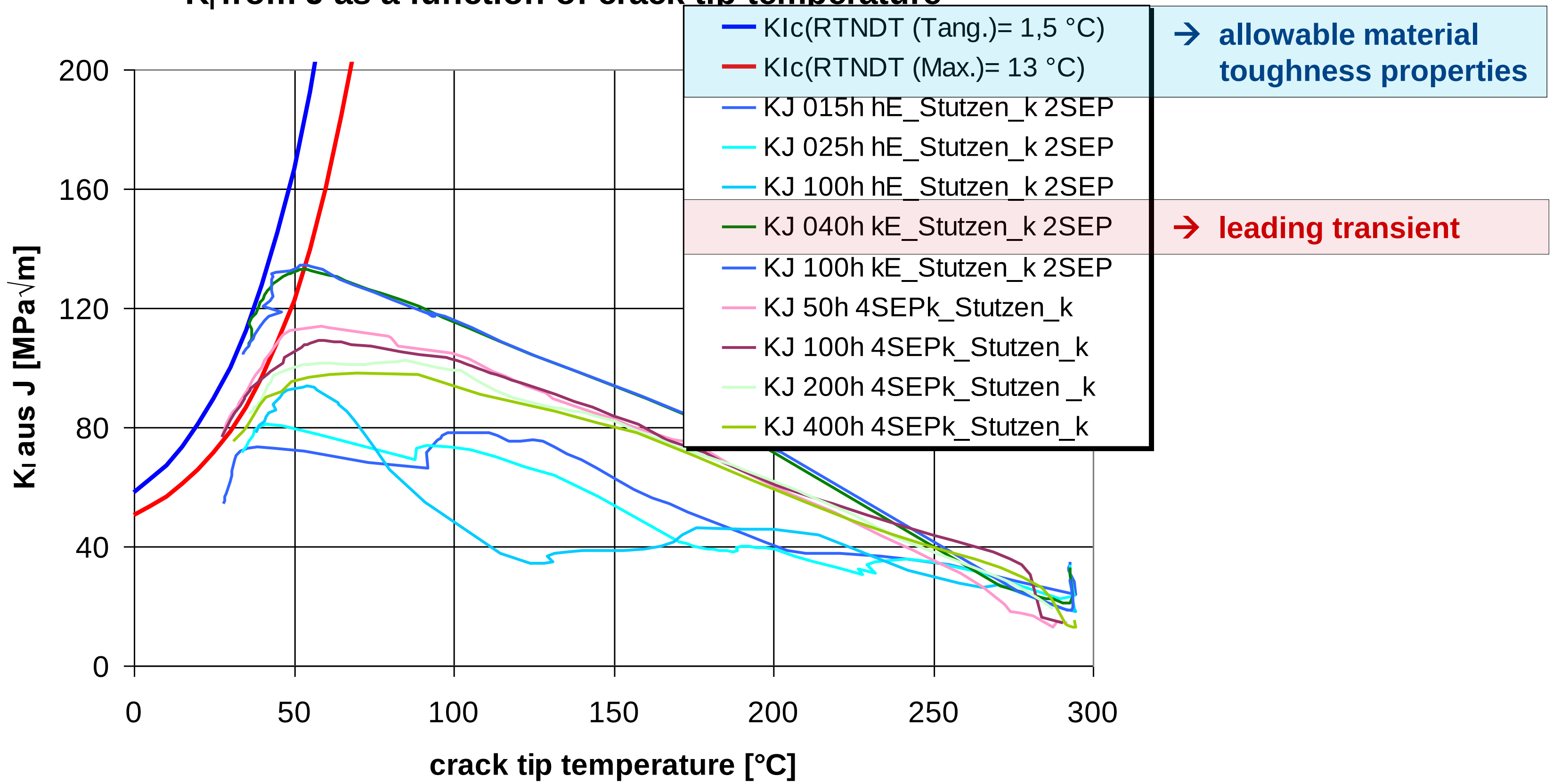


Hot leg leak 200 cm², Submodel for crack in nozzle region, flaw depth 20 mm

RPV Integrity Concepts

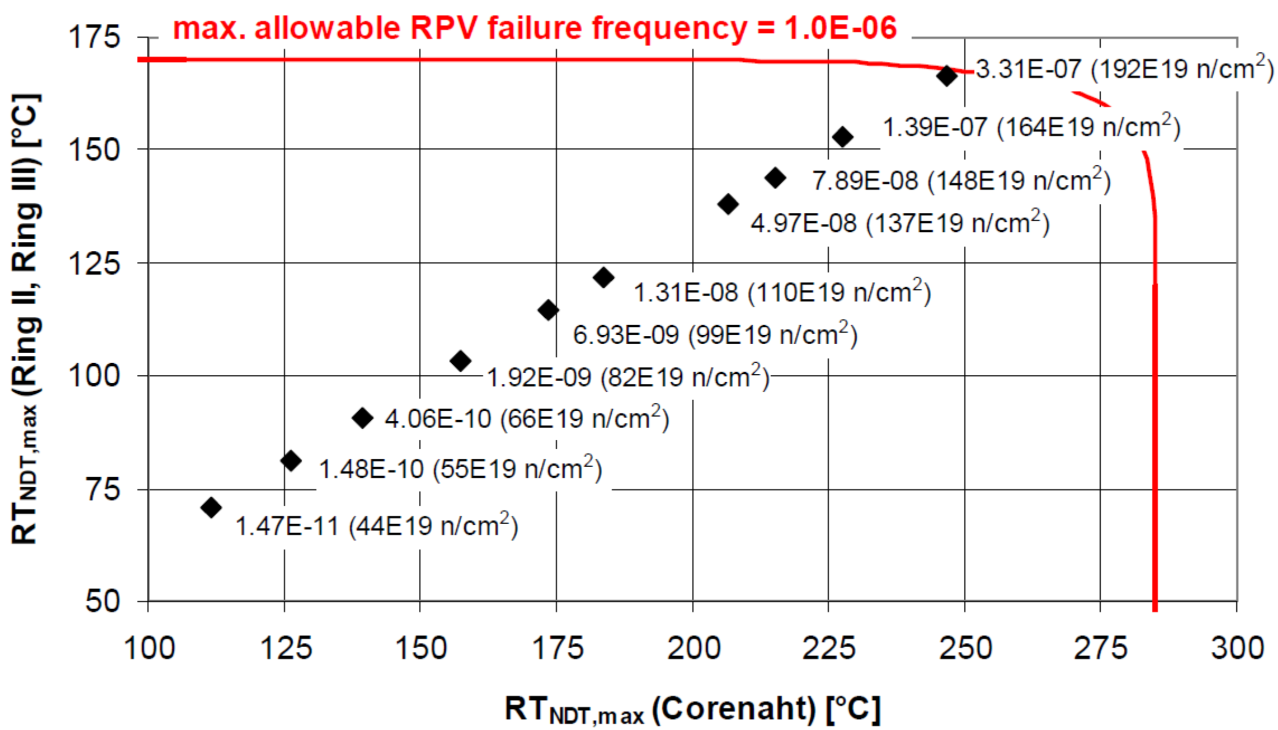
❑ Results of deterministic PTS analysis (example) [4]

Konvoi, cold leg nozzle, flaw depth 10 mm,
K_I from J as a function of crack tip temperature



RPV Integrity Concepts

- Probabilistic PTS analysis [8], [9], [10], [11], [12], [13]
  - Probability per year for failure and crack initiation of the RPV
  - Define PTS-Screening Criterion (allowed reference temperature for a maximum allowed failure probability, see [10])
  - Quantify the margins of the deterministic PTS analysis



SPECIFIC ISSUES IN IRRADIATION BEHAVIOUR

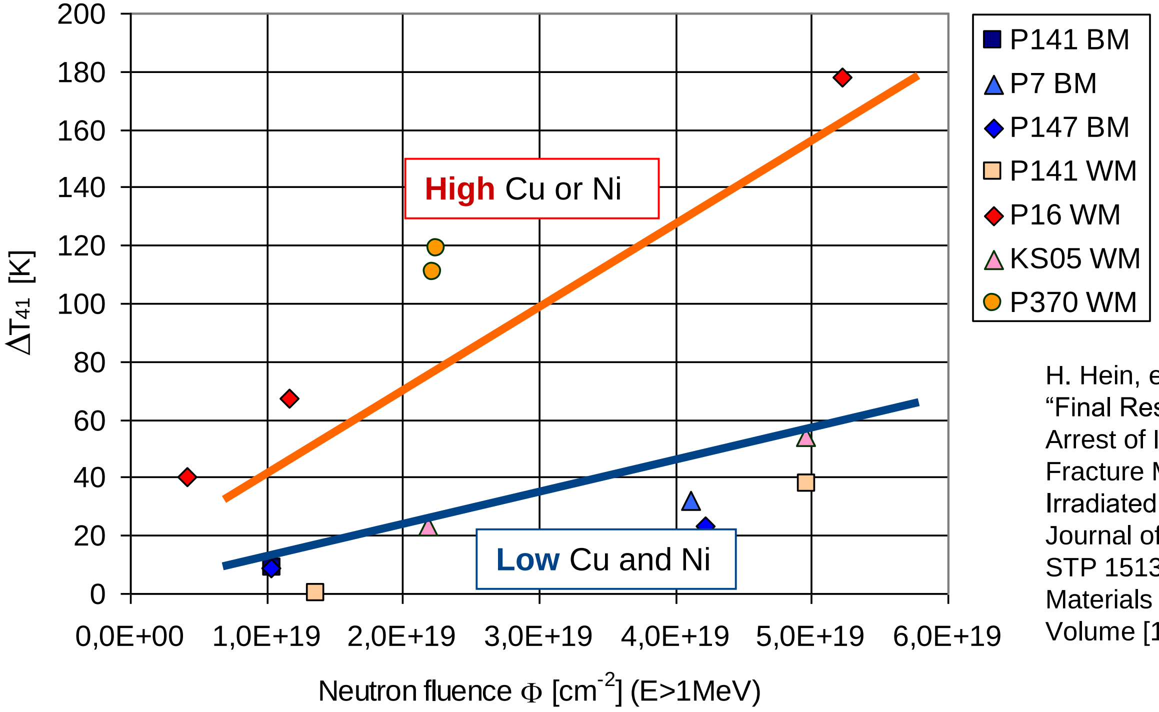
Specific Issues in Irradiation Behaviour

- Chemical composition
- Advantageous RPV design feature
- Long Term operation (see presentation J. May: "RPV Long-Term Operation Issues" and references [16-22], [24-26])
  - Neutron flux effects
  - Late blooming effects
  - Predictive models
  - Reconstitution technique
  - Countermeasures
- National particularities in RPV irradiation surveillance programmes

Specific Issues in Irradiation Behaviour

❑ Chemical composition

- Impact of high contents of Cu and Ni in RPV steel welds on T_{41} shift



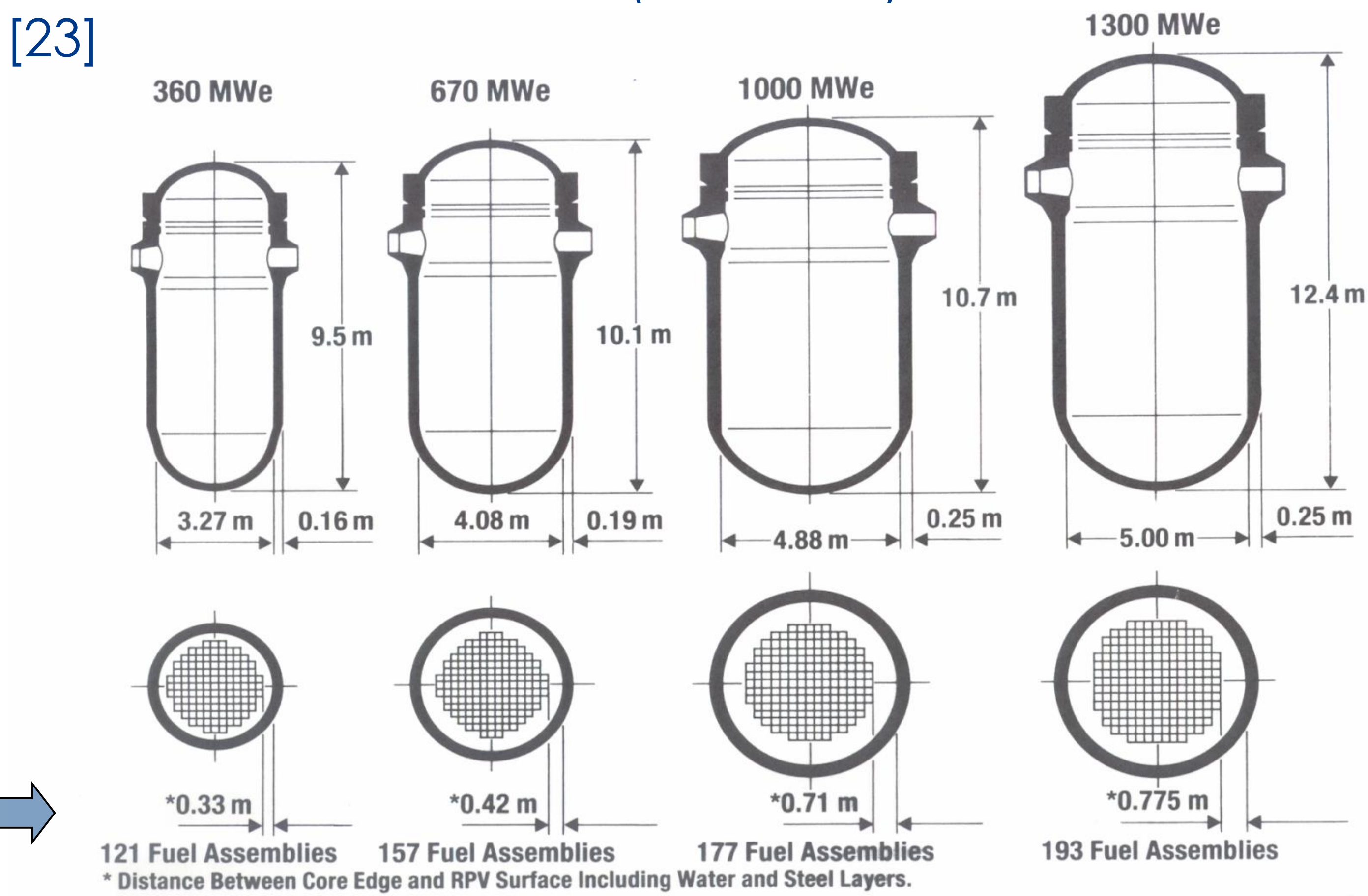
H. Hein, et al
"Final Results from the Crack Initiation and Arrest of Irradiated Steel Materials Project on Fracture Mechanical Assessments of Pre-Irradiated RPV Steels Used in German PWR"
Journal of ASTM International (2010),
STP 1513 on Effects of Radiation on Nuclear Materials and the Nuclear Fuel Cycle: 24th Volume [15]

Low irradiation embrittlement for most of the irradiated materials except for weld metals P370 WM (0,22 % Cu) and P16 WM (1,7 % Ni)

Specific Issues in Irradiation Behaviour

SOTERIA

- Advantageous RPV design feature: large water gap
  - Neutron fluences in n/cm² (E > 1 MeV) after 32 EFPY for German PWR [23]

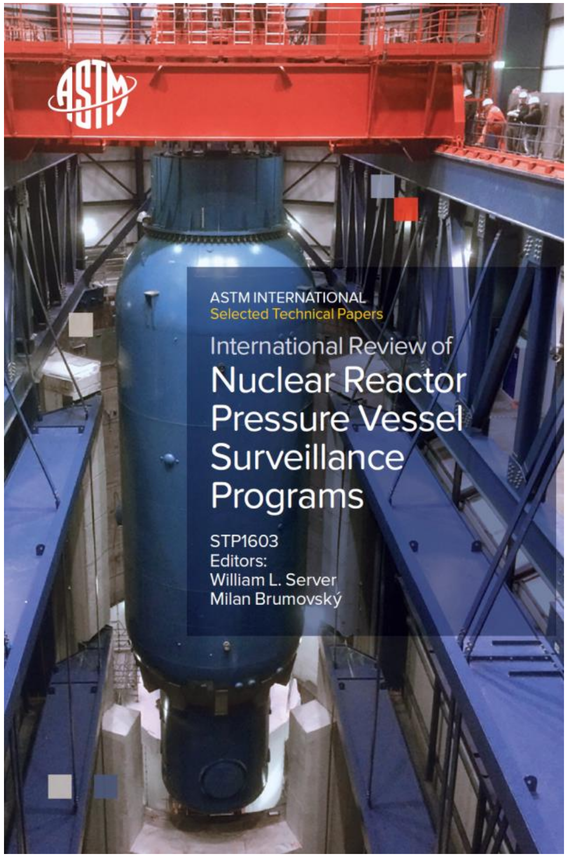


2,8E19 **1,3E19** **1E19** **3E18**

Specific Issues in Irradiation Behaviour

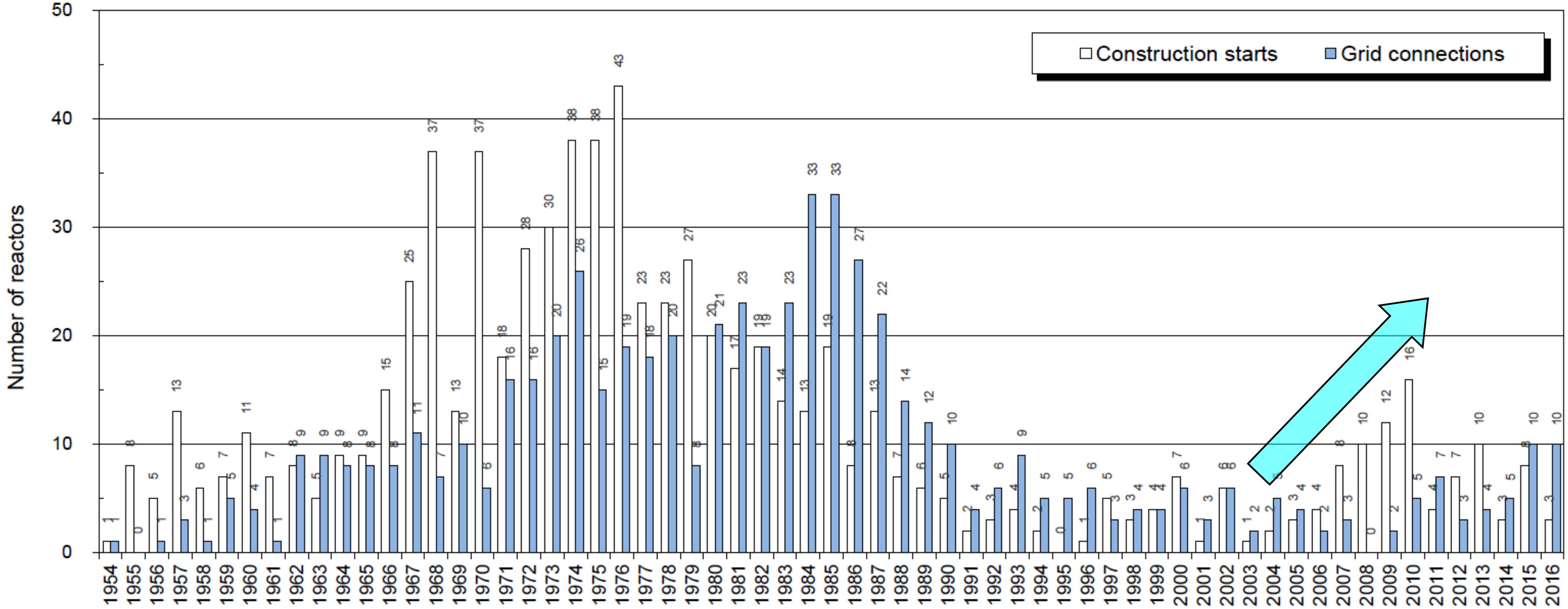
❑ National particularities in RPV irradiation surveillance programmes

- Special publication of technical experts from 11 countries on RPV irradiation surveillance programs [27]
  - Topics discussed include actual surveillance capsule testing and associated results; applications to evaluating the irradiated material toughness results; and identification of problem areas identified from conducting international surveillance programs.
  - 24 peer-reviewed papers divided into five key categories:
    - Bases for RPV Surveillance Programs
    - Neutron Dosimetry for Surveillance Programs
    - National Surveillance Programs
    - Surveillance for Long-Term Operation
    - Experience from Surveillance Programs



Outlook

- ❑ Annual construction starts and connections to the grid (1954-2016)
  - Tendency of increasing number of new NPP builds between 2004 – 2010 decelerated after 2011



IAEA Reference Data Series No.2 2017 Edition
Nuclear Power Reactors in the World [14]

Conclusions

- Reactor Pressure Vessel (RPV) is very important for reactor operation and safe inclusion of fission products
- Irradiation by fast neutrons is the most important ageing mechanism of the RPV
- RPV irradiation behavior is managed by dedicated irradiation surveillance programmes (mechanical testing of specimens irradiated nearer to the core)
- Surveillance results are used in RPV integrity assessment
- Proof of safety against brittle fracture of the RPV is mandatory

References

[1] Ilg, U., König, G., Erve, M., "Das Werkstoffkonzept in deutschen Leichwasserreaktoren – Beitrag zur Anlagensicheheit, Wirtschaftlichkeit und Schadensvorsorge", International Journal for Nuclear Power, atw 53 (2008), No. 12

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