RPV LONG-TERM OPERATION ISSUES

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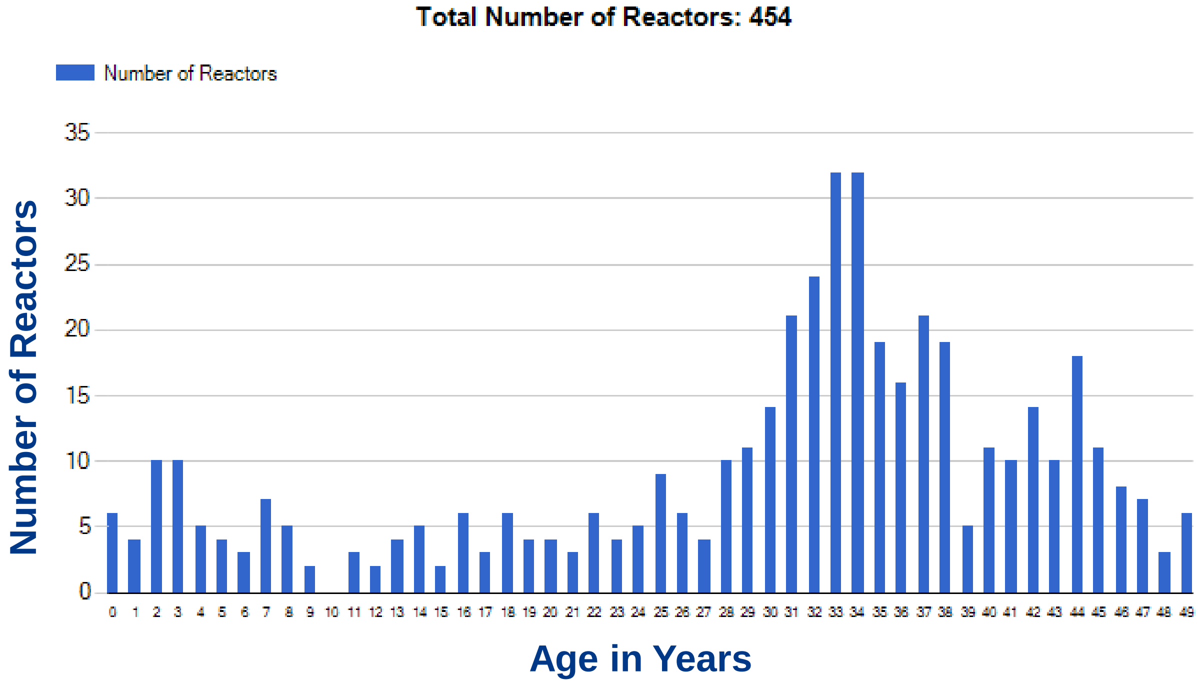
INTRODUCTION

Introduction

- ☐ Long-Term Operation (LTO) acc. to IAEA Service Series 17:
  - Operation beyond the established time frame originally set forth by the license term, design limits, standards or regulations
  - Justification by safety assessment considering life limiting processes and features for structures, systems and components
- ☐ IAEA Power Reactor Information System (PRIS), 08/2018:


Total Number of Reactors: 454

Introduction

- ❑ Background of Long Term Operation
  - Increasing age of the existing NPPs and envisaged lifetime extensions from typically 40 years up to an EOL of 60 or even 80 years
  - For all components and equipment the consequences of prolonged operation time are assessed
  - Reactor pressure vessel (RPV) is a life limiting key component of light water reactors (LWR), which almost cannot be replaced
  - Need for an improved understanding and prediction of RPV irradiation embrittlement effects under Long Term Operation (LTO)
  - Irradiation effects caused by high neutron fluences must be considered adequately in safety assessments; unknown effects might appear
  - In this context the availability of microstructural data is also essential for the understanding of the involved mechanisms

=> LTO: Usually beyond 40 years of operation

Introduction

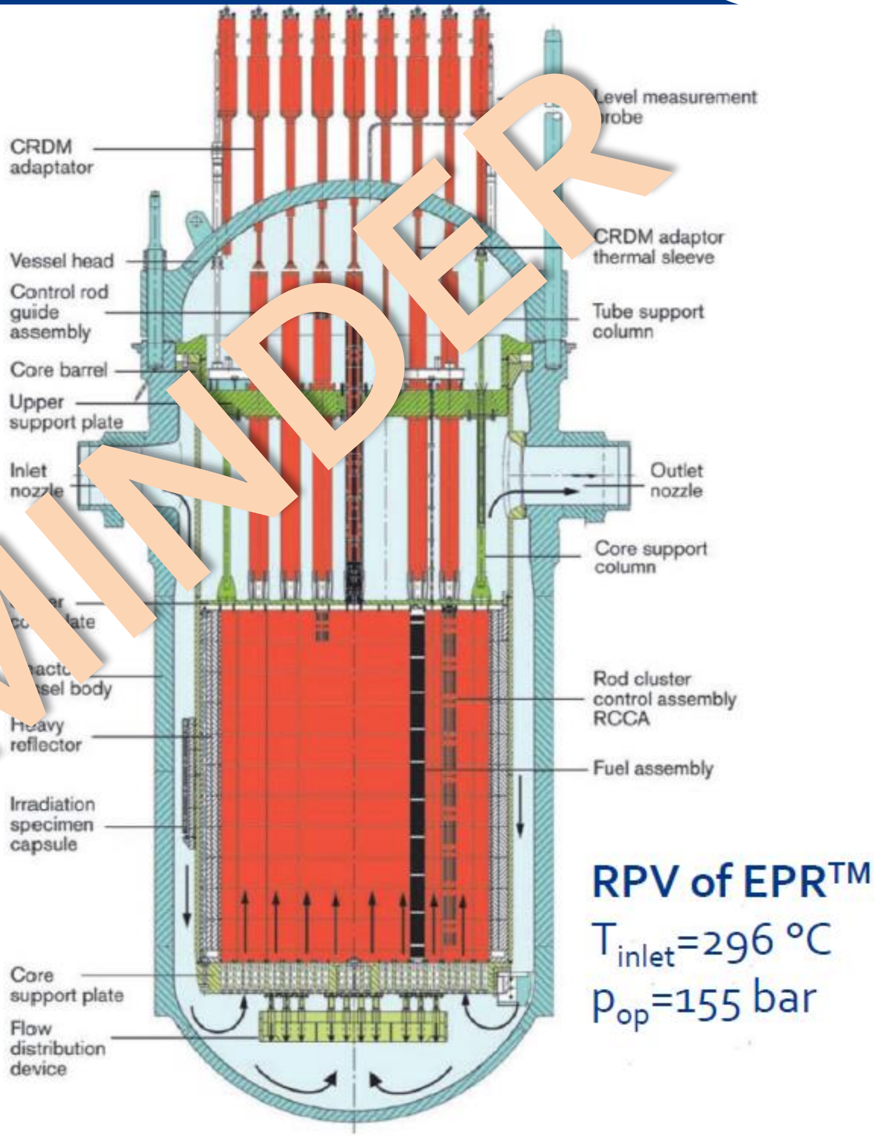
- ☐ A general introduction to Reactor Pressure Vessel (RPV) and it´s surveillance has been provided during the morning session in the lectures of Milan Brumovsky and Hieronymus Hein

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™

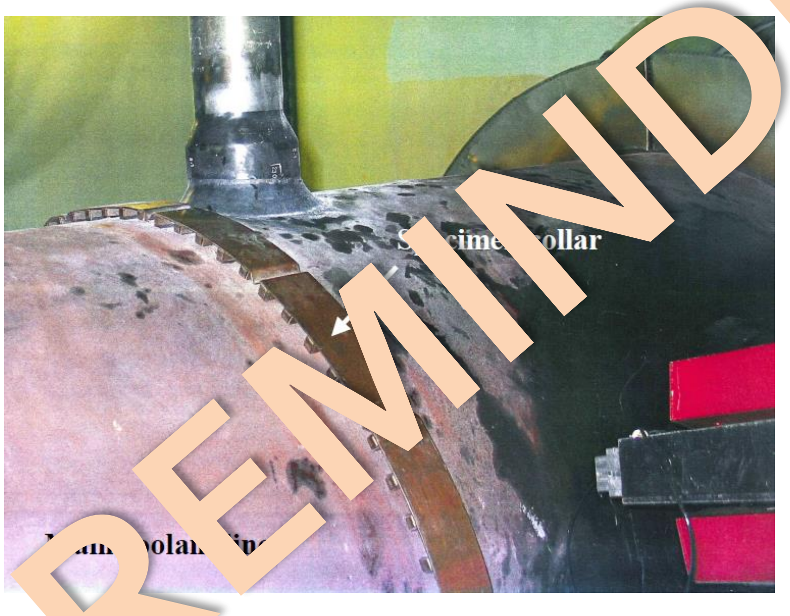
T_{inlet}=296 °C

p_{op}=155 bar

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



[Ch. Eiselt et al., PVP2015-45558, 2014]

- 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

RPV Ageing Mechanisms

❑ Corrosion of RPV low alloy steels

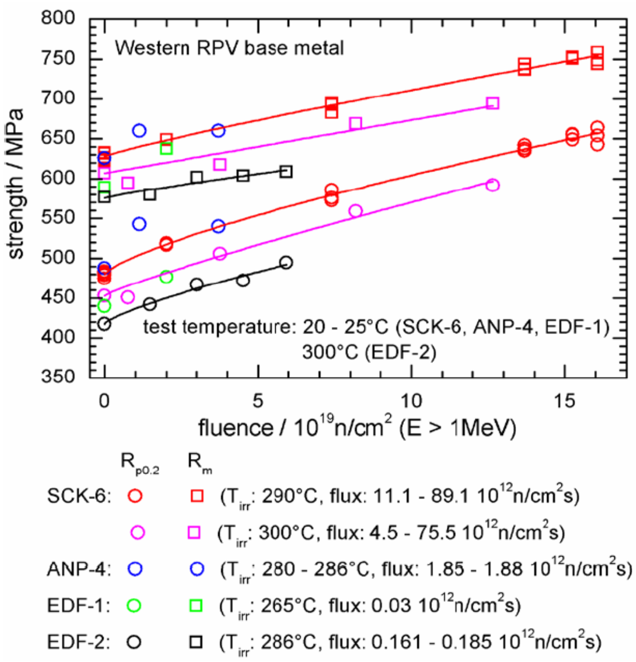
- Inner ferritic steel surface is protected by austenitic weld overlay cladding
- High-temperature water forms protective oxides (magnetite, hematite) at ferritic steels => sufficient corrosion resistance even without cladding
- Environmentally assisted cracking (EAC) does not occur under designed normal operating conditions
- Outer RPV surface:
  - Generally not subject to atmospheric corrosion
  - However: Boric acid corrosion may occur under accidental conditions (e.g. small leaks at penetrations)

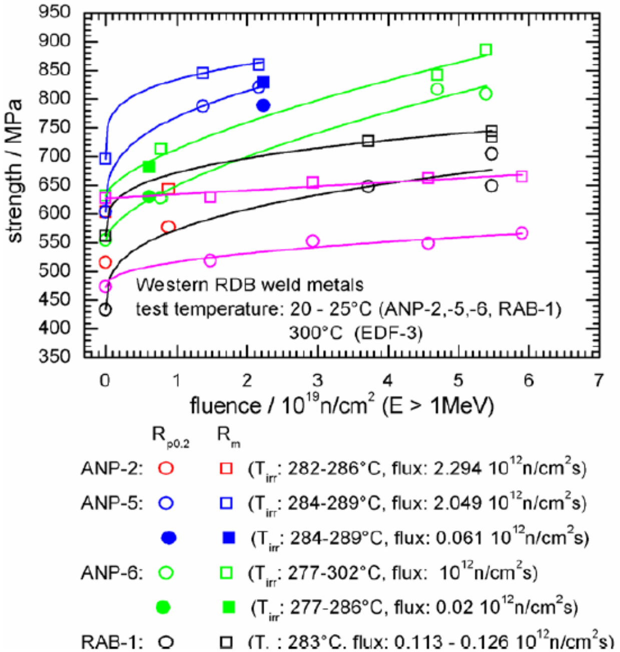
Accidental Boric Acid Corrosion at RPV outer surface

RPV Ageing Mechanisms

Influence of fast neutrons on mechanical properties of RPV steels

- In former times a saturation of irradiation hardening and embrittlement was assumed, as e.g. indicated by old prediction equation of U.S. NRC Reg. Guide 1.99 Rev. 2
- Today we know that a complete saturation does not exist



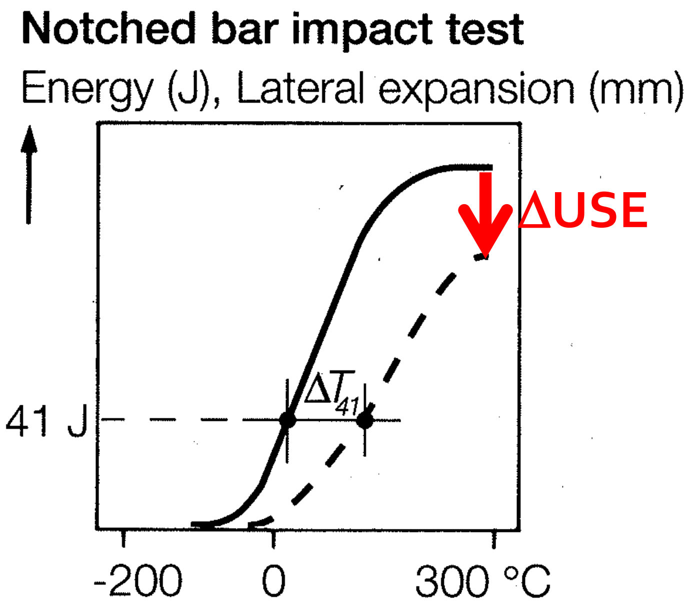


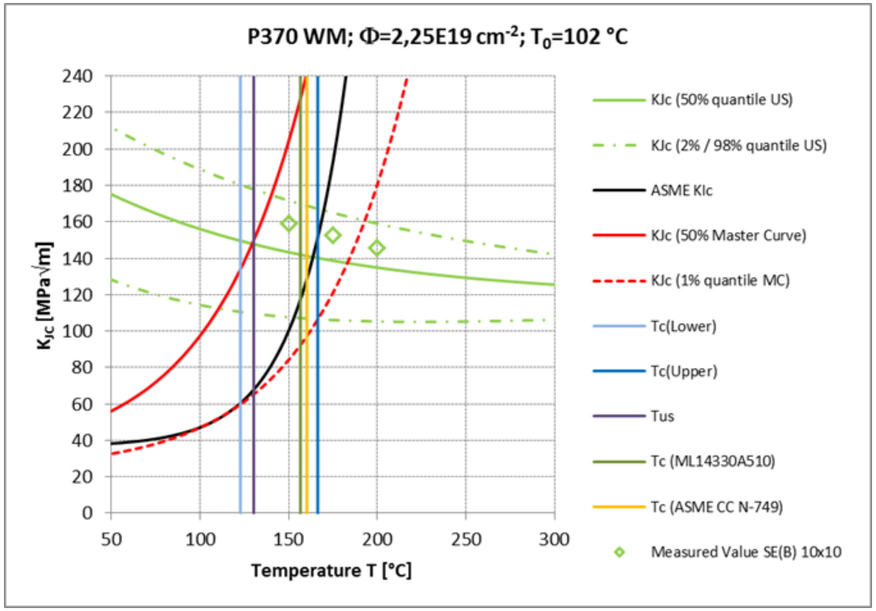
[LONGLIFE Deliverable D4.5, 2014]

RPV Ageing Mechanisms

Influence of fast neutrons on mechanical properties of RPV steels

- ❑ Besides reference temperature increase, also the reduction of the Upper Shelf is important for LTO, as determined from Charpy or J-R tests
- ❑ Formerly an upper shelf value of 220 MPa√m was assumed in safety assessment also for highly irradiated RPV materials => not always realistic



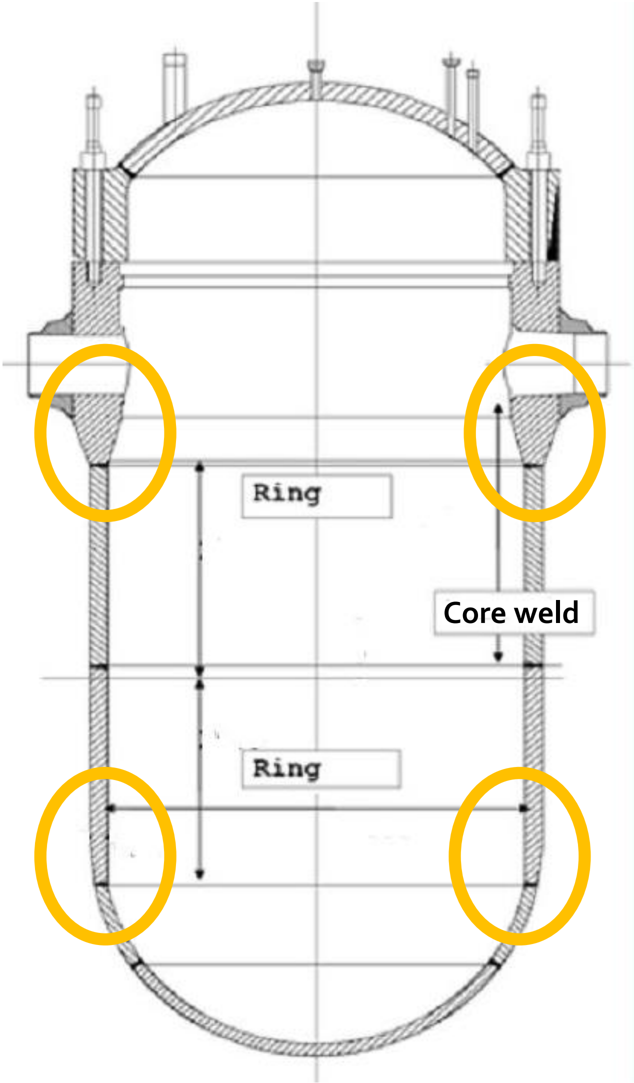


[J. Kobiela et al., Fontevraud 9, 2018]

RPV Ageing Mechanisms

Extension of RPV beltline during LTO

- ❑ Effects of neutron irradiation have to be addressed only for materials in the "beltline' of the RPV
- ❑ Commonly accepted definition of the beltline: fluence of at least 1 × 10^{17} cm^{-2} (E > 1 MeV)
- ❑ Extended Beltline as consequence of LTO
  - Increasing fluence and possible "albedo effect"
  - Additional base and weld materials above 1E17 cm^{-2}
  - Initial properties sometimes unknown
  - Materials not covered by irradiation surveillance program
  - Very conservative assumptions might be required

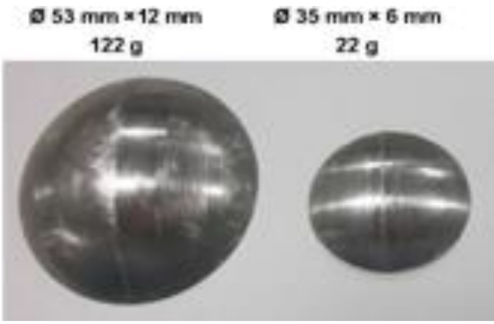


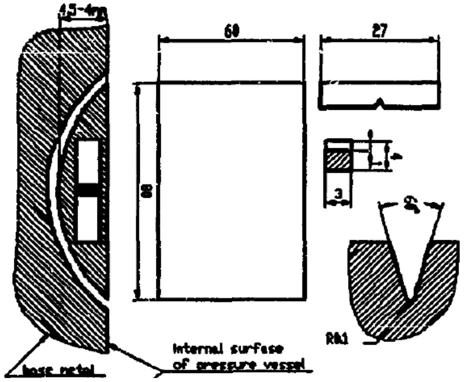
More information: *[Nanstad et al., NUREG/CR-7153 Vol. 3, 2014]*

RPV Ageing Mechanisms

Extension of RPV beltline during LTO

- ❑ Possibilities to treat Extended Beltline issues:
  - More accurate determination of neutron fluence
  - Detailed assessment of available manufacturing records, archive materials
  - Generic properties for material classes with similar manufacturing history and composition
  - Extraction of small specimens (boat samples, scraping samples) from RPV (e.g. nozzles) => chemical analysis, miniature specimen testing
  - More refined methods in structural integrity assessment, e.g. use of smaller flaws, stress intensity factor correlations
  - Special care about combined effect of irradiation and thermal ageing for hot leg nozzle, including HAZ => verification on decommissioned RPV might be considered





Kryukov et al., Nuc. Eng. Des. 160, 1996

More information: *[Nanstad et al., NUREG/CR-7153 Vol. 3, 2014]*

RPV IRRADIATION SURVEILLANCE PROGRAMS

RPV Irradiation Surveillance Programs

Surveillance Programs and Long Term Operation

- For most RPV the original surveillance program was not designed to cover LTO; e.g. ASTM E185:

Minimum recommended number of surveillance capsules and their withdrawal schedule (EFPY of RPV)

	Predicted TTS		
	≤56°C	56°C-111°C	>111°C
Minimum number of capsules	3	4	5
Withdrawal sequence:			
Capsule 1	6	3	1.5
Capsule 2	15	6	3
Capsule 3	EOL	15	6
Capsule 4		EOL	15
Capsule 5			EOL

EOL: End of Life (Design Lifetime)
EFPY: Effective Full Power Years
TTS: Transition Temperature Shift (e.g. ΔT_{41})

- Nevertheless, reliable material data for LTO fluence are required
- RPV may benefit from standby surveillance capsules or the former switch to low-leakage core loading

RPV Irradiation Surveillance Programs

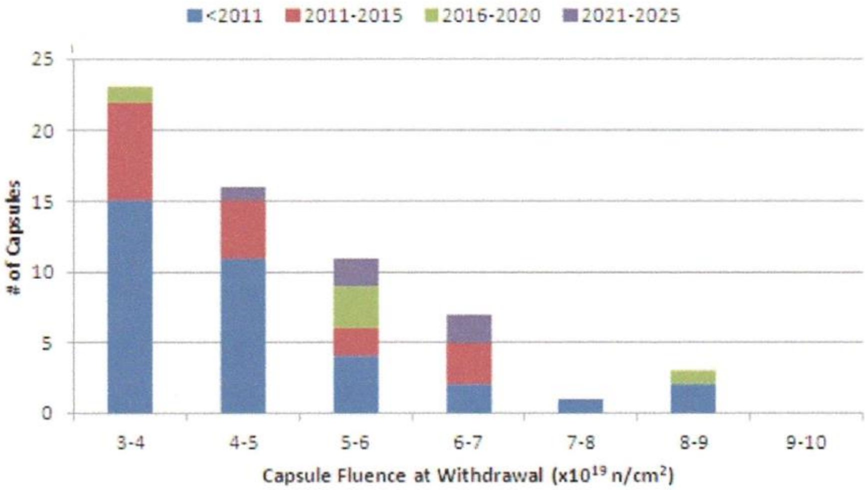
Surveillance Programs and Long Term Operation

- ❑ In the U.S., coordinated programs exist to generate LTO data:
  - EPRI Coordinated Reactor Vessel Surveillance Program (**CRVSP**) to delay the next planned capsule withdrawals of 13 plants by up to 10 years
  - EPRI PWR Supplemental Surveillance Program (**PSSP**) to develop a significant amount of high-fluence data on key materials: Irradiation of supplemental surveillance capsules containing previously-irradiated PWR materials (specimen reconstitution)
  - BWR: Boiling Water Reactor Owners Group (BWROG) Supplemental Surveillance Program (**SSP**), BWR Vessels and Internals (**BWRVIP**) Integrated Surveillance Program (**ISP**)

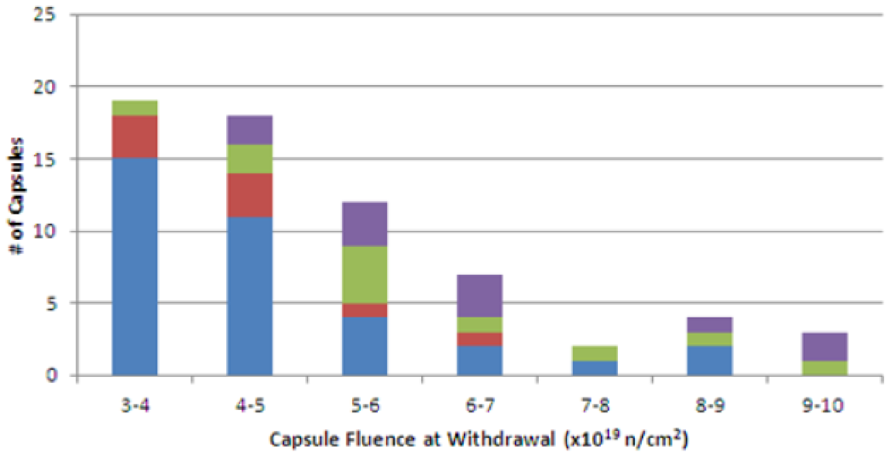
RPV Irradiation Surveillance Programs

Surveillance Programs and Long Term Operation

Before CRVSP:



After CRVSP:



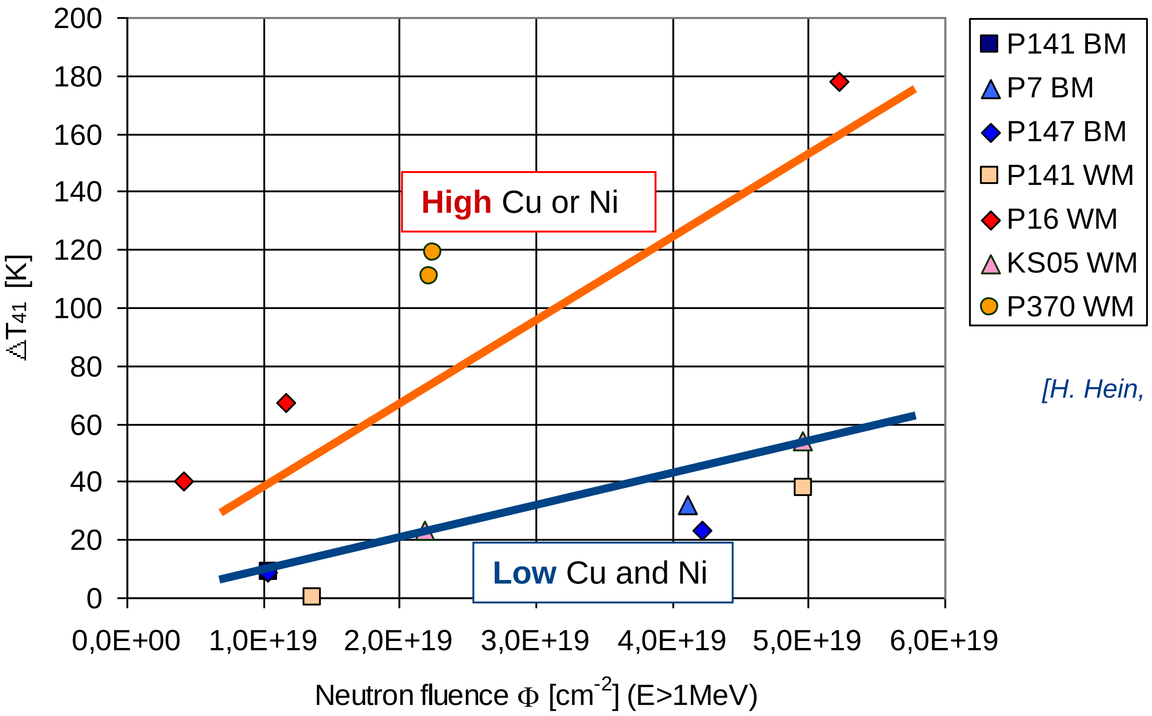
[W. Server et al., Int. Workshop on RPV surveillance and embrittlement, Prague, 2015]

PREDICTIVE MODELS

Predictive models

❑ Chemical composition

- Impact of high contents of Cu and Ni in RPV steel welds on T_{41} shift
- At high fluences (LTO) reference temperature strongly depends on composition



[H. Hein, SOTERIA Symposium 2012]

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

Predictive models

- ❑ Chemical composition
  - Continuous improvement of prediction equations of irradiation embrittlement to support LTO
  - Large surveillance data bases required

	Fluence	Flux	Temp.	Cu	Ni	P	Mn	Si	C
10CFR50.61a	X	X	X	X	X	X	X		
ASTM E900-02	X		X	X	X				
ASTM E900-15	X		X	X	X	X	X		
FIM 2010	X			X	X	X			
JEAC4201-2007	X	X	X	X	X				
Reg Guide 1.99 Rev. 2	X			X	X				
RR-UCSB	X	X	X	X	X	X	X	X	X

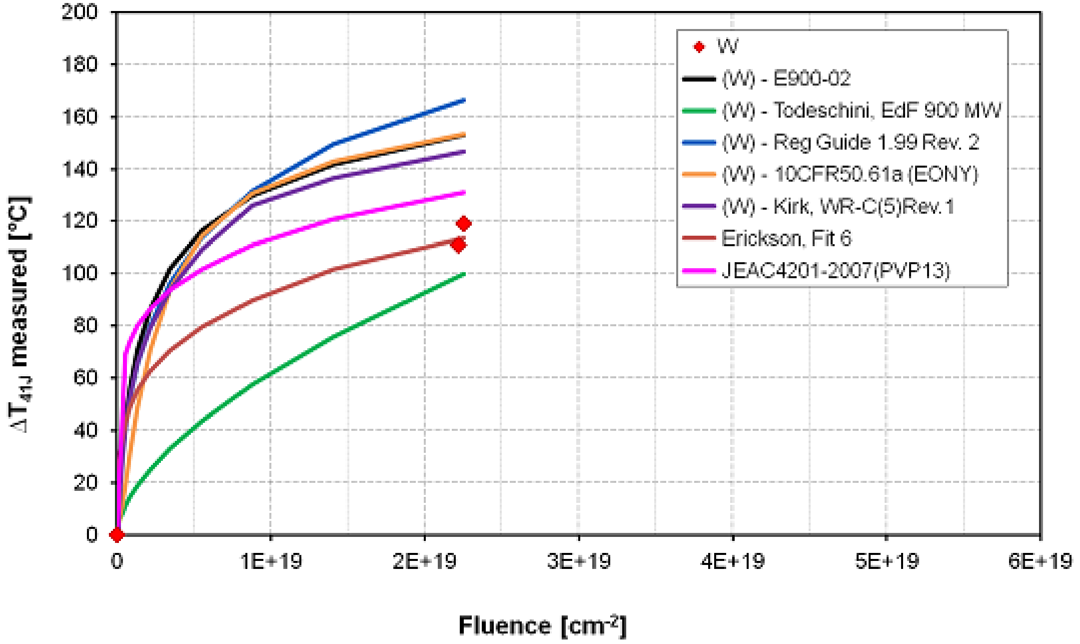
[after M. Kirk]

Predictive models

❑ Chemical composition

- Available predictive models can show strong differences in irradiation shift prediction
- For specific materials a dedicated prediction equation based on a small representative data base can be more suitable than a general model

ANP-5



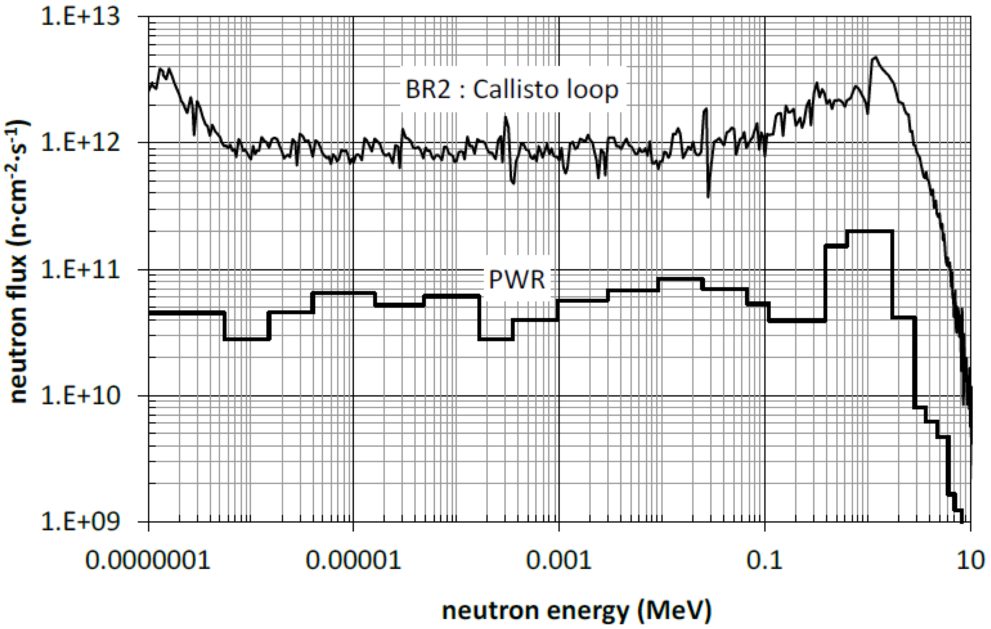
[H. Hein, LONGLIFE Final Workshop, 2014]

IRRADIATION BEHAVIOUR - LTO ISSUES

Irradiation Behaviour - LTO Issues

❑ Neutron flux effects

- High flux irradiation in test reactors to simulate LTO material condition after only few weeks of irradiation time
- Neutron flux, temperature, spectrum and operating conditions are factors of influence
- transferability of surveillance specimens and MTR results to RPV wall?
  => More Details on Flux Effect in lecture of F. Bergner, A. Ulbricht



Neutron flux distribution in the BR2 – Callisto loop in comparison to a typical PWR spectrum

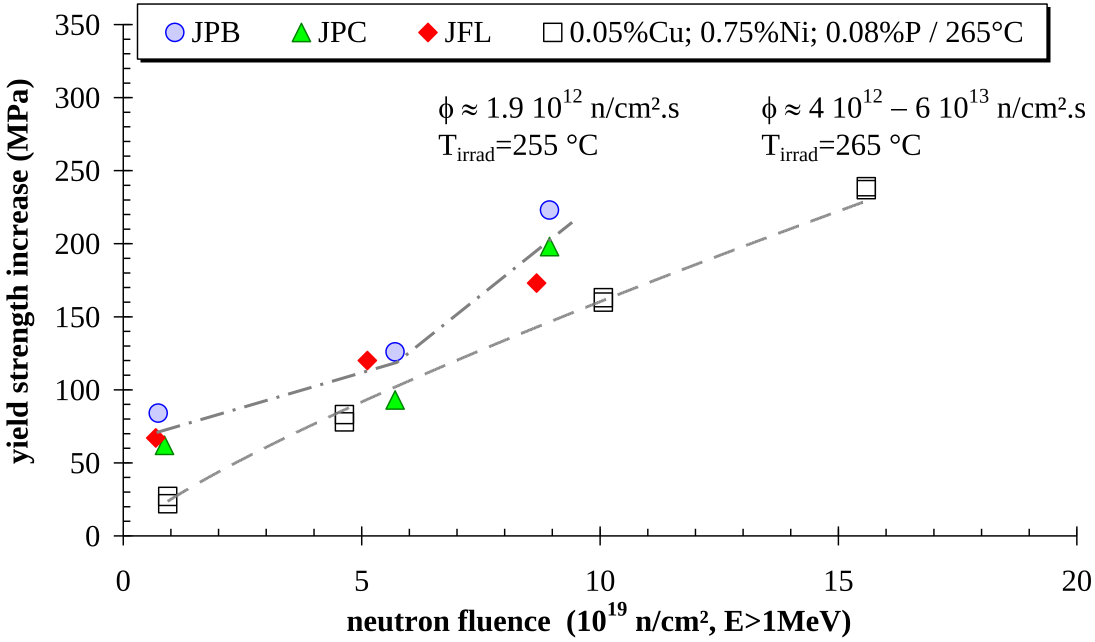
[H. Hein, LONGLIFE Final Workshop, 2014]

Irradiation Behaviour - LTO Issues

❑ Late Blooming Effects

- First findings by Odette et al
- Possible significant increase of irradiation embrittlement at high fluences
  - Low or no Cu content
  - High Ni and Mn
  - Low irradiation temperature
  - High fluence (>>1E19 n/cm², E>1MeV)

Steel	Cu	Ni	Mn	P	Mo	Cr	C	Si
JPB (A533B cl.1)	0.01	0.83	1.42	0.017	0.54	0.15	0.18	0.26
JPC (A533B cl.1)	0.01	0.81	1.45	0.007	0.54	0.15	0.18	0.27
JFL (A508 cl.3)	0.01	0.75	1.42	0.004	0.52	0.16	0.17	0.25



[E. Altstadt et al., Proceedings of the 18th International Conference on Nuclear Engineering ICONE18, 2010]

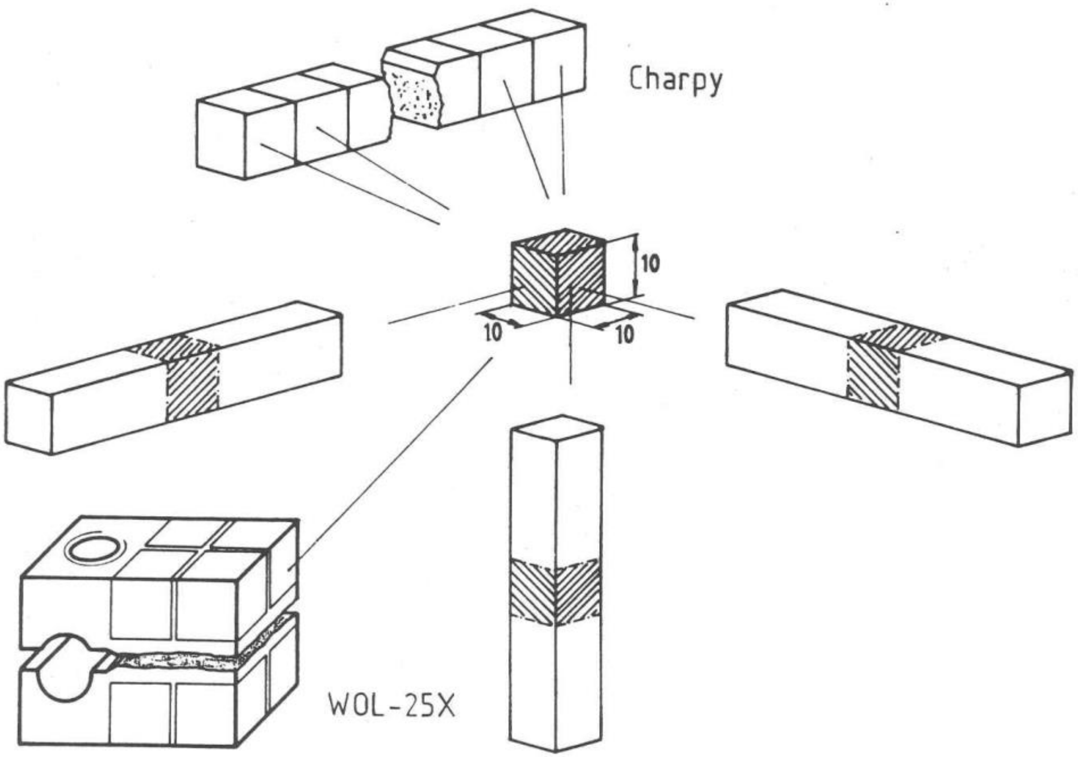
Irradiation Behaviour - LTO Issues

Reconstitution technique

- ☐ Manufacturing of new specimens from tested or untested (irradiated) specimens
  - Surveillance capsules sometimes contain only small amount of material
  - More material might be required to complete the Charpy energy transition curve or to perform fracture toughness tests (e.g. master curve) that were not originally foreseen when surveillance capsules were designed
- ☐ Possibility to irradiate specimens, that were already tested, to higher fluences and generate new surveillance data
- ☐ Possibility to change existing specimen type or orientation

Irradiation Behaviour - LTO Issues

Reconstitution technique

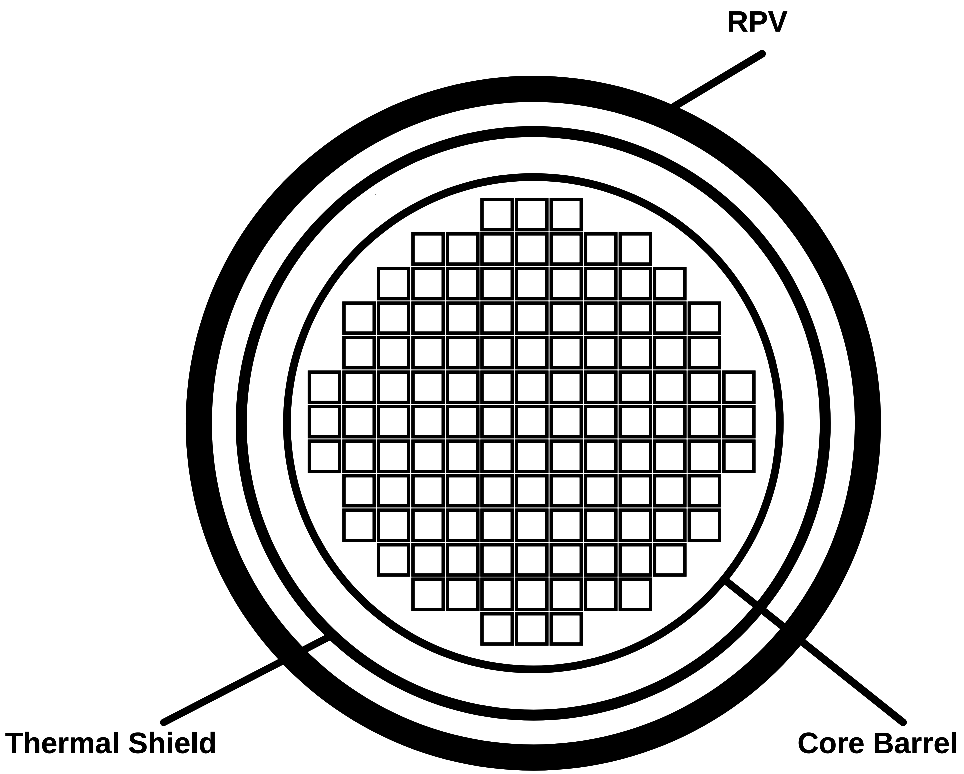


[Klausnitzer et al., MPA-Seminar 17, 1991]

COUNTERMEASURES

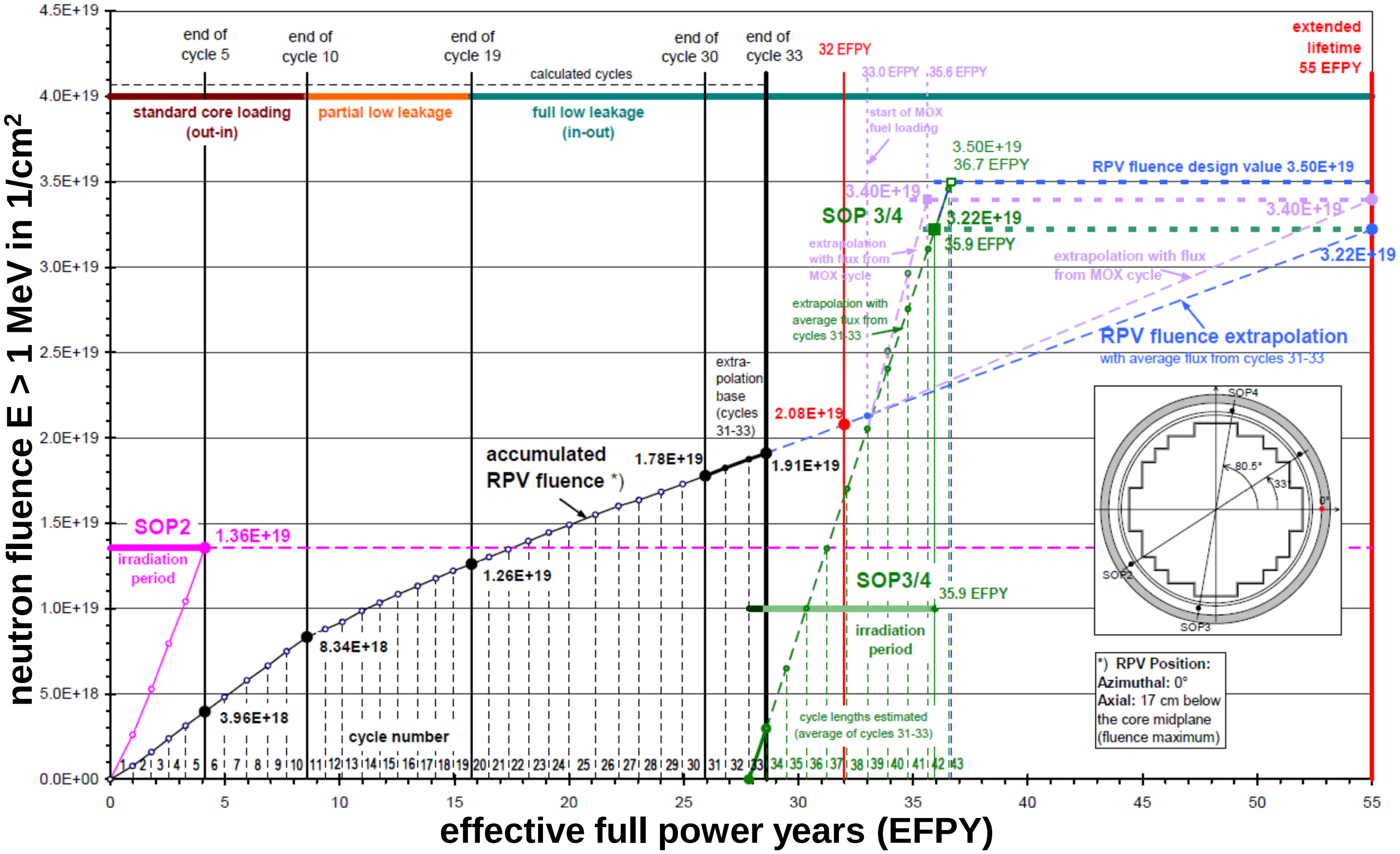
Countermeasures

- ❑ Core Loading Management (reduction of neutron flux)
  - Low leakage core: Changing from out-in fuel loading scheme (new fuel assembly at core edges) to in-out loading scheme (partly burnt-up fuel assembly at core periphery)



Countermeasures

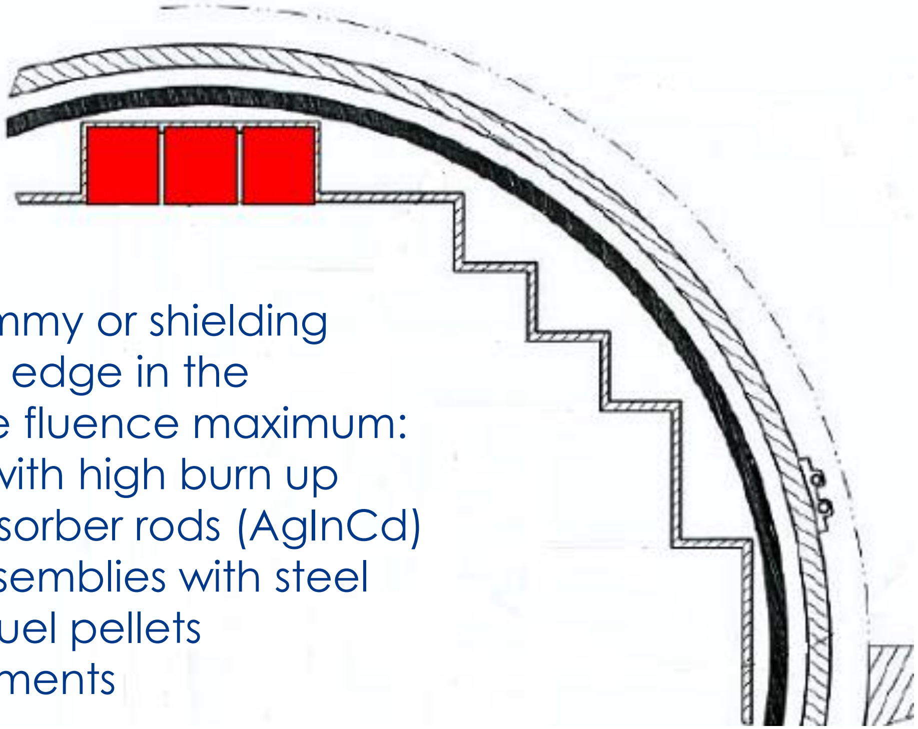
- ❑ Many NPP switched already in the 1980'ies to low leakage core
- ❑ Hence, sometimes surveillance capsules cover LTO fluences



[Barthelmes et al., NEI 2010]

Countermeasures

- ❑ RPV Neutron Shielding (reduction of neutron flux)
  - Shielding fuel assemblies
  - Internals replacement

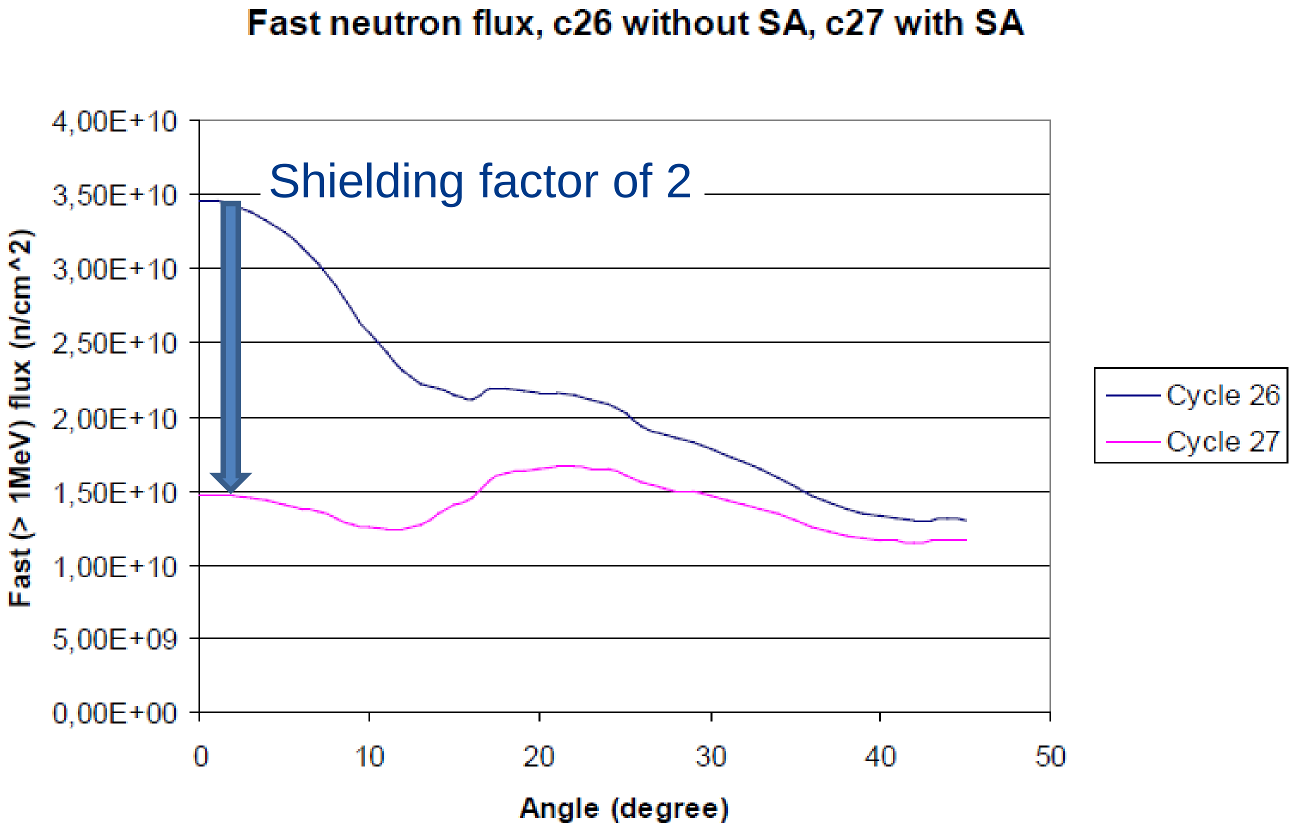


Example for use of dummy or shielding assemblies at the core edge in the azimuthal region of the fluence maximum:

- fuel assemblies with high burn up and inserted absorber rods (AgInCd)
- modified fuel assemblies with steel rods instead of fuel pellets
- special steel elements

Countermeasures

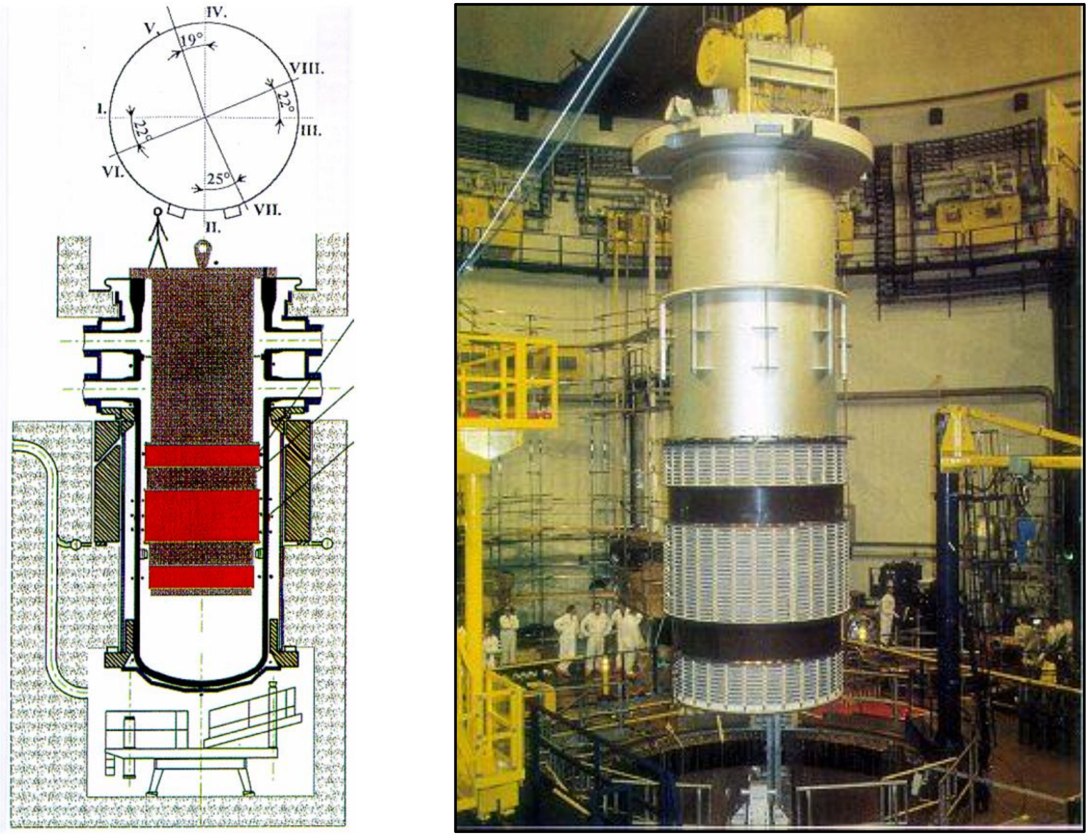
- RPV Neutron Shielding (reduction of neutron flux)
  - Example for the effect of shielding fuel assemblies for a western PWR



[LONGLIFE Deliverable D7.4, 2013]

Countermeasures

- Thermal Annealing (recovery of material properties)
  - Recovery heat treatment



SKODA RPV annealing device

[Brumovsky, ATHENA Workshop, 2004]

Countermeasures

- ☐ Increase the water temperature in the storage tanks of Emergency Core Cooling System
  - Reduction of load in PTS case
- ☐ Higher accuracy allows to reduce some over-conservative margins in safety assessment:
  - Neutron fluence calculations
  - CFD analysis
  - Safety analysis (e.g. 3D-FE, XFEM, probabilistic methods)
  - Consideration of warm pre-stress (WPS) effect, crack arrest, constraint effect
- ☐ Direct determination of fracture toughness instead of indirect evaluation according to the RT_{NDT} concept may especially in case of base materials results in more realistic and lower reference temperatures

CONCLUSIONS

Conclusions

- ☐ 60+ operational years as new standard NPP-lifetime
  - Design life of 60 years for new NPP (e.g. EPR ™)
  - Life Time Extension activities for existing NPP fleet
    - USA: extended license life renewals of many NPPs
    - Europe: Switzerland, the Netherlands, France, Spain, Sweden, …
- ☐ RPV ageing is of major importance for Long-Term Operation of a NPP
- ☐ Main challenge is to generate high fluence data representative for RPV wall under LTO conditions
  - Coordinated surveillance programs supporting multiple RPV
  - Additional surveillance capsules have been inserted in a number of RPV to support LTO, e.g. in the Netherlands, Sweden, Switzerland…