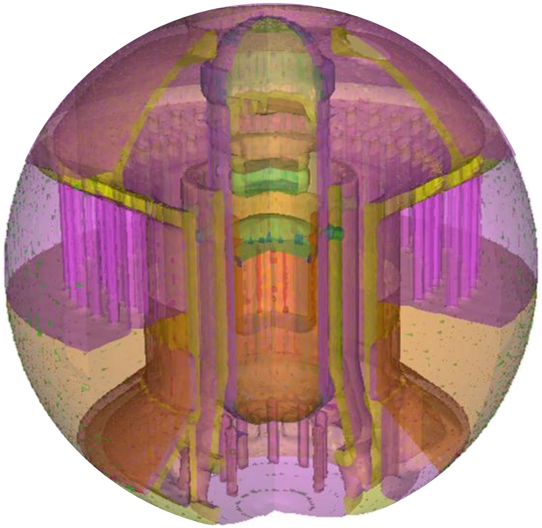
Activation calculation for the dismantling and decommissioning of a light water reactor using MCNP™ with ADVANTG and ORIGEN-S



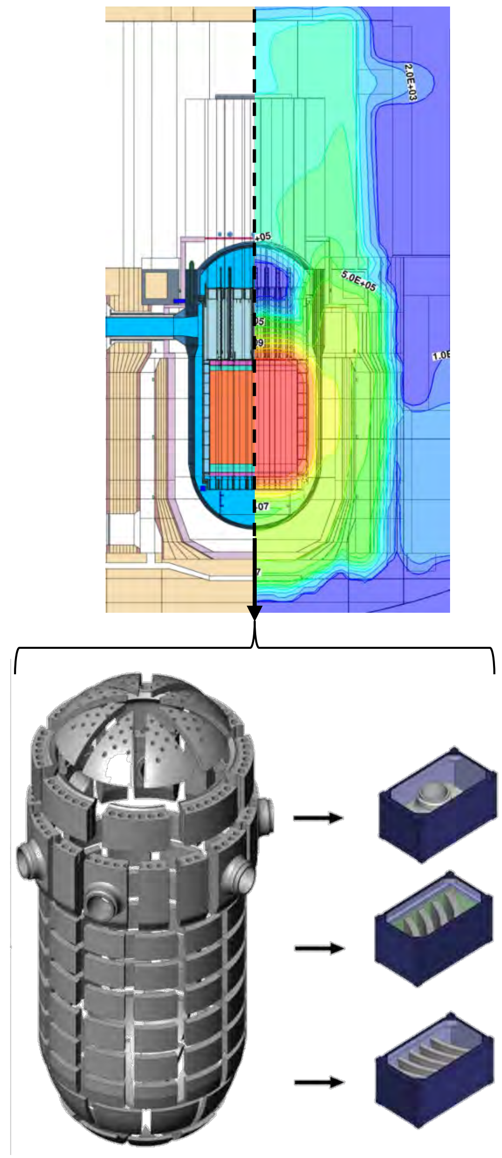
Dr. L. Schlömer[1)], Prof. Dr. P.-W. Phlippen[1)], B. Lukas[2)]

[1)] WTI Wissenschaftlich-Technische Ingenieurberatung GmbH, 52428 Jülich, Germany
[2)] EnBW Kernkraft GmbH, 76661 Philippsburg, Germany

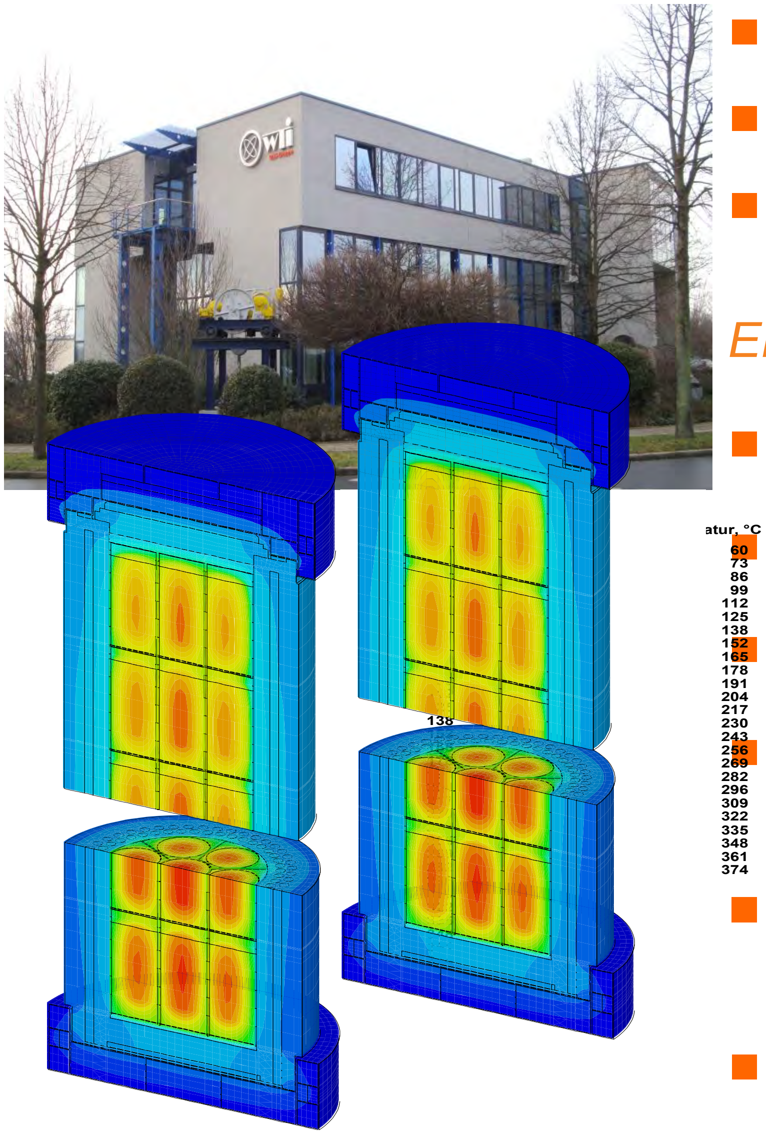
ANS Annual Meeting
June 11-15, 2017, San Francisco

Content

- Company profiles
- Situation & objective
- Calculation procedure & model
- Validation
- Results
- Decommissioning & packaging concepts
- Conclusion & lessons learned



WTI - The Engineering Company of the GNS-Group



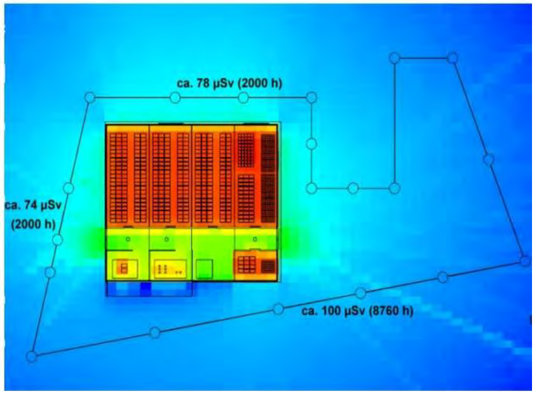
- 75 employees
- 60 scientists and engineers
- Sales 2016: 8.8 Mio. EUR

Engineering Services for:

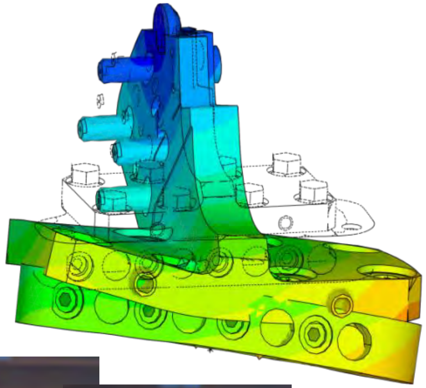
- Planning and construction of plants
- Decommissioning planning
- Safety analysis & Licensing procedures
- Nuclear waste management (waste disposal, development of packages)
- Calculations (shielding, criticality, thermodynamic, mechanical)
- Research & development for industrial applications

WTI - Calculations

- Nuclear analyses
  - Criticality safety analyses
  - Determination of radioactive inventories
  - Activation from neutron irradiation
  - Shielding for casks and storage buildings
  - Planning for optimised cask loadings



- Thermodynamic and flow analyses
  - Transport and storage of spent fuel casks
  - Thermal load of buildings
  - Coolant distribution in storage buildings



- Mechanical analyses
  - Static and dynamic analyses
  - Stability and fracture mechanics analyses

- Validation of software tools and methods

EnBW Energie Baden-Württemberg AG is an European utility with solid shareholders

EnBW

Introduction and company profile

Overview

- Germany‘s third largest utility; in Europe within TOP 10
- Business activities in several European countries (GER, CZ, TR, CH, A, HU)
- Four business units: Generation & Trading, Renewable Energies, Grids, Sales
- Approximately 20,000 employees
- In 2015 annual revenue 21 billion Euro and Adj. EBITDA 2.1 billion Euro
- Two strong main shareholders (state of BaWü and a group of municipalities)
- Clear strategy: **Energiewende. Safe. Hands on.**

Wide balanced portfolio is the corporate backbone

Introduction and company profile

Sales

- **Adjusted EBITDA 2015:** €255 million
- **Employees:** 3,300
- **Task/products:**
  Sale of electricity, gas and other products; providing of energy-related services; advisory service; “Sustainable City” project development; support for local authorities; collaboration with public utilities

Grids

- **Adjusted EBITDA 2015:** €886 million
- **Employees:** 8,086
- **Task/products:**
  Transport and distribution of electricity and gas, providing of grid-related services, operating grids for third parties and water supply services

Renewable Energies

- **Adjusted EBITDA 2015:** €287 million
- **Employees:** 815
- **Tasks/products:**
  Project development and management, construction and operation of power plants generating power from renewable energies from hydropower, onshore and offshore wind energy, photovoltaics and bioenergy

Generation and Trading

- **Adjusted EBITDA 2015:** €777 million
- **Employees:** 5,167
- **Tasks/products:**
  Advisory service, construction, **operation and decommissioning of thermal generation plants**; electricity trading; risk management; development of gas midstream business, district heating; waste management/ environmental services

Nuclear Business in Transformation – from Operation to Decommissioning

EnBW Kernkraft GmbH – Nuclear Power Plants

EnBW

EnBW Kernkraft GmbH – nuclear power plants

Obrigheim (KWO)

KWO
- Pressurized water reactor
- Power rating: 357 MW
- Start of operation: 1969
- End of operation: 2005

Philippsburg (KKP)

KKP 1
- Boiling water reactor
- Power rating: 926 MW
- Start of operation: 1979
- End of operation: 2011

KKP 2
- Pressurized water reactor
- Power rating: 1.468 MW
- Start of operation: 1984
- End of operation: 2019P

Neckarwestheim (GKN)

GKN I
- Pressurised water reactor
- Power rating: 840 MW
- Start of operation: 1976
- End of operation: 2011

GKN II
- Pressurized water reactor
- Power rating: 1.400 MW
- Start of operation: 1989
- End of operation: 2022P

Employees: ~1.600

- In decommissioning
- In post-operation
- In operation

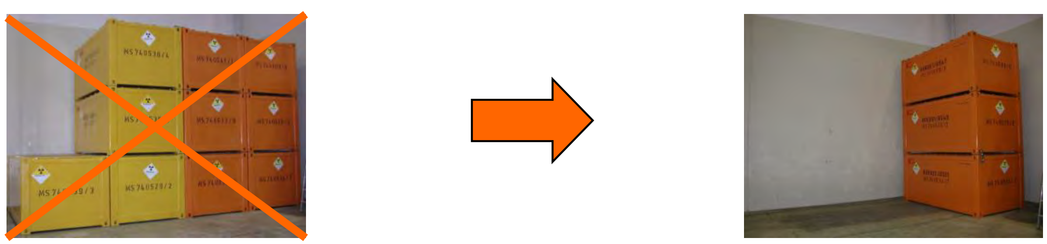
Situation & objective (1/2)

- Situation:
  After shut-down nuclear power plants have to be decommissioned
- The knowledge of radioactivity levels in activated components is required for
  - Decommissioning licensing procedure,
  - Planning of segmentation and packaging,
  - Definition of probing regions and number of samples,
  - Prediction of decommissioning costs.

- Completed WTI-projects for EnBW
  - Boiling water reactor: KKP1 (✓)
  - Pressurized water reactors: GKN I (✓), GKN II (✓) and KKP2 (✓)
- Ongoing WTI-project for RWE
  - Pressurized water reactor: Emsland (KKE)
- Acquisition WTI-projects for PreussenElektra GmbH
  - Pressurized water reactors: Unterweser (KKU), Grafenrheinfeld (KKG), Brokdorf (KBR), Grohnde (KWG) and Ohu (KKI 2)

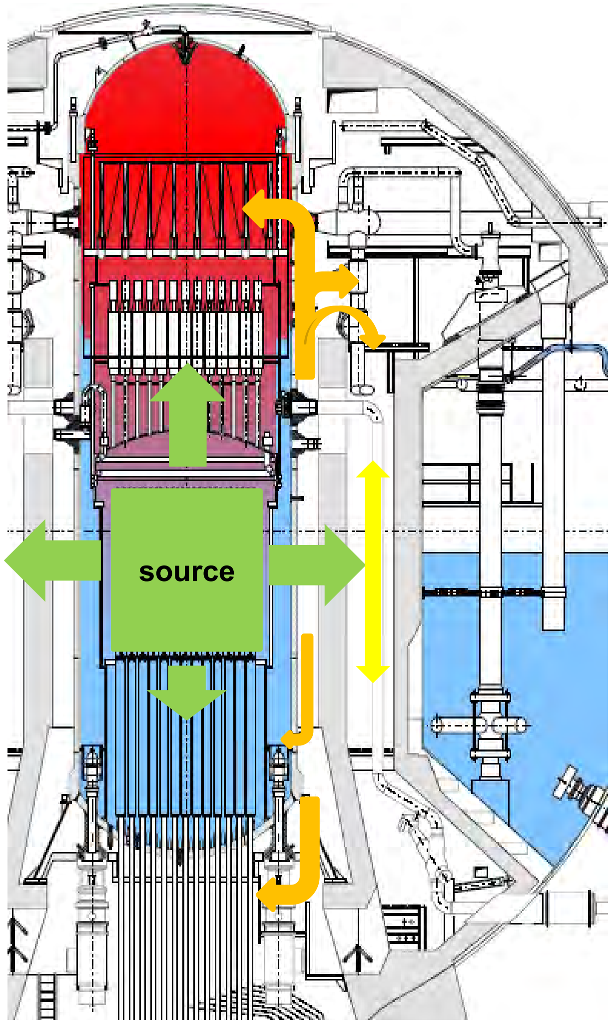
Situation & objective (2/2)

- Solution
  - Use of state-of-the-art Monte-Carlo-codes (MCNP™) coupled with modern variance reduction techniques (ADVANTG)
  - Detailed calculation of activation and decay (ORIGEN-S)
- Main targets
  - Radiological characterization of all relevant components of a light water reactor
  - Reduction of samples and related costs
  - Cost-efficient and optimized decomissioning concepts



Calculation procedure & model (1/5)

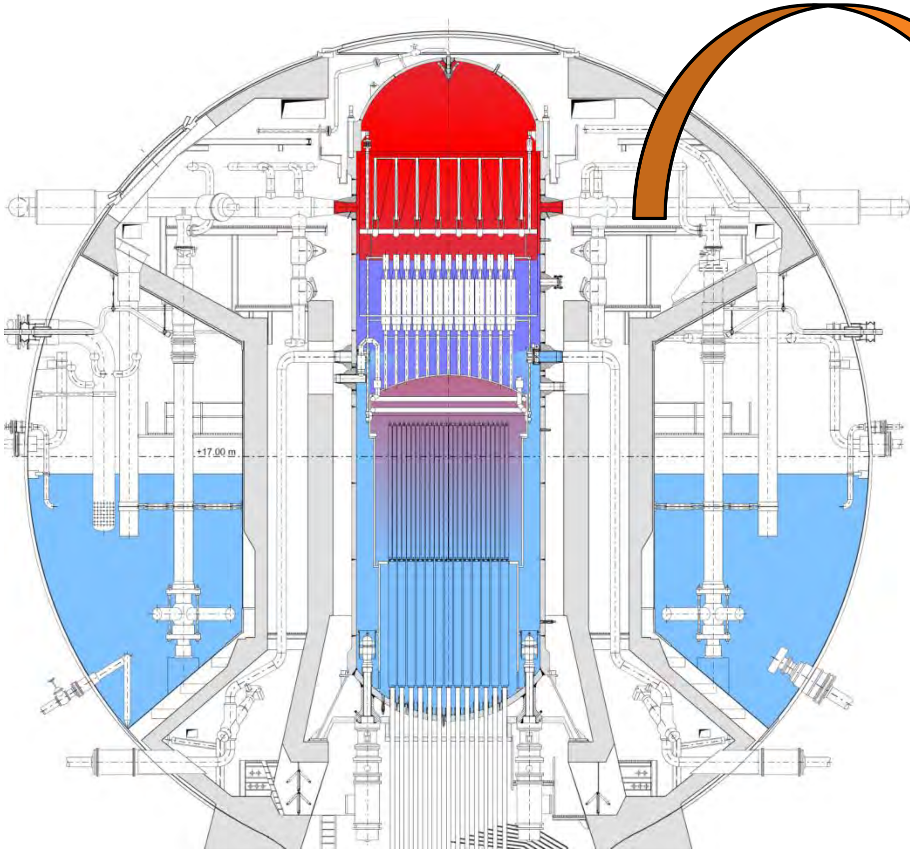
- MCNP™ – modelling of BWR (or PWR) as 3D-geometry
  - Core → Merging of fuel assemblies (density & burnup)
  - Core-near and core-far components (e. g. bioshield)
- Analysis of the reactor-life-cycle as basis for the local neutron source distribution → **Representative phases**
  - Neutron source distribution in the core
  - Water density distribution in the core region and in the RPV
- Segmentation
  - Material compositions & neutron flux spectra/flux distributions
- Activation calculation with ORIGEN-S
  - Input → Neutron spectra and flux densities from MCNP™
  - Alloying and trace elements to be activated
  - Nuclear data based on ENDF/B-VII- and JEFF 3.0-data
  - Validation of computational model and source term

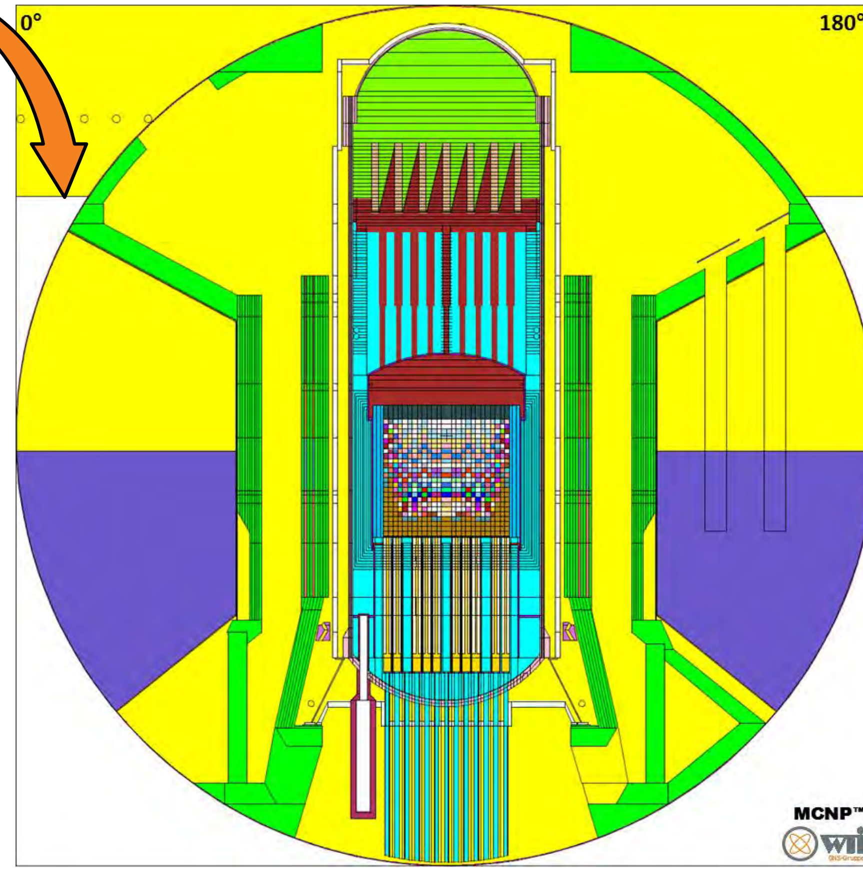


Example: BWR

Calculation procedure & model (2/5)

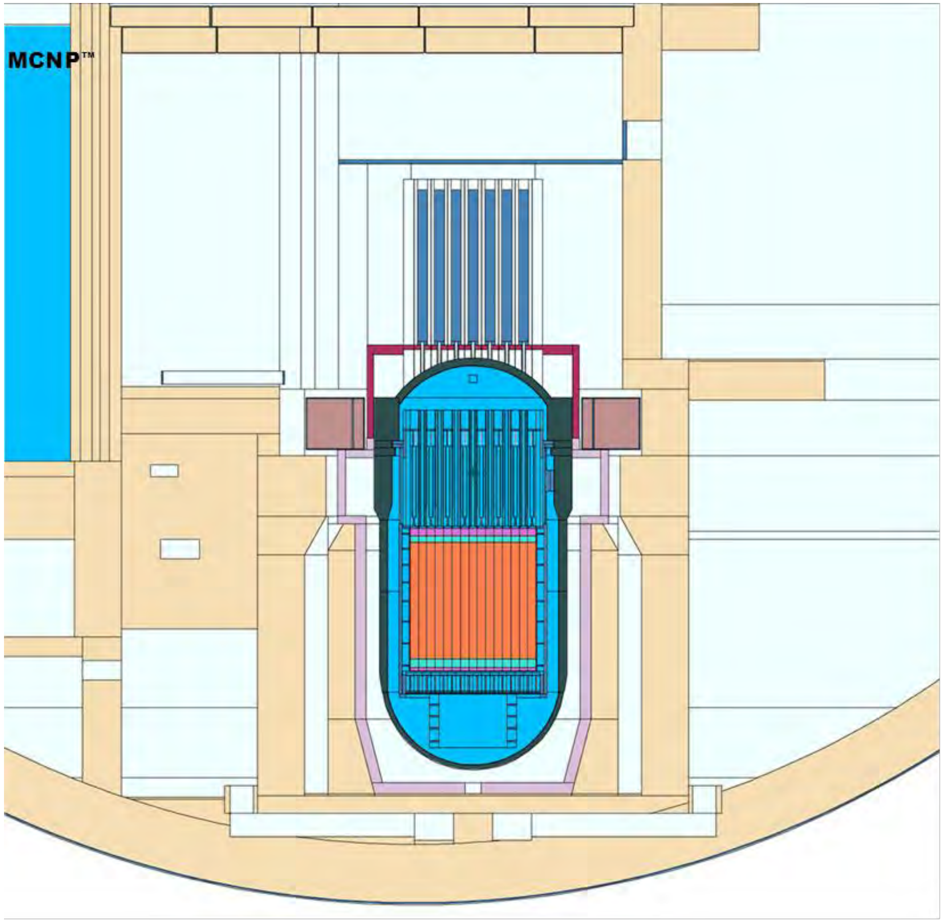
- Technical drawing - BWR
- Detailed MCNP™-model

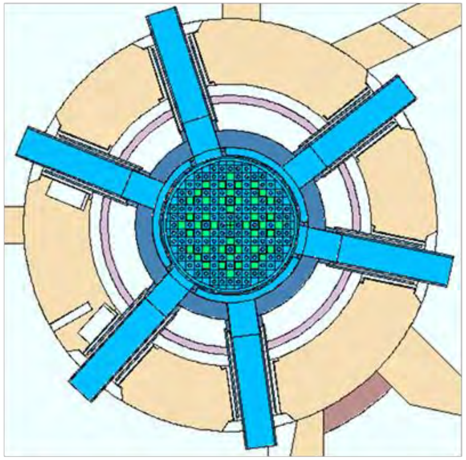


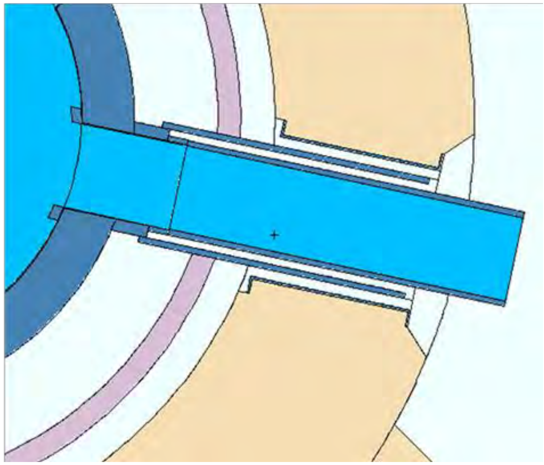


Calculation procedure & model (3/5)

- Detailed MCNP^{TM}-model (PWR)

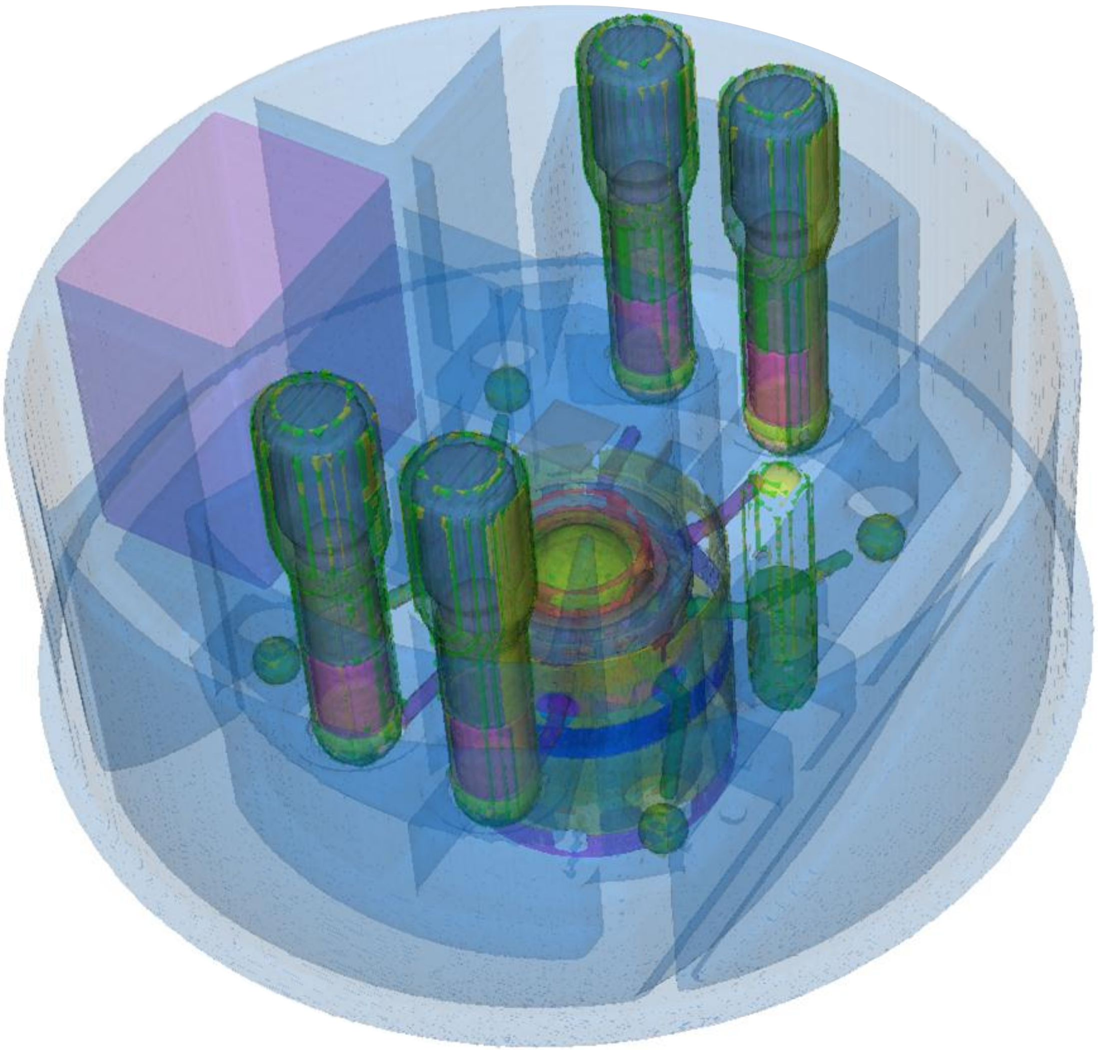




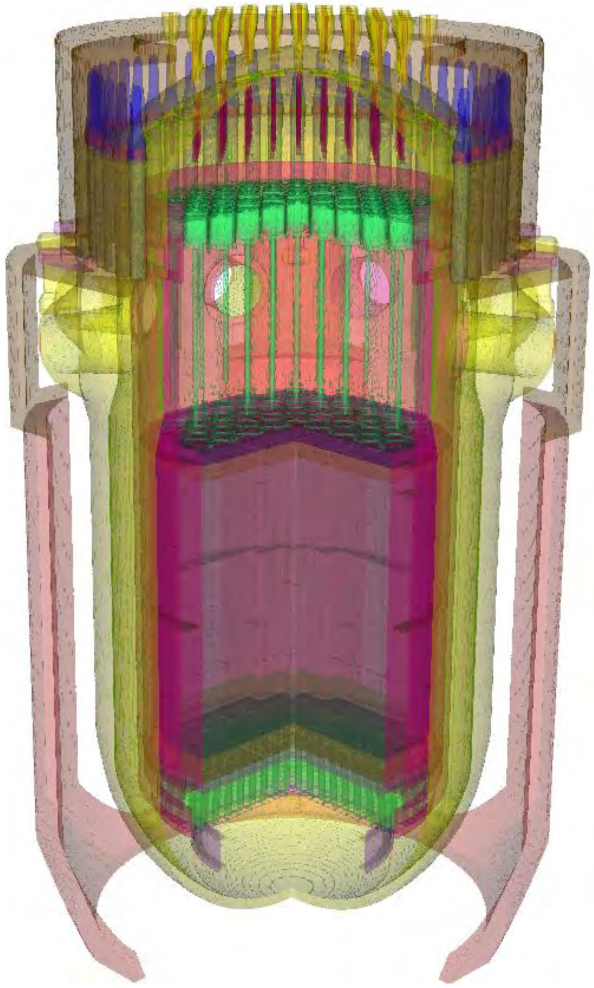


Calculation procedure & model (4/5)

- Full MCNP™-model (PWR)

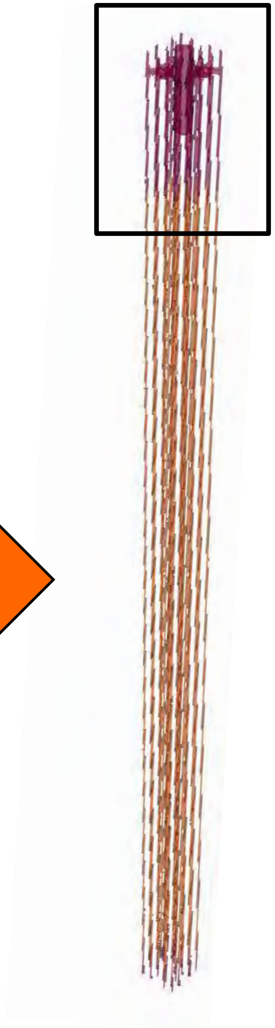


- Reactor pressure vessel



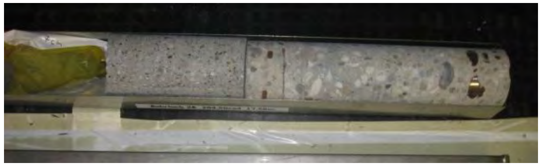
Calculation procedure & model (5/5)

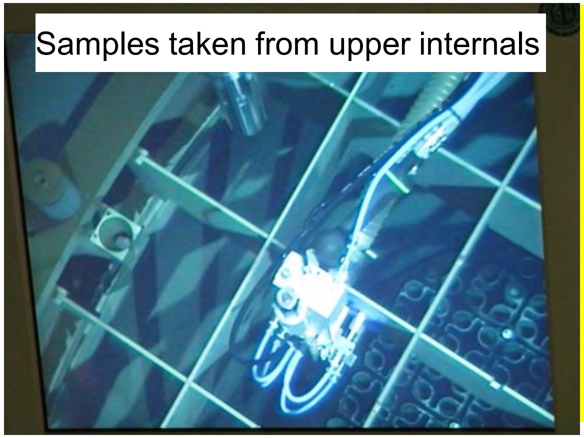
- Control rods and guide tubes



Validation (1/9)

- Basis of validation:
  - Samples
    - Small samples (e. g. cuttings)
    - bore holes, probing of internals
  - Activation detectors (core-near and core-far)
  - Gamma dose rate measurements after shut-down
  - Neutron dose rate measurements during operation
  - Neutron flux density measurements during operation





Samples taken from upper internals

Main objectives:
Validated integral neutron flux, neutron spectra and activation results in

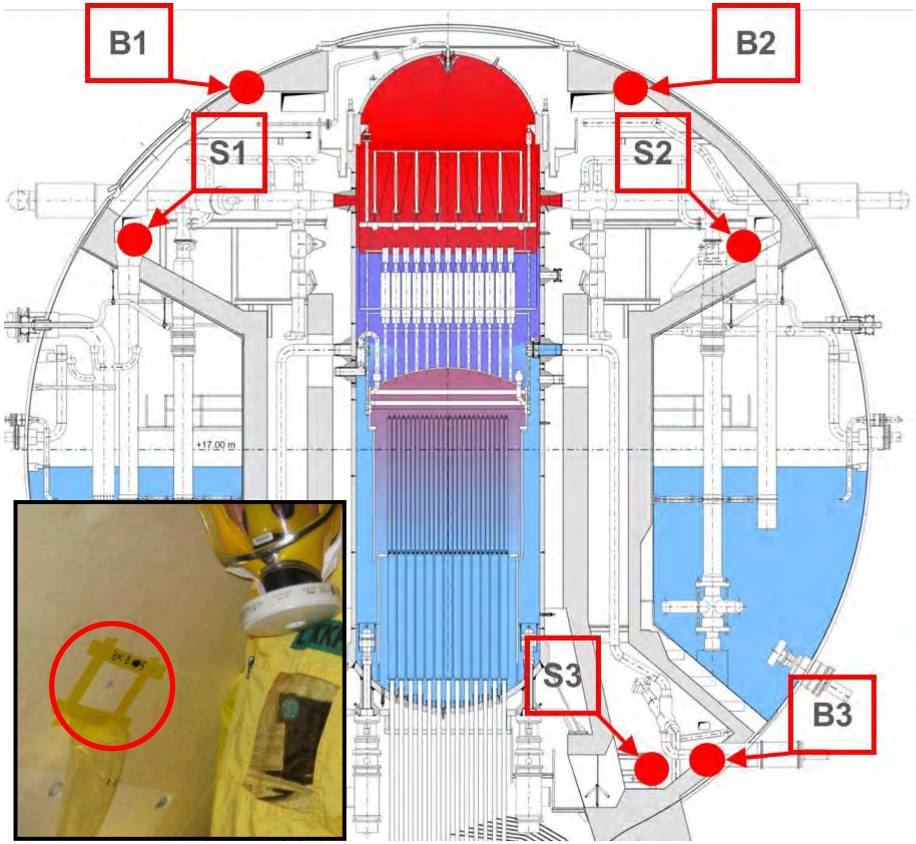
- Core-near and
- Core-far regions

Validation - Samples (2/9)

- Samples are only taken from components outside the RPV
  - Drilling chips
- Results shown as relation calculation(C)/measurement(M) for concrete (B) and steel (S) structures
  (Example: BWR, PWR similar)

sample	nuclide		
	Co-60	Cs-134	Eu-152
S1	1.3	*	*
S2	1.6	*	*
S3	1.5	*	*
B1	4.8	2.6	8.0
B2	3.7	2.2	7.0
B3	-	-	-

*: Not measured, -: Measured activity below detection limit



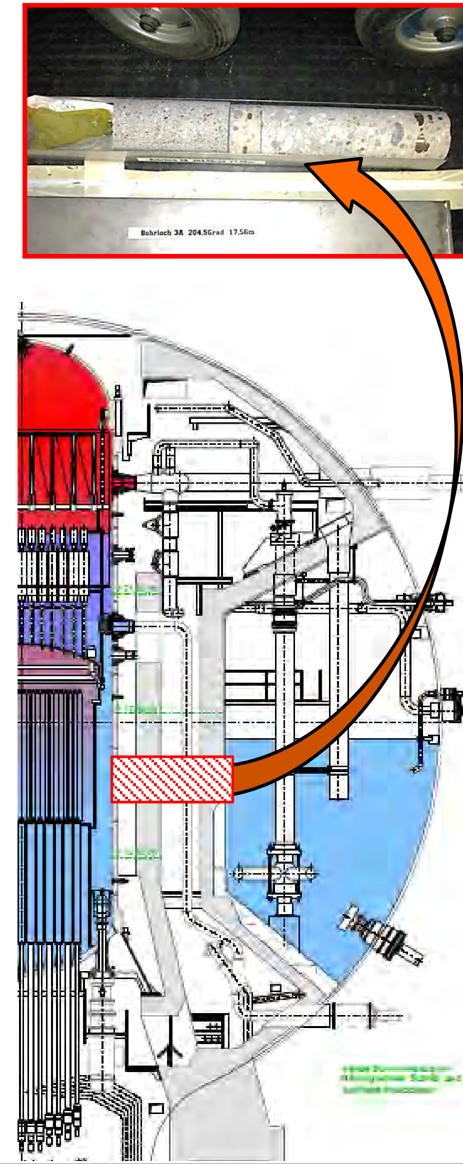
- Results show good agreement for Co-60 and Cs-134
- Traces of europium in concrete are strongly varying

Validation - Samples (3/9)

- Bore hole samples contain
  - Concrete and armed concrete structure (biological shield)
  - Small samples of the RPV
- Typical results shown as relation C/M
- H-3 overestimated
  → Escapes partly during operation
- Generally slight overestimation
- Results behave similar for BWR and PWR

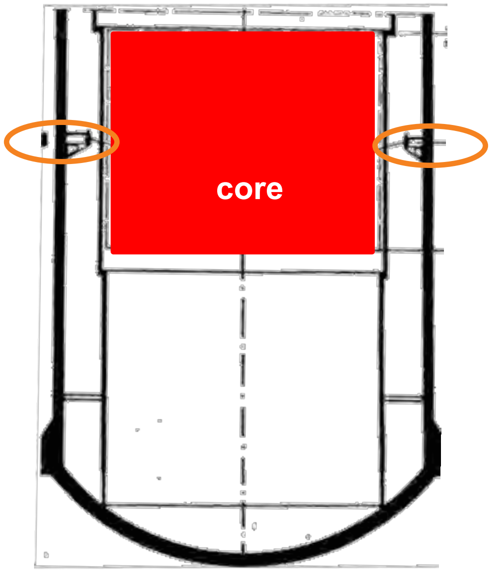
bore hole sample position	nuclide	concrete of biological shield			steel sample of RPV
		towards RPV	in the middle	towards annulus	
mid level of the active zone (direct radiation dominates)	H-3	7.1	6.7	-	*
	C-14	2.2	-	-	*
	Mn-54	*	*	*	2.3
	Co-60	0.9	5.6	-	1.2
	Cs-134	1.4	3.8	-	*
	Eu-152	4.1	3	-	*
	Eu-154	4.1	2.6	-	*
4 m above the active zone (streaming dominates)	H-3	19	2.9	2.8	*
	C-14	2.2	0.1	-	*
	Mn-54	*	*	*	6.8
	Co-60	0.9	-	4.6	1.8
	Cs-134	2	-	-	*
	Eu-152	5.7	-	2	*
	Eu-154	5.1	-	-	*

*: Not measured, -: Measured activity below detection limit

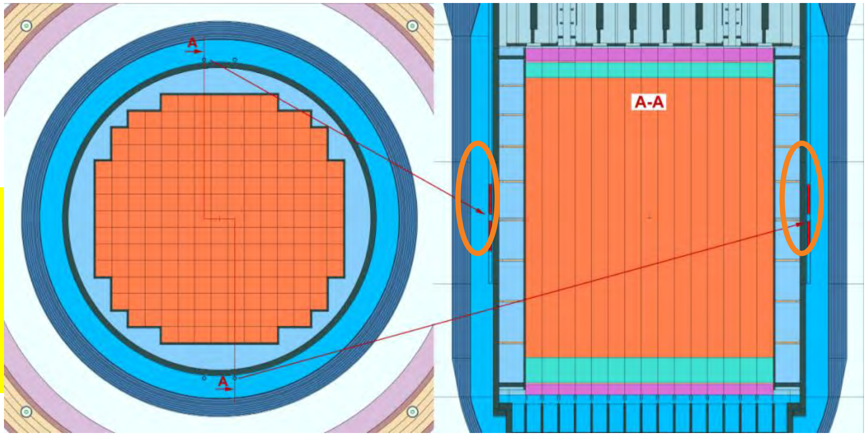


Validation - Activation detectors (4/9)

- Analyses of samples
- Measurement of reaction rates and derivation of fast neutron fluence
- Detectors
  - Fe-54 (n, p) Mn-54
    → short half-life: $T_{1/2}$(Mn-54) = 312 d
  - Nb-93 (n, n‘) Nb-93m
    → longer half-life: $T_{1/2}$(Nb-93m) ≈ 16 a
- Two ways to calculate the reaction rates
  - Directly with MCNP™
  - With ORIGEN-S using MCNP™-results → WTI method
- Deviation:
  C/M from (1.0 ± 0.1) to (1.9 ± 0.2) for both ways and reactor types



Example: BWR

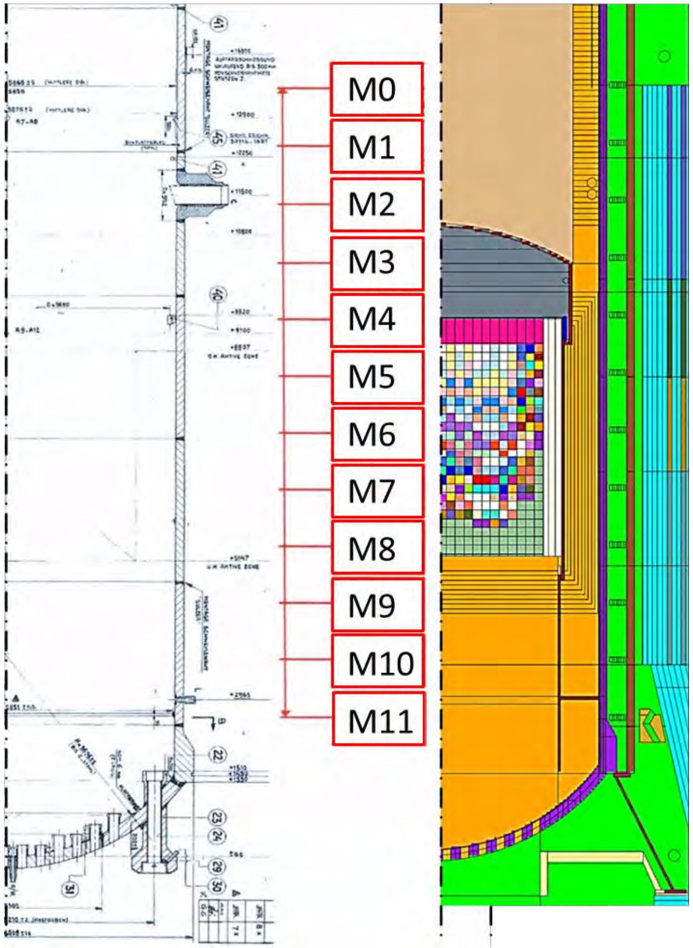


Example: PWR

Validation - Measurement of gamma dose rates (5/9)

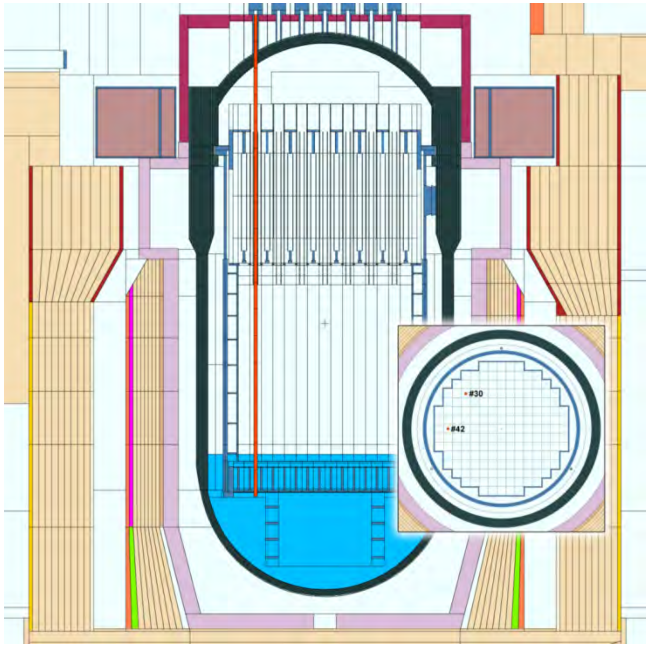
- Dose rate measurements between RPV and biological shield after decontamination of the primary circuit (BWR)
  → Main contribution: Activation products
- Calculated activities are used to estimate the dose rates in the post-operational phase
- Azimuthal varying heterogeneous activation was included
- Major contribution of the shroud to the dose rate along the core height
- Dose rates agree with C/M ≈ 2 to 3
- Same agreement as core-near activation detectors

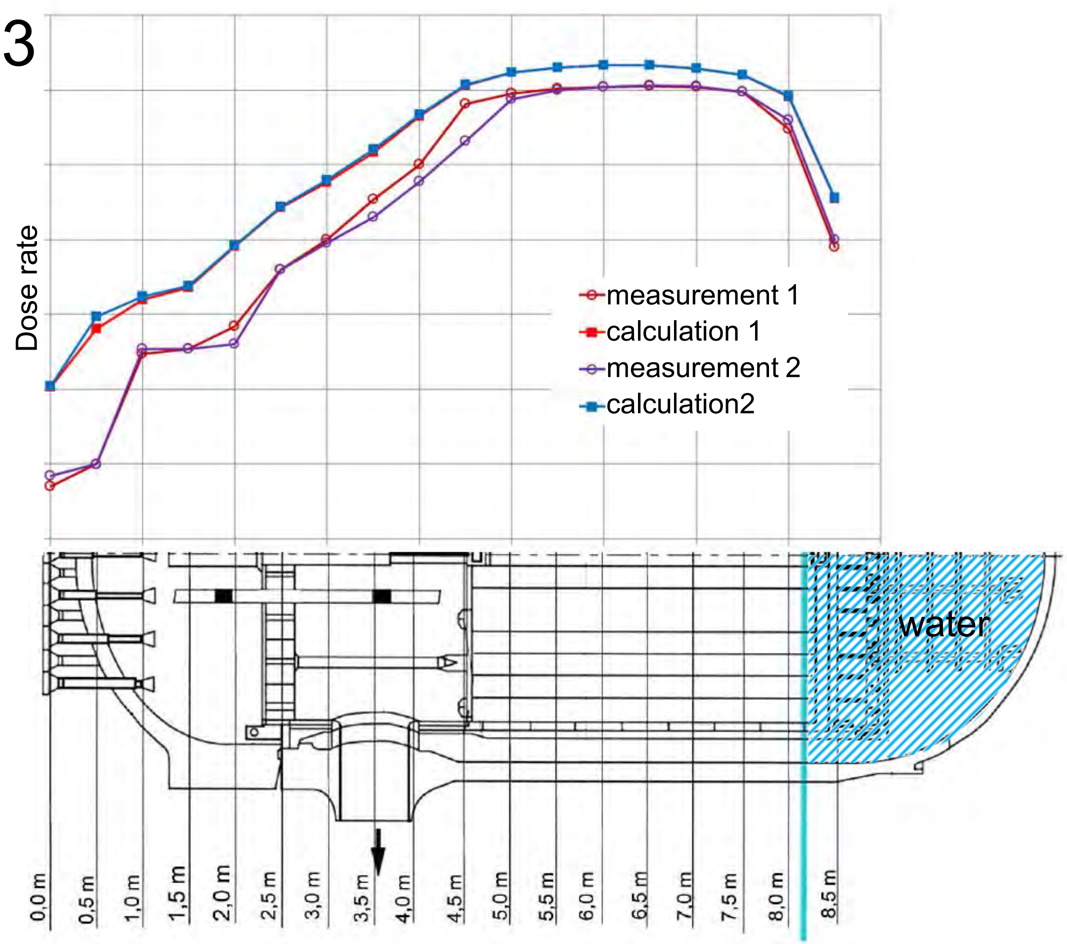
receptor point	C/M
M0	1.2
M1	2
M2	2.7
M3	1.7
M4	2.3
M5	2.2
M6	2.1
M7	1.8
M8	3
M9	2.6
M10	2.9
M11	2



Validation - Measurement of gamma dose rates (6/9)

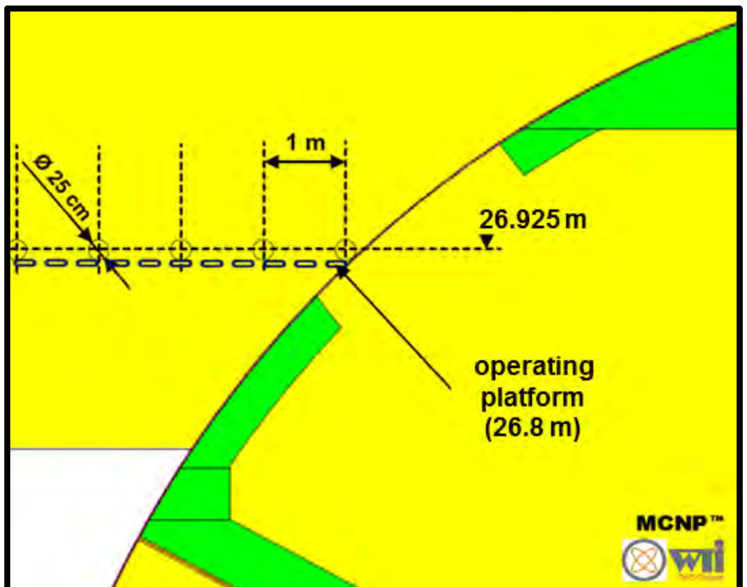
- Comparison of measured and calculated dose rates (PWR)
  - Measurement along control rod positions inside a water-free RPV
- Results with C/M ≈ 2 to 3 agree as in the case of a BWR

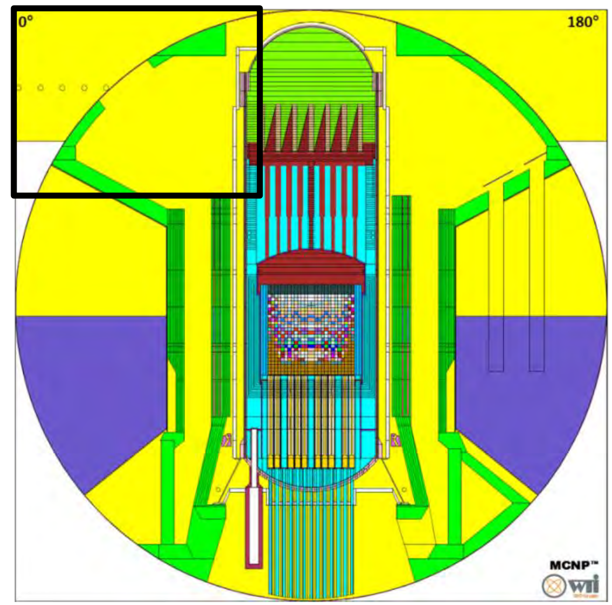




Validation - Measurement of neutron dose rates (7/9)

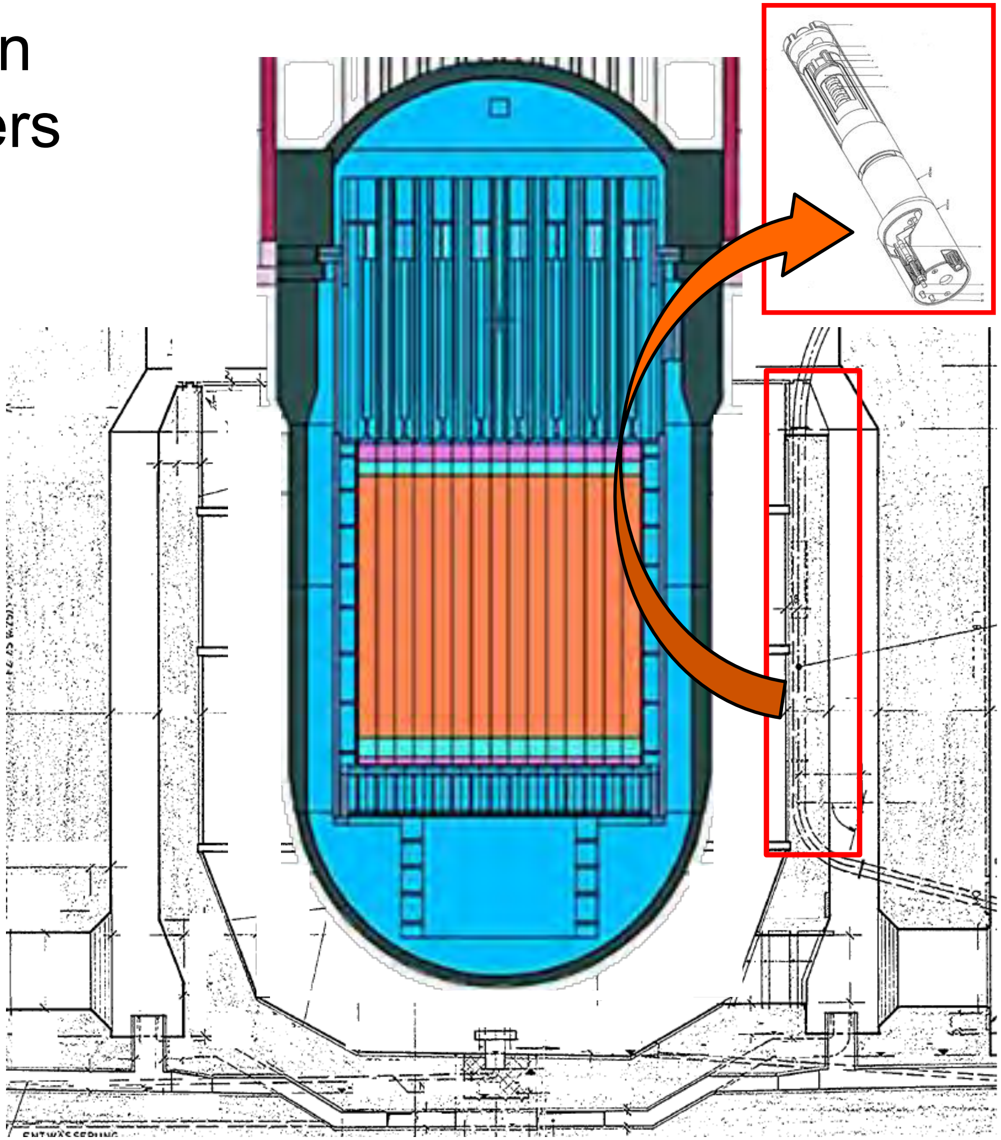
- Neutron dose rates measured in 2 m to 4 m distance from the entrance of the containment during operation
  → Neutron streaming
  - Neutron detector Berthold Lb6411 was used
- Detector-Characteristics applied in calculation
- C/M ≈ 1 in about 3 m distance from the entrance





Validation - Flux measurements (8/9)

- Measurement of currents in neutron-ionization chambers during reactor operation
- Currents converted to local neutron flux densities in comparison to calculations
- Results show agreement with C/M = (2.7 ± 0.6)
  - Same accuracy as for previously shown validation results



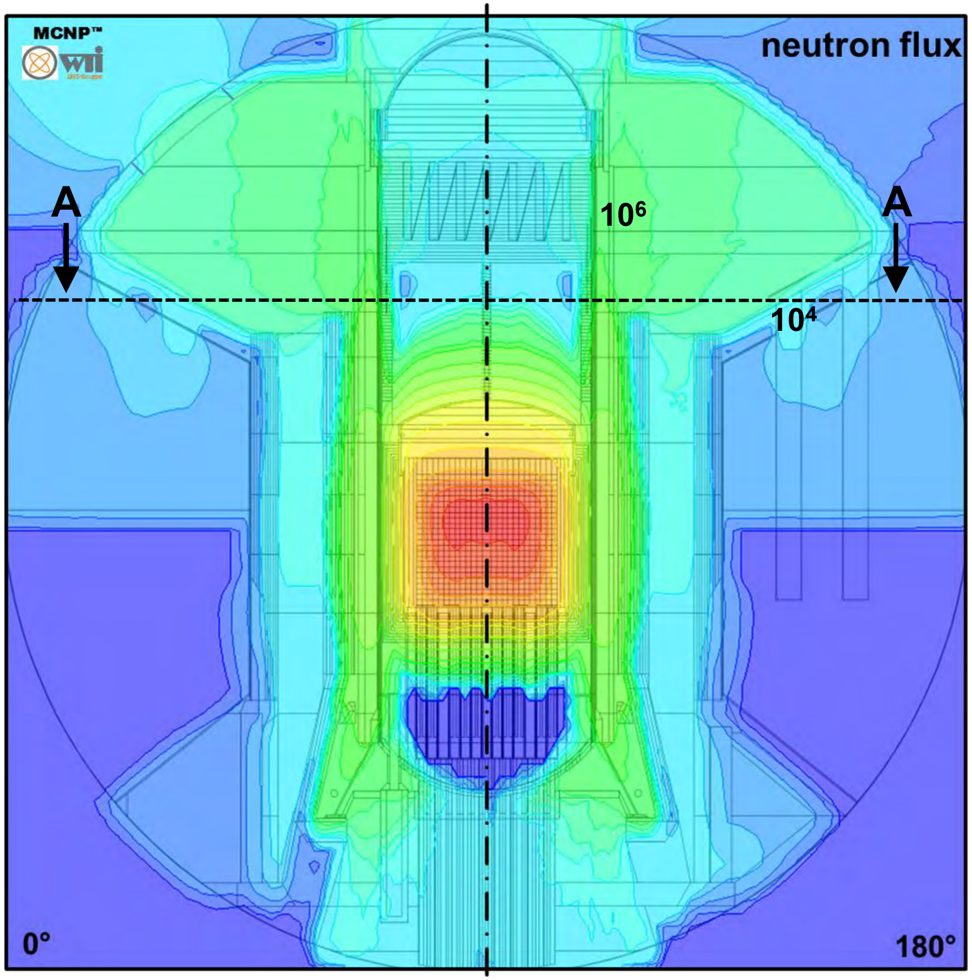
Validation - Summary (9/9)

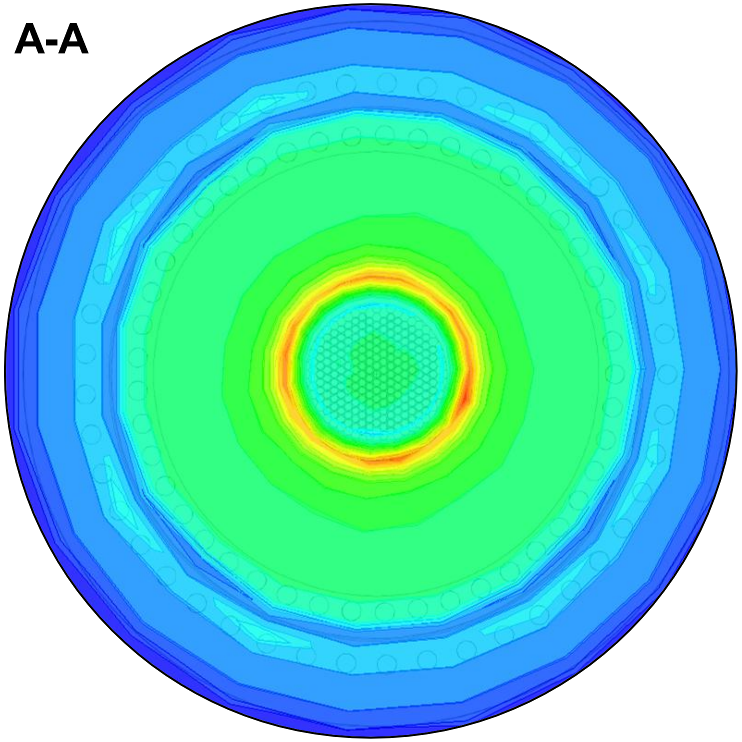
- All methods of validation show similar results for both reactor types
  - Good agreement between measurements and calculated neutron flux density distributions, radioactivities and derived dose rates
  - Agreement between the computational codes is demonstrated (code-to-code comparison)
- The developed method reproduces the neutron flux density distribution and activities appropriately in
  - Core-near and
  - Core-far regions

The developed WTI-method to calculate neutron flux density distributions during full power operation for activation analyses is validated!

Results - Neutron flux density distributions (BWR)

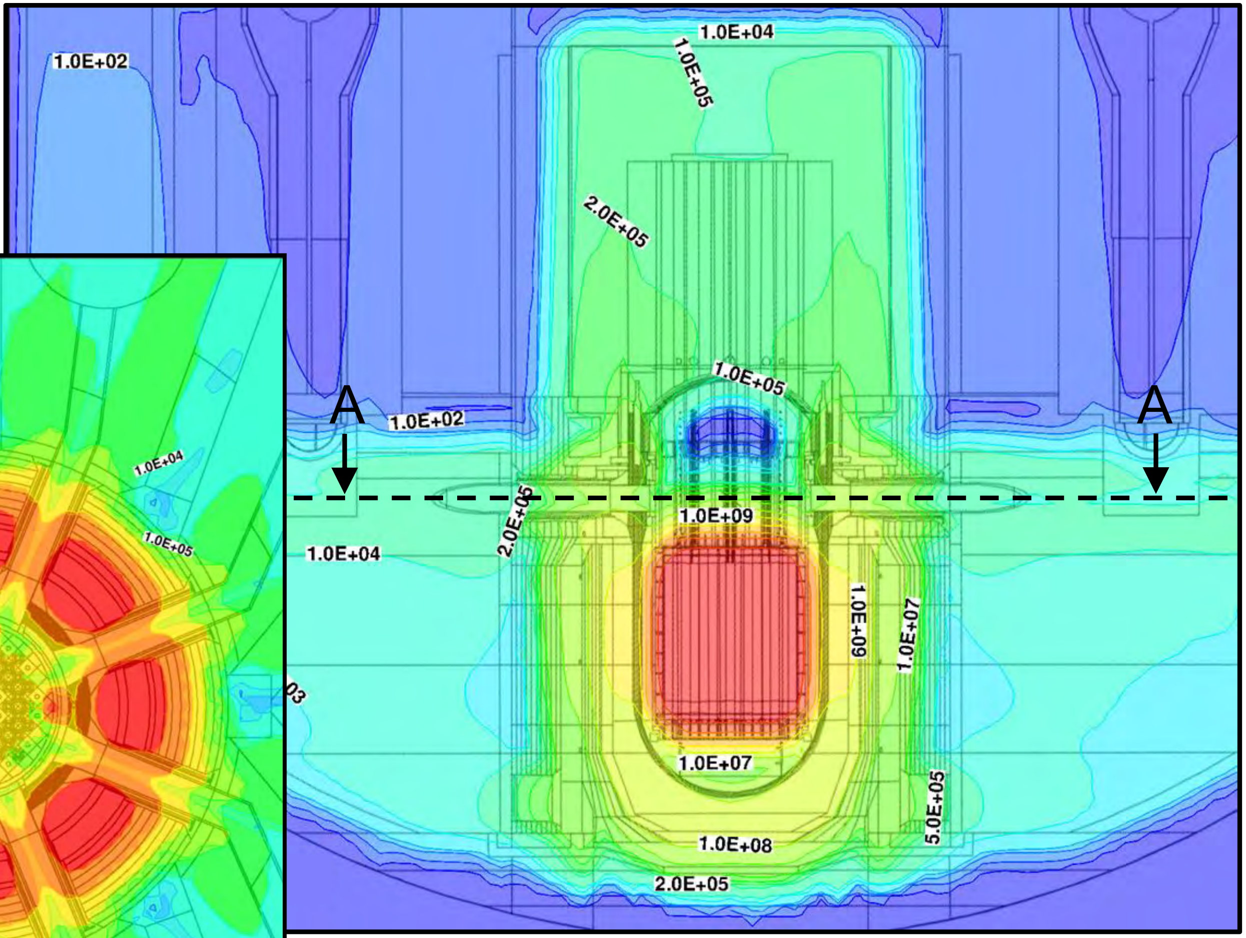
- Neutron flux density distribution during full power operation, 1/(cm² s)

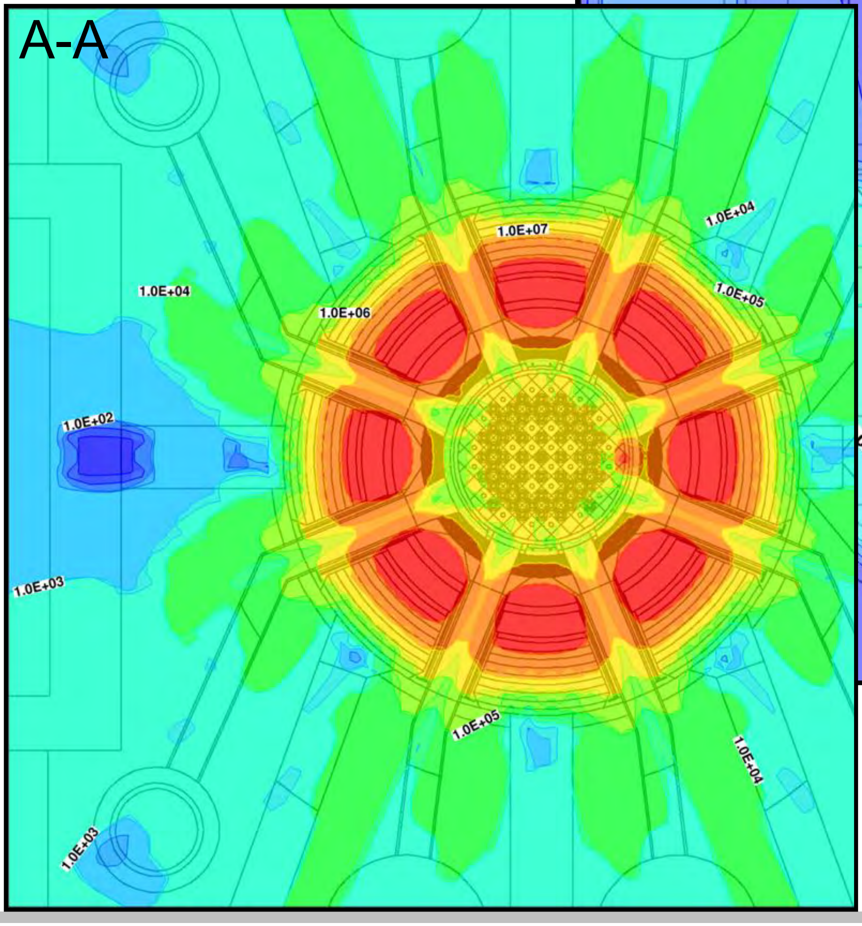




Results - Neutron flux density distributions (PWR)

- Streaming along primary coolant pipes

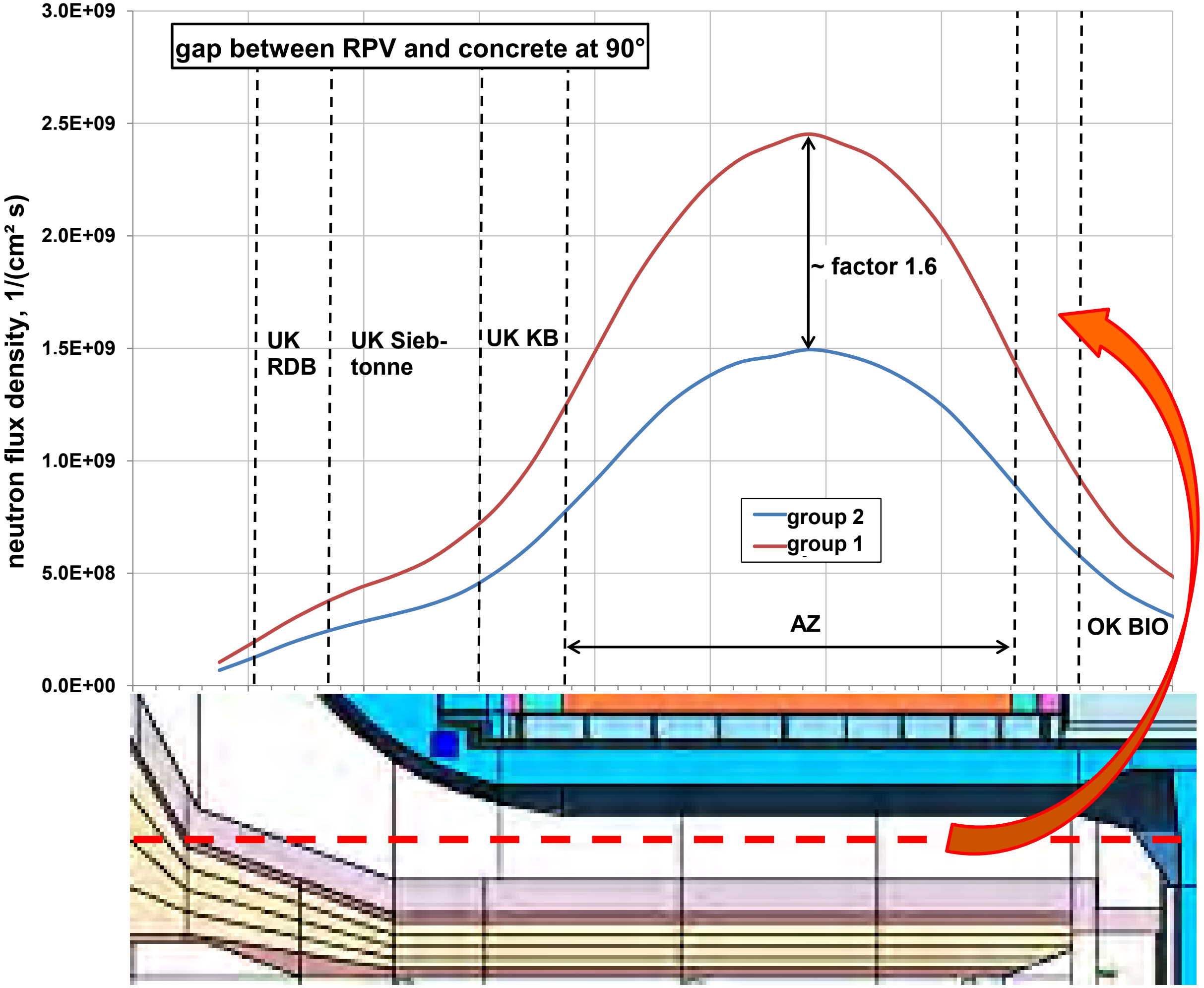




- Neutron flux density distribution at full power operation, 1/(cm² s)

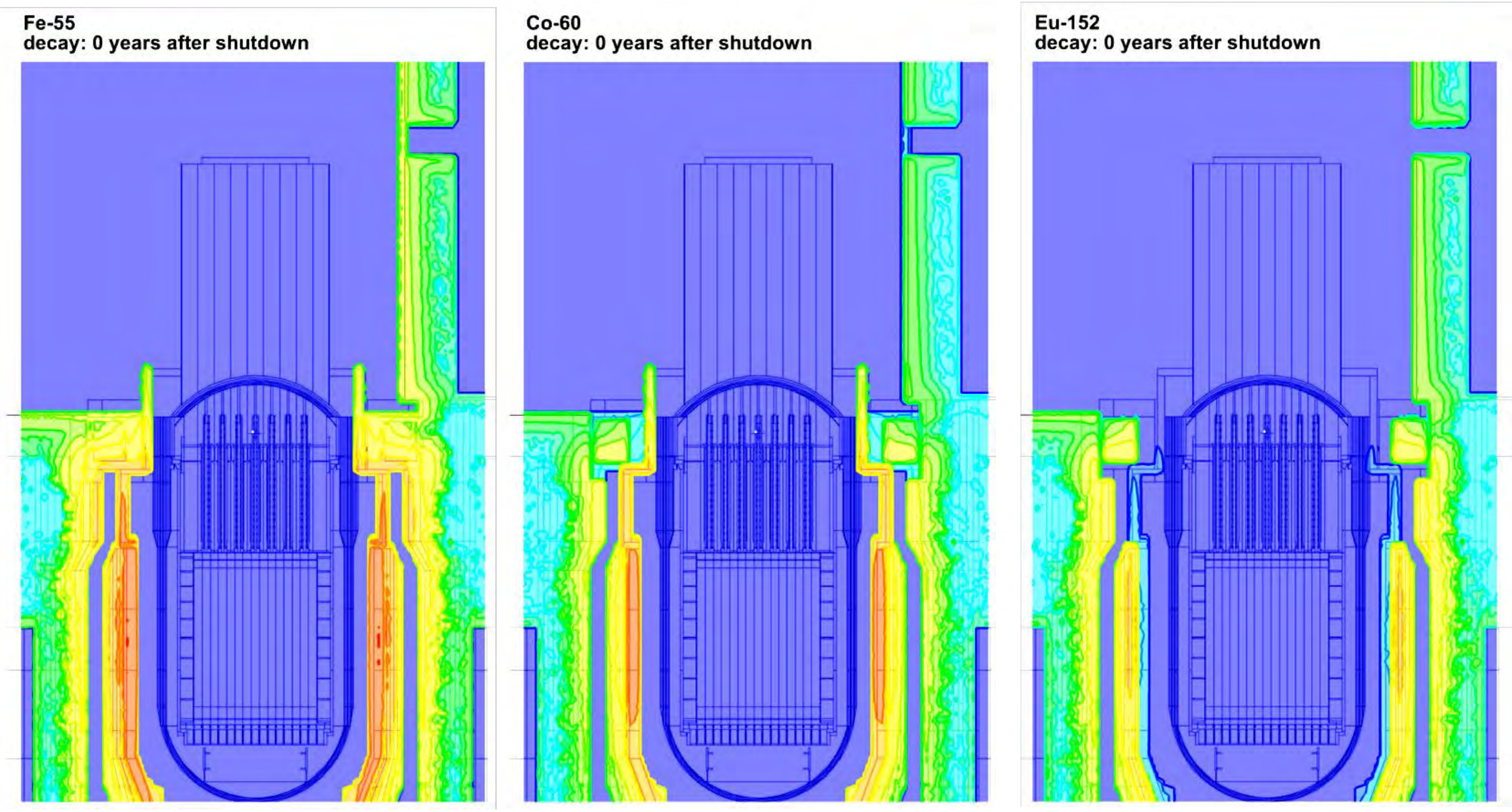
Results - Representative phases

- Difference between grouped operation cycles
- Results show the need of creating repre-sentative cycle groups



Visualization of activity distributions

- Example: Distribution in concrete structures



Decommissioning & packaging concepts (1/3)

- Further use of calculated radioactivities

Basic data:
- Radioactivities
- Mass
- Geometry and dimensions
- Product group

Choose of disposal method

Release of radioactive material (§29 StrlSchV)

Melting of steel components (use as e. g. shielding)

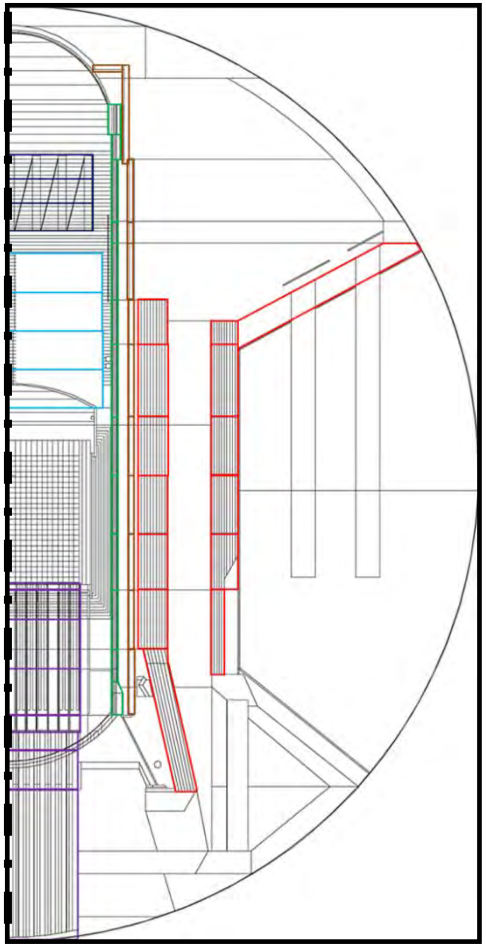
Development of a packaging concept (transport & storage of radioactive material)

Decommissioning & packaging concepts (2/3)

- Release of radioactive material
- Detailed information of radioactivity distribution inside the containment required → Radioactive decay
- Trace elements in unradiated materials (basis composition) are important for a possible release

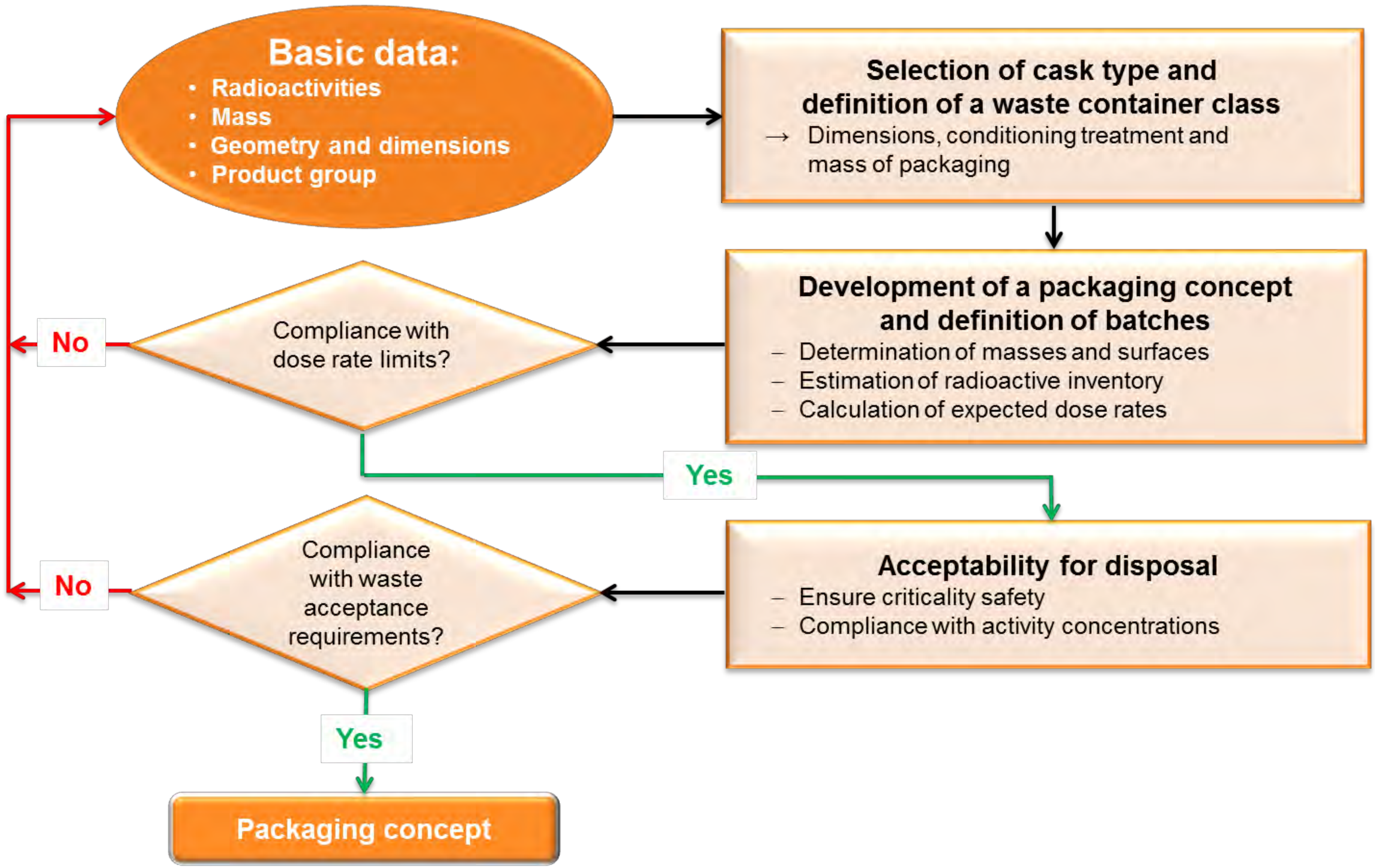
time	release of radioactive material		
	solid material	concrete structures	concrete structures without U & Th
reference date	3%	31%	53%
+ 10 years	6%	40%	82%

- As function of the specific reference date optimized decommissioning strategies can be realized → Choose of disposal method



Decommissioning & packaging concepts (3/3)

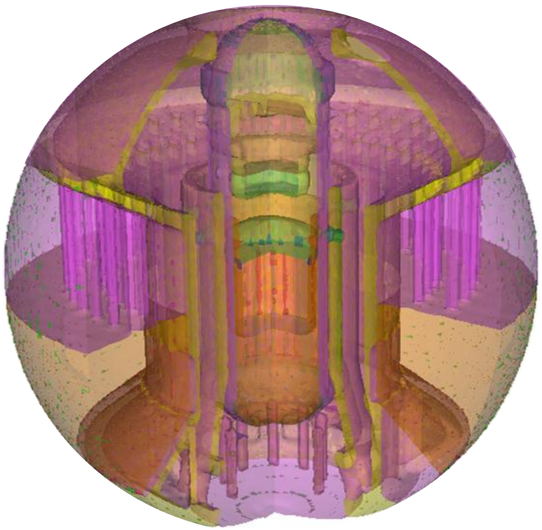
- Packaging concept



Conclusion and lessons learned

- Prediction of activities improved by application of the Monte-Carlo-Method and the developed procedure
- Applied method suitable and validated for the determination of radioactive inventory of a nuclear power plant from neutron activation
- Validation demonstrates similar C/M-values along all references
  - Strong confidence in the developed calculation method
    → Method can be used for the calculation of radioactive inventories of ***all*** nuclear facilities
- The developed and **validated** method
  - Reduces significantly the amount of samples
  - Can be used to create cost-effective and optimized packaging concepts

Activation calculation for the dismantling and decommissioning of a light water reactor using MCNP™ with ADVANTG and ORIGEN-S



Dr. L. Schlömer[1)], Prof. Dr. P.-W. Phlippen[1)], B. Lukas[2)]

[1)] WTI Wissenschaftlich-Technische Ingenieurberatung GmbH, 52428 Jülich, Germany
[2)] EnBW Kernkraft GmbH, 76661 Philippsburg, Germany

ANS Annual Meeting
June 11-15, 2017, San Francisco