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

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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

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** | **Grids** |
|-----------|-----------|
| Adjusted EBITDA 2015: €255 million | Adjusted EBITDA 2015: €886 million |
| Employees: 3,300 | Employees: 8,086 |
| **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 | **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** | **Generation and Trading** |
|-----------------------|---------------------------|
| Adjusted EBITDA 2015: €287 million | Adjusted EBITDA 2015: €777 million |
| Employees: 815 | Employees: 5,167 |
| **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 | **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 Kernkraft GmbH – nuclear power plants

**Obrigheim (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)
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 decommissioning 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
Detailed MCNP™-model (PWR)
Calculation procedure & model (4/5)

- Full MCNP™-model (PWR)

- Reactor pressure vessel
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

**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)

  Results show good agreement for Co-60 and Cs-134

  Traces of europium in concrete are strongly varying

| sample | 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
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

### Table: Validation - Samples (3/9)

| bore hole sample position | nuclide  | concrete of biological shield | steel sample of RPV |
|---------------------------|----------|-------------------------------|---------------------|
|                           |          | towards RPV | in the middle | towards annulus | |
| 4 m above the active zone (streaming dominates) | H-3      | 2.2          | -             | -              | * |
|                           | C-14     | *            | *             | *              | 2.3 |
|                           | Mn-54    | *            | *             | *              | 1.2 |
|                           | Co-60    | 0.9          | 5.6           | -              | * |
|                           | Cs-134   | 1.4          | 3.8           | -              | * |
|                           | Eu-152   | 4.1          | 3             | -              | * |
|                           | Eu-154   | 4.1          | 2.6           | -              | * |

| mid level of the active zone (direct radiation dominates) | H-3 | 19 | 2.9 | 2.8 | * |
|----------------------------------------------------------|-----|----|-----|-----|---|
| C-14                                                     | 2.2 | 0.1| 0.0 | * |
| 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

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Analyses of samples

Measurement of reaction rates and derivation of fast neutron fluence

Detectors
- Fe-54 (n, p) Mn-54 → short half-life: $T_{1/2}(\text{Mn-54}) = 312 \text{ d}$
- Nb-93 (n, n') Nb-93m → longer half-life: $T_{1/2}(\text{Nb-93m}) \approx 16 \text{ a}$

Two ways to calculate the reaction rates
- Directly with MCNP™
- With ORIGEN-S using MCNP™-results → WTI method

Deviation:
C/M from $(1.0 \pm 0.1)$ to $(1.9 \pm 0.2)$ for both ways and reactor types
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

![Diagram showing dose rate comparison with measurements and calculations for different positions in a water-free environment.](image-url)
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

- $C/M \approx 1$ 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 \( C/M = (2.7 \pm 0.6) \)
  - 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 representative cycle groups

![Graph showing neutron flux density and gap between RPV and concrete at 90°](image)

- Factor ~ 1.6
- Group 1 vs. Group 2
- AZ and OK BIO
Visualization of activity distributions

- Example: Distribution in concrete structures

- Fe-55 decay: 0 years after shutdown
- Co-60 decay: 0 years after shutdown
- Eu-152 decay: 0 years after shutdown
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)

www.siempelkamp.com
Release of radioactive material

Detailed information of radioactivity distribution inside the containment required → Radioactive decay

Trace elements in unirradiated materials (basis composition) are important for a possible release

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

| time           | release of radioactive material | concrete structures without U & Th |
|----------------|-------------------------------|-----------------------------------|
| reference date | 3%                            | 31%                               |
| + 10 years     | 6%                            | 40%                               |
|                | 82%                           |                                   |
Decommissioning & packaging concepts (3/3)

Packaging concept

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

- Selection of cask type and definition of a waste container class
  - Dimensions, conditioning treatment and mass of packaging

- Development of a packaging concept and definition of batches
  - Determination of masses and surfaces
  - Estimation of radioactive inventory
  - Calculation of expected dose rates

- Acceptability for disposal
  - Ensure criticality safety
  - Compliance with activity concentrations

- Compliance with dose rate limits?
  - Yes
  - Compliance with waste acceptance requirements?
    - Yes
    - Packaging concept
    - No
    - No

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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
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