Reactor Dosimetry in NPP Lifetime Management and Decommissioning Tasks

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OUTLINE

Introduction

REACTOR DOSIMETRY Tasks
Units in Operation

REACTOR DOSIMETRY and PTSA
Lifetime Extension

REACTOR DOSIMETRY
in Decommissioning

General Conclusion
Introduction (1)

- There are six power units at Kozloduy Nuclear Power Plant (KNPP) in Bulgaria. Two of them (VVER 1000/320 type) are in operation now when other four (VVER 440/230 type) are shut down. For the Units 5 and 6 that are in operation the lifetime extension task is one of the most important. For the Units 1 to 4 that are shut down the task of radiological characterization for decommissioning purposes is of crucial interest.
Introduction (2)

- More than thirty years, since 1989 the Institute for Nuclear Research and Nuclear Energy of Bulgarian Academy of and Sciences (INRNE) has provided for KNPP a scientific assistance in the field of rector dosimetry which is a tool for nondestructive assessment of reactor pressure vessel (RPV) metal embrittlement.
Introduction (3)

- The data for the neutron fluence accumulated on the RPVs of all units during the operated cycles was assessed by calculation and verified by ex-vessel activation detectors. Assessment of the neutron fluence on the so called surveillance samples-witness has been done according to the Surveillance program of Units 5 and 6.
Reactor Dosimetry Tasks

Units in Operation

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### Reactor Pressure Vessel (RPV)

#### Current state

↓

**Neutron Embrittlement**

\[ \Delta T_F = A_F F^{1/3} \]

#### Rest Lifetime

↓

**Rest cycles**

\[ LT = \frac{(F_{\text{max}} - F)}{F_{\text{avr}}} \]

\[ F_{\text{max}} \leftarrow T_k^a \leftarrow PTS \]

#### Reduction of neutron fluence

↓

**Operation management**

- low leakage scheme
- dummy cassettes
- weld axial level

### Surveillance locations

**Surveillance Program**

**witness-samples (surveillances) treatment**

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NEUTRON FLUENCE ASSASMENT (LiM)

- Loading / Operational History DATA
- RC Simulation Code
  - Power and Burnup Distribution
  - (R,θ,Z)-source (TORT)
- XS Libraries, BGL 446, 1000
- GIP
- Material XS DATA (TORT)
- Decay DPA'XS Constant Det' XS
- TORT
- RESULTS Fluence, Activity, Damages
- Measured Activities, Uncertainty, Correlation
  - Least Squares Adjustment
  - "Best estimated Fluence"
- MCNP XS DATA
  - MCNP
  - VEGO
  - Body Model (R,θ,Z)-meshes
  - Decay DPA'XS Constant Det' XS
- Task parameters (XS, Densities, Dimensions), Uncertainty, Correlation, Sensitivity

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NEUTRON FLUENCE AND DETECTORS’ ACTIVITY CALCULATION

**TORT** deterministic discrete ordinate codes

**BGL** multigroup library

for VVER-1000 and VVER-440

**BUGLE96** multigroup library for PWR

**MCNP** Monte Carlo code

**MCNPDATA** library with continuous neutron cross section energy dependence

**DOSRC, VISDO** code for fixed sources

generating and geometry model visualization

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NEUTRON FLUENCE AND DETECTORS’ ACTIVITY CALCULATION

DOSRC, VISDO - sources generating and geometry visualization
Sources of **Calculation Uncertainties**:

- **plant independent parameters:**
  - nuclear data

- **plant dependent parameters:**
  - constructional data
    - geometry dimensions, densities and materials’ content
  - operational data
    - neutron source etc.

- approximations of calculation methods
## Calculation uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Fluence, %</th>
<th>Cu detector, %</th>
<th>Fe detector, %</th>
<th>Nb detector, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron XS inelastic</td>
<td>8.3(4.9*)</td>
<td>35.(14.*)</td>
<td>31.(16.*)</td>
<td>13.(8.3*)</td>
</tr>
<tr>
<td>Iron XS absorption</td>
<td>2.3</td>
<td>9.7</td>
<td>5.7</td>
<td>3.1</td>
</tr>
<tr>
<td>Chromium XS inelastic</td>
<td>4.9</td>
<td>6.4</td>
<td>6.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Chromium XS elastic</td>
<td>1.5</td>
<td>0.84</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Chromium XS absorption</td>
<td>0.12</td>
<td>0.43</td>
<td>0.27</td>
<td>0.15</td>
</tr>
<tr>
<td>Hydrogen XS elastic</td>
<td>2.5</td>
<td>1.4</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Oxygen XS elastic</td>
<td>2.8</td>
<td>1.8</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Source spectrum</td>
<td>4.8</td>
<td>12.</td>
<td>7.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Source spatial distribution</td>
<td>3.9</td>
<td>3.3</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Steel density</td>
<td>2.5</td>
<td>3.7</td>
<td>3.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Moderator density</td>
<td>5.4</td>
<td>3.7</td>
<td>4.3</td>
<td>5.2</td>
</tr>
<tr>
<td>RPV inner radius</td>
<td>7.4</td>
<td>4.2</td>
<td>3.7</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18.(12.*)</strong></td>
<td><strong>41.(20.*)</strong></td>
<td><strong>36.(19.*)</strong></td>
<td><strong>23.(12.*)</strong></td>
</tr>
</tbody>
</table>
BEST ESTIMATED FLUENCE

after 1D adjustment VVER-1000

<table>
<thead>
<tr>
<th>Cu detector</th>
<th>Fe detector</th>
<th>Nb detector</th>
<th>Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \hat{\Gamma}$, %</td>
<td>STD, %</td>
<td>$\delta \hat{\Gamma}$, %</td>
<td>STD, %</td>
</tr>
<tr>
<td>-5.5</td>
<td>4.5</td>
<td>-5.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Tasks for further improvement:

- Sensitivity matrices in maximum irradiated positions
- XS uncertainty correlation matrices
- XS data improvement
Methodology Validation (NPP)

Device for Irradiation of Detectors in the Air Cavity Behind the VVER-1000 RPV

Unit 5, cycles 6

\[ ^{54}\text{Fe}(n,p)^{54}\text{Mn} \]

\[ ^{63}\text{Cu}(n,\alpha)^{60}\text{Co} \]

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Methodology Validation (NPP surveillance)

Location of surveillance assembly in VVER-1000/320

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Methodology Verification (Benchmark)

LR0 in Rez, Czech Republic

VVER-440 Mock-up standard

VVER-440 Mock-up dummy

VVER-1000 Mock-up

Conformity Mock-up – NPP Unit

Attenuation and Spectra

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The neutron fluence evaluation methodology is being developed under research projects USA NRC, IAEA and EC in close collaboration of Russia, Czech Republic, Germany, Spain, Bulgaria, Belgium, Hungary and Ukraine, and especially within the activity of the European Working Group on Reactor Dosimetry (EWGRD) and WGRD-VVER group of the countries operating VVER. The WGRD-VVER group was created in 1990. The EWGRD activity is dated from 1994.
Conclusions

✓ The RD methodology developed in the Institute for Nuclear Research and Nuclear Energy of Bulgarian Academy of Science is at the state of the art level.

✓ The state of the art RD provides reliable assessment results (with uncertainty less than 10%) for neutrons with energy above .1 MeV.

✓ Further efforts are needed to achieve the same level of accuracy for thermal neutrons and gammas.
Reactor Dosimetry and PTS Analysis in Lifetime Extension
FIG. 1. Integrity assessment related to the PTS.
Integrity assessment: $K_i$ and $[K_{ic}]$ dependency on temperature

$K_i \leq [K_{ic}]$

$[K_{ic}]$ - allowable stress intensity factor

$K_i$ - crack loading in terms of stress intensity factor

$T_k^a$ - RPV maximum allowable critical brittle fracture temperature

FIG. 7. Integrity assessment.
Critical temperature of brittleness $T_K$

$$T_K = T_{K0} + \Delta T_F + \Delta T_T + \Delta T_N$$

$$\Delta T_F = A_F \cdot (F \cdot 10^{-22})^n$$

Master Curve (MC) approach (VERLIFE)

$$[K_{ic}] = 25.2 + 36.6 \cdot \exp [0.019 (\Delta T)]$$

$\Delta T = RT_0 = T_0 + \sigma$; Reference temperature $T_0$

PNAE G-7-002-86 doc – accidental situation

$$[K_{ic}] = 26 + 36 \cdot \exp [0.02 (\Delta T)]$$, $\Delta T = T - T_k$

base metal

$$[K_{ic}] = 74 + 11 \cdot \exp [0.0385 (\Delta T)]$$, $\Delta T = T - T_k$

weld metal

$$[K_{ic}] = 35 + 53 \cdot \exp [0.0217 (\Delta T)]$$, $\Delta T = T - T_k$

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Fields of study
(ALPHABETIC ARRANGEMENT)

MATERIAL SCIENCE
REACTOR DOSIMETRY
STRUCTURAL ANALYSIS
THERMAL HYDRAULICS

FIG. 1. Integrity assessment related to the PTS.
Developing the team approach ...

N.B. example from non-nuclear industry; FFP = fitness for purpose

from N. Taylor presentation at JRC WS 11-13.10.2006

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Conclusions

- Application of FFP approach requires clear description of the uncertainties of the results of all disciplines involved. Uncertainty decreasing is a way for increasing of the limit values without reduction of conservatism.

- Another useful approach consists in application of local $T_{k}^{a}$ distribution over RPV. The local assessment could let us to increase the fluence limit value taking into account that the positions of the highest fluence does not coincide with positions where stress intensity factor $K_{I}$ reaches its highest values during PTS accident.
Reactor Dosimetry in Decommissioning Task
Available Documents

• [1] “Nuclear Data Requirements for Fission Reactor Decommissioning,” IAEA INDC(NDS)-269, January 1993


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Consultants Meetings
Advisory Group Meeting
Vienna, Austria: 12–16 February 1996

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### TABLE II. THE MOST IMPORTANT ACTIVATION REACTIONS CONSIDERED [3]

<table>
<thead>
<tr>
<th>Parent</th>
<th>Nuclear reaction</th>
<th>Daughter nuclide</th>
<th>Principal emissions</th>
<th>Half-life of daughter (a)</th>
<th>Abundance of parent nuclide in parent element (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-6</td>
<td>n,α</td>
<td>H-3</td>
<td>β⁺</td>
<td>12.3</td>
<td>7.5</td>
</tr>
<tr>
<td>C-13</td>
<td>n,γ</td>
<td>C-14</td>
<td>β⁺</td>
<td>5 730</td>
<td>1.1</td>
</tr>
<tr>
<td>N-14</td>
<td>n,p</td>
<td>C-14</td>
<td>β⁺</td>
<td>5 730</td>
<td>99.6</td>
</tr>
<tr>
<td>Na-23</td>
<td>n,2n</td>
<td>Na-22</td>
<td>β⁺, EC</td>
<td>2.6</td>
<td>100</td>
</tr>
<tr>
<td>Na-23</td>
<td>γ,n</td>
<td>Na-22</td>
<td>β⁺, EC</td>
<td>2.6</td>
<td>100</td>
</tr>
<tr>
<td>Cl-35</td>
<td>n,γ</td>
<td>Cl-36</td>
<td>β⁻ (β⁺, EC)</td>
<td>301 000</td>
<td>75.8</td>
</tr>
<tr>
<td>K-39</td>
<td>n,p</td>
<td>Ar-39</td>
<td>β⁻</td>
<td>269</td>
<td>93.3</td>
</tr>
<tr>
<td>Ca-40</td>
<td>n,γ</td>
<td>Ca-41</td>
<td>EC</td>
<td>103 000</td>
<td>96.9</td>
</tr>
<tr>
<td>Fe-54</td>
<td>n,p</td>
<td>Mn-54</td>
<td>EC, γ</td>
<td>0.86</td>
<td>5.9</td>
</tr>
<tr>
<td>Mn-55</td>
<td>n,2n</td>
<td>Mn-54</td>
<td>EC, γ</td>
<td>0.86</td>
<td>100</td>
</tr>
<tr>
<td>Fe-54</td>
<td>n,γ</td>
<td>Fe-55</td>
<td>EC, X</td>
<td>2.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Ni-58</td>
<td>n,γ</td>
<td>Ni-59</td>
<td>EC, X</td>
<td>76 000</td>
<td>68.3</td>
</tr>
<tr>
<td>Ni-62</td>
<td>n,γ</td>
<td>Ni-63</td>
<td>β⁻</td>
<td>100</td>
<td>3.6</td>
</tr>
<tr>
<td>Co-59</td>
<td>n,γ</td>
<td>Co-60</td>
<td>β⁺, γ</td>
<td>5.3</td>
<td>100</td>
</tr>
<tr>
<td>Zn-64</td>
<td>n,γ</td>
<td>Zn-65</td>
<td>EC, β⁺</td>
<td>0.67</td>
<td>48.6</td>
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<tr>
<td>Zr-92</td>
<td>n,γ</td>
<td>Zr-93</td>
<td>β⁻</td>
<td>1 500 000</td>
<td>17.1</td>
</tr>
<tr>
<td>Parent</td>
<td>Nuclear reaction</td>
<td>Daughter nuclide</td>
<td>Principal emissions</td>
<td>Half-life of daughter (a)</td>
<td>Abundance of parent nuclide in parent element (%)</td>
</tr>
<tr>
<td>---------</td>
<td>------------------</td>
<td>------------------</td>
<td>--------------------</td>
<td>---------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Mo-92</td>
<td>n,γ</td>
<td>Mo-93</td>
<td>EC, X</td>
<td>3 500</td>
<td>14.8</td>
</tr>
<tr>
<td>Nb-93</td>
<td>n,γ</td>
<td>Nb-93m</td>
<td>IT, X</td>
<td>15.8</td>
<td>100</td>
</tr>
<tr>
<td>Nb-93</td>
<td>n,γ</td>
<td>Nb-94</td>
<td>β⁻, γ</td>
<td>20 000</td>
<td>100</td>
</tr>
<tr>
<td>Mo-94</td>
<td>n,p</td>
<td>Nb-94</td>
<td>β⁻, γ</td>
<td>20 000</td>
<td>9.3</td>
</tr>
<tr>
<td>Mo-98</td>
<td>n,γ</td>
<td>Tc-99</td>
<td>β⁻</td>
<td>213 000</td>
<td>24.1</td>
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<tr>
<td>Ag-107</td>
<td>n,γ</td>
<td>Ag-108m</td>
<td>EC, γ</td>
<td>130</td>
<td>51.8</td>
</tr>
<tr>
<td>Ag-109</td>
<td>n,γ</td>
<td>Ag-110m</td>
<td>β⁻, γ</td>
<td>0.68</td>
<td>48.2</td>
</tr>
<tr>
<td>Sn-124</td>
<td>n,γ</td>
<td>Sb-125</td>
<td>β⁻, γ</td>
<td>2.76</td>
<td>5.8</td>
</tr>
<tr>
<td>Ba-132</td>
<td>n,γ</td>
<td>Ba-133</td>
<td>EC, X, γ</td>
<td>10.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Eu-151</td>
<td>n,γ</td>
<td>Eu-152</td>
<td>EC, X, β⁻, γ</td>
<td>13.5</td>
<td>47.8</td>
</tr>
<tr>
<td>Eu-153</td>
<td>n,γ</td>
<td>Eu-154</td>
<td>β⁻, γ, X</td>
<td>8.6</td>
<td>52.2</td>
</tr>
<tr>
<td>Eu-154</td>
<td>n,γ</td>
<td>Eu-155</td>
<td>β⁻, γ, X</td>
<td>4.76</td>
<td>0</td>
</tr>
<tr>
<td>Ho-165</td>
<td>n,γ</td>
<td>Ho-166m</td>
<td>β⁻, γ, X</td>
<td>1 200</td>
<td>100</td>
</tr>
</tbody>
</table>
TABLE VII. RADIOACTIVE INVENTORY OF A TYPICAL WWER 440 (GREIFSWALD UNIT 1) FOR MAJOR COMPONENTS [3]

<table>
<thead>
<tr>
<th>Components</th>
<th>Radioactivity (Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor pressure vessel</td>
<td>1.0E+14</td>
</tr>
<tr>
<td>Reactor tube system</td>
<td>9.4E+14</td>
</tr>
<tr>
<td>Fuel assembly basket</td>
<td>1.0E+16</td>
</tr>
<tr>
<td>Reactor cavity with core bottom</td>
<td>2.0E+15</td>
</tr>
<tr>
<td>Annular water tank</td>
<td>7.0E+12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.3E+16</strong></td>
</tr>
</tbody>
</table>

Assumptions: 1350 MW(th), 17 years of irradiation, 9 EFPY (approx.), 6 years after shutdown.
TABLE XII. RADIOACTIVE INVENTORY OF TRINO PWR (ITALY) [3]

<table>
<thead>
<tr>
<th>Radionuclides</th>
<th>Activity (Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-55</td>
<td>3.01E+15</td>
</tr>
<tr>
<td>Co-60</td>
<td>1.89E+15</td>
</tr>
<tr>
<td>Ni-63</td>
<td>7.26E+14</td>
</tr>
<tr>
<td>Mn-54</td>
<td>2.81E+13</td>
</tr>
<tr>
<td>Ni-59</td>
<td>5.97E+12</td>
</tr>
<tr>
<td>H-3</td>
<td>3.73E+12</td>
</tr>
<tr>
<td>Cs-134</td>
<td>4.63E+12</td>
</tr>
<tr>
<td>Ar-39</td>
<td>8.55E+12</td>
</tr>
<tr>
<td>Ag-108m</td>
<td>4.20E+11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.7E+15</strong></td>
</tr>
</tbody>
</table>

Assumptions: 870 MW(th), 23 years of irradiation, 10.6 EFPY, 5 years after shutdown.
The principal activation products present in reactor materials at shutdown are \(^{55}\text{Fe},^{60}\text{Co},^{59}\text{Ni},^{63}\text{Ni},^{39}\text{Ar},^{94}\text{Nb}\) (in steels); \(^{3}\text{H},^{14}\text{C},^{41}\text{Ca},^{55}\text{Fe},^{60}\text{Co},^{152}\text{Eu},^{154}\text{Eu}\) (in reinforced concretes) and \(^{3}\text{H},^{14}\text{C},^{152}\text{Eu}\) and \(^{154}\text{Eu}\) (in graphites). In terms of radiation levels, \(^{60}\text{Co}\) is the most predominant radionuclide. For steels, \(^{55}\text{Fe}\) and \(^{60}\text{Co}\) account for the major part of the inventory in the first ten years after shutdown. In the following 50 years, most of this activity has decayed, leaving the longer lived nickel, niobium and silver isotopes to dominate. For graphites and concretes, the short term decay is dominated by \(^{3}\text{H}\), leaving the longer lived \(^{14}\text{C},^{41}\text{Ca}\) and Eu isotopes to dominate in the longer term. After decay periods of more than 100 years, sufficient gamma activity from trace rare earth elements (e.g. Eu) is present to warrant the adoption of semiremote dismantling methods for reactor bioshields.
FIG. 3. Calculated decay of principal radionuclides (Trino NPP).

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RELATIVE IMPORTANCE OF RADIONUCLIDES WITH TIME
VVER 500 Armenian NPP - calculated

FIG. 1-6-2. Decay of calculated total activity of main radionuclides in the reactor pressure vessel of WWER 500 [9]. Assumptions: average power 1800 MW(th), 50 years of irradiation.

FIG. 1-6-3. Decay of calculated total activity of main radionuclides in the concrete bioshield of WWER 500 [9]. Assumptions: average power 1800 MW(th), 50 years of irradiation.
PARAMETERS INFLUENCING THE RADIONUCLIDE INVENTORY

For all reactor types, the radionuclide composition of activated and contaminated materials may vary within a very wide range.

The most important factors and parameters are:

- the neutron fluence,
- the duration of the operation,
- the time elapsed after reactor shutdown.
- Reactor type, design, power level and shutdown period;
- Composition of construction materials, including trace elements;
- Operational parameters, e.g. chemistry of the heat transfer medium, and maintenance;
- Unplanned events.
NEUTRON ACTIVATION ASSESSMENT (DT)
Updated INRNE Methodology

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NEUTRON ACTIVATION ASSESSMENT (DT)

In comparison with discussed in [3] is updated by

- 3D transport codes application
- EASY code implementation (appropriate ORIGEN alternative)

Tasks for further improvement:

- XS libraries generation appropriate for thermal neutrons energy range
- Methodology benchmarking (based on JPDR data [1]) for methodology verification/validation
- International collaboration improvement
- FFP approach implementation
General Conclusions

✓ The RD methodology developed in the Institute for Nuclear Research and Nuclear Energy of Bulgarian Academy of Science for Surveillance Program at NPP is on the state of the art level

✓ This methodology could be modified for the decommissioning purposes

✓ Tasks for the further methodology improvement are determined

✓ Application of FFP approach should be very useful for NPP problems management
Thank you