Spent fuel characterisation Program for the Implementation of Repositories

WP2 & WP4

Development of measurement methods and techniques to characterise spent nuclear fuel

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Interim storage or final disposal of spent nuclear fuel

Characterisation of Spent Nuclear Fuel (SNF) is required for a safe, secure and economic storage and disposal.

Main observables of interest:

- Decay heat
- Neutron and gamma-ray emission
- Reactivity
**Quality of predicted observables** depends on:

- Quality of the **calculation methods** (codes + nuclear data)
- Quality of the **irradiation history** + **engineering details** of the SNF

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**Decay heat / mW**

- **Time / year**
  - $10^{-1}$
  - $10^{0}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$

**Neutron emission rate / s$^{-1}$**

- **Time / year**
  - $10^{0}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$

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**PWR UO$_2$ pellet**

- $^{235}$U/U = 4.8 %
- $m(U) = 4.4$ g
- Burnup = 44 GWd/tU
Present status: e.g. decay heat

Experiments on PWR at CLAB (1998)
Different codes (cal3 = SIEMENS)

Calorimeter at CLAB

\[
\frac{P_{\text{cal}1}}{P_{\text{exp}}} = 1.03 \pm 0.06
\]

\[
\frac{P_{\text{cal}2}}{P_{\text{exp}}} = 0.97 \pm 0.03
\]

\[
\frac{P_{\text{cal}3}}{P_{\text{exp}}} = 0.91 \pm 0.03
\]
Present status: e.g. decay heat

Calorimeter at CLAB

Experiments at CLAB (2003 - 2004)
Calculations: ORIGEN-S

\[
P_{\text{cal}} / P_{\text{exp}} = 1.00 \pm 0.04
\]

\[
P_{\text{cal}} / P_{\text{exp}} = 1.02 \pm 0.02
\]
Present status: e.g. decay heat

Calorimeter at CLAB

Calculations: ORIGEN-S

\[
P_{\text{cal}} / P_{\text{exp}} (1998) = 0.97 \pm 0.03
\]

\[
P_{\text{cal}} / P_{\text{exp}} (2003 - 2004) = 1.02 \pm 0.02
\]
Objective:

Develop **innovative Non-Destructive Analysis (NDA)** techniques and **improve existing** ones for the characterization of **Spent Nuclear Fuel (SNF)**, to:

- Reduce bias effects and uncertainties of experimental data
- Validate & improve theoretical models (including nuclear data)
- Verify irradiation histories and improve incorrect data
- Define correlation procedures between observables e.g. gamma-ray ⇔ heat

Separation between WP2 & WP4: logistic reasons

**WP2**: radionuclide sealed sources and reference materials

**WP4**: highly radioactive irradiated nuclear material
WP2 & WP4

• Develop, improve and validate **NDA** techniques to **directly** measure
  – decay heat
  – neutron emission
  – gamma-ray emission
  – reactivity
  – nuclide vector

  **avoiding** complex and time consuming **chemical analysis**

• Make use of other efforts:
  – Next Generation Safeguards Initiative (NGSI) of DOE/NNSA
  – EURATOM/DOE/SKB agreement (Action Sheet -50)
  – JAEA/JRC collaboration agreement (characterisation of melted fuel by NDA)
  – FP7 project: First Nuclides
  – International projects: ARIANE, MALIBU, REGAL
Example: decay heat

Improve fundamental understanding of measurement process
Identify the main metrological parameters, e.g. source terms

PWR UO₂ pellet

\(^{235}\text{U}/\text{U} = 4.8\% \\
m(\text{U}) = 4.4 \text{ g} \\
\text{Burnup} = 44 \text{ GWd/tU}
Example: decay heat

Cooling time: \( 5 \text{ y} < t < 50 \text{ y} \) (\( \beta^- \) decay of FP)

- Fission yields
- Specific heat FP: e.g. \(^{90}\text{Sr}/Y\) and \(^{137}\text{Cs}/\text{Ba}\)

*Specific power* \( \mu \text{W/GBq} \)

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<tbody>
<tr>
<td>(^{90}\text{Sr})</td>
<td>31.4</td>
<td>27.2</td>
<td>JEF-2.2</td>
</tr>
<tr>
<td>(^{90}\text{Y})</td>
<td>150.0</td>
<td>148.0</td>
<td>149.5</td>
</tr>
<tr>
<td>(^{90}\text{Sr}/^{90}\text{Y})</td>
<td>183.0 ± 2.7</td>
<td>181.4</td>
<td>175.2</td>
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Example: decay heat

Cooling time: 10 y < t \quad (^{241}\text{Am and } ^{238,239,240}\text{Pu})
- Production: $\sigma(n,\gamma)$ and $\sigma(n,f)$
- Specific heat

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<tr>
<th>Nuclide</th>
<th>Specific power $\mu W / \text{GBq}$</th>
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<tr>
<td>$^{241}\text{Am}$</td>
<td>900.3 ± 3.5</td>
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<tr>
<td>$^{238}\text{Pu}$</td>
<td>896.2 ± 0.5</td>
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<tr>
<td>$^{239}\text{Pu}$</td>
<td>840.4 ± 1.1</td>
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<tr>
<td>$^{240}\text{Pu}$</td>
<td>843.1 ± 1.1</td>
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Example: neutron emission

Identify metrological parameters of the measurement process

![Graph showing neutron emission rate over time for different isotopes.](image)

- **Total**
- *(s.f)*
- *(α,n)*

**PWR UO₂ pellet**

- ²³⁵U/U = 4.8 %
- m(U) = 4.4 g
- Burnup = 44 GWd/tU
NDA methods: improve & refine existing NDA technique

Fuel assemblies

- **Decay heat**
  - Calorimetry
  - Gamma-ray spectrum

- **Gamma-ray emission**
  - Tomography
  - Gamma-ray spectrometry

- **Reactivity (collaboration with LANL, Action Sheet-50)**
  - Differential Die-Away (DDA)
  - Differential Die-Away Self-Interrogation (DDSI)
NDA methods: innovative NDA techniques

Fuel assemblies

• Radiation hard neutron detector (Diamond technology)
  – Miniature detector (control channels)
  – Stand-alone
  – Integrated in e.g. DDA, DDSI, SINRD

• Gamma-ray detectors: LaBr, CeBr, CZT
  – Spectrometry
  – Tomography

• Reactivity
  – Self-Interrogation Neutron Resonance Densitometry (SINRD) (SCK•CEN)
Small samples

- **Direct NDA measurement of observables (outside hot cell)**
  - Heat, neutron, gamma-ray, nuclide vector
  - Transport sample from hot cell to device
  ⇒ Avoid chemical analysis

- **Use of well-characterised samples with documented history**
  - FP7: First Nuclides
  - REGAL project organised by SCK•CEN
NDA methods: innovative NDA techniques

Small samples

• **Proof- of-principle: neutron output**
  – Direct related to Cm-quantity

• **Final objective**
  – Neutron and gamma-ray emission
  – Heat by calorimetry (including existing solutions)
  – Nuclide vector by Neutron Resonance Transmission Analysis (NRTA)
Facilities

Small samples

SCK•CEN

Fuel assemblies

- NPP Preussen Elektra
- CLAB –Sweden
Facilities: SCK•CEN (Mol, Belgium)

Small samples

- **Small sample objective**
  - Test calculation models on well-defined samples
  - Measurement of nuclear data (specific heat)

- **Samples from previous & ongoing projects**
  - Profit from the FP7 “First Nuclides” project
  - Well-known radiation history
  - Radio-chemically analysed
  - Sliced pellet sample available
  - Solute samples available
Facilities: SCK•CEN (Mol, Belgium)

Small samples • Analysis of encapsulated spent fuel samples (e.g. 3 pellets)
NDA methods: improve & refine existing NDA technique

Fuel assemblies

Measurements on a wide variety of SFA (BU, IE, CT)
• Define realistic performance values (uncertainties)
• Define correlation schemes between different observables
• Use NDA results to improve irradiation histories
Fuel assemblies

- Fuel pool inside reactor building holds ~ 700 fuel assemblies in each plant
Facilities: Preussen Elektra (NPP-site, Germany)

Fuel assemblies

- Fuel is loaded into dry storage casks after about 5 - 10 years of shutdown cooling for interim storage
Facilities: Preussen Elektra (NPP-site, Germany)

- Example plant 1 (18x18) spent fuel inventory in pool
- MOX and UOX
- BU: 50-60 MWd/kgU
- CT ~ 1 - 15 y
Facilities: Preussen Elektra (NPP-site, Germany)

- Example plant 2 (16x16) spent fuel inventory in pool
- UOX
- BU: 45-53 MWd/kgU
- CT ~ 1 -15 y
Facilities: CLAB (Oskarshamn, Sweden)

Fuel assemblies
- Central Interim Storage Facility for Spent Nuclear Fuel
- LWR fuel assemblies (~ 6300 t BWR and PWR fuel stored)
- Service pool with fuel handling machine
- Calorimeter (BWR and PWR fuel)
- $\gamma$-spectrometry scan equipment with collimator
- Experiences from earlier projects
- Approximate fuel properties:
  - 7 fuel types BWR
  - 7 fuel types PWR
  - BU range 10 - 55 GWD/tU
  - CT range (2) 5 - 30 y
  - IE range 2-5%
SKB: business case example

Encapsuation plant

- Optimisation of canister packing
  - Maximum decay heat criteria (~ 1 700 W)
  - Max. mean decay heat per assembly if equally distributed:
    - PWR ~ 425 W,
    - BWR ~ 142 W
  - ~ 6 000 canisters
- Cast iron inserts for
  - 4 PWR or
  - 12 BWR assemblies
SKB: business case example

- **Cost per canister**
  - \( \sim 1 \text{ M€} \)

- **SKB 50 decay heat**
  - BWR: mean CT = 17 y, mean decay heat = 165 W
  - PWR: mean CT = 18 y, mean decay heat = 590 W

- **Example**
  - 1% increase in number of canisters: 50 M€ in increased costs

Reduction in bias and uncertainty of decay heat will improve packing efficiency and reduce empty positions.
Thanks for your attention