ND-PIE on MTR fuel plates at SCK•CEN: a comparison with destructive analysis

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Fuel qualification programs for low enriched MTR-fuel

New ND-PIE instruments
have been developed at SCK•CEN
Introduction

Fuel qualification programs for low enriched MTR-fuel

BONAPARTE bench

Flat plate configuration

Curved plate configuration

Fuel plate/meat swelling
Introduction

Fuel qualification programs for low enriched MTR-fuel

BONAPARTE bench

Fuel plate/meat swelling [%]  →  Burn-up
Introduction

Fuel qualification programs for low enriched MTR-fuel

!!New at SCK•CEN!!

ND-PIE gamma spectrometry on full MTR plates to measure Burn-up

Average fuel plate burn-up = 39.84 %U235
Maximum fuel plate burn-up = 61.39 %U235
Fuel qualification programs for low enriched MTR-fuel

!!New at SCK•CEN!!

ND-PIE gamma spectrometry on full MTR plates to measure Burn-up

Need for validation
Introduction

Fuel qualification programs for low enriched MTR-fuel

!!New at SCK•CEN!!

ND-PIE gamma spectrometry on full MTR plates to measure Burn-up

radiochemical analysis

= Destructive-PIE

More accurate

Burn-up
Fuel qualification programs for low enriched MTR-fuel

!!New at SCK•CEN!!

ND-PIE gamma spectrometry on full MTR plates to measure Burn-up

radiochemical analysis
= Destructive-PIE

Burn-up
Basics of BU measurements by fission products

- Burn-up is a measure of how much the fuel has been utilized (fuel utilization) and be expressed in:

  - \( \frac{N_f}{N_i} \) [%]: FIMA, number of Fissions per Initial heavy Metal Atoms

  - \( \frac{N_f}{N_{fissile}} \) [%]: FIFA, number of Fissions per Initial Fissile Atoms

  - \( \frac{N_f}{V} \) [fissions/cm\(^3\)]: fission density, number of fissions per volume fuel

  - \( \frac{E_r}{m_{iHM}} \) [GWd/t\(_{HM}\)]: energy released per initial heavy metal mass

  - Others: \( \frac{N_f}{L} \) (fuel rod), \( \frac{N_f}{A} \) (fuel plates),...
Basics of BU measurements by fission products

On condition:

- FP is stable, or has a $T_{1/2}$ long enough so it is representative for the irradiation history and still present after cooling time
- Measurable so it can be quantified ($\gamma$-spect, radiochemical analysis)
- Amount of FP ~ number of fission $N_f$ (proportional)

- ND-PIE $\gamma$-spectrometry: Cs-137
- D-PIE radiochemical analysis: Nd-143+Nd-144, Nd145+Nd-146, Nd-148, Nd-150, Cs-137, Ce-144
ND-PIE gamma spectrometry - System

- Rotatable chuck originally designed for fuel pins
- In-cell collimator
ND-PIE gamma spectrometry - System

- High purity Ge-detector
- 20% efficiency Cryo pulse cooling
ND-PIE gamma spectrometry - System

Positioning device for flat plates developed
- different size of fuel plates
- Mapping: moving in X & Y over collimator

New DENAL collimator 3x3mm
- Field of view 5x5mm
ND-PIE gamma spectrometry - System

Positioning device for curved plates developed
- different size and curvatures of fuel plates
- Mapping: moving in X & θ over collimator

New DENAL collimator 3x3mm
- Field of view 5x5mm
ND-PIE gamma spectrometry - Efficiency calibration

Development and certification of new calibration sources
- Dedicated holders
ND-PIE gamma spectrometry - Efficiency calibration

Development and certification of new calibration sources
- Dedicated holders
- Spent fuel plate sections
- Certified by radiochemical analysis of adjacent section
  - Flat plate: $8.29 \times 10^9$ Bq Cs-137 at 2010/10/19
  - Curved plate: $1.22 \times 10^{10}$ Bq Cs-137 at 2005/05/13
ND-PIE gamma spectrometry - Efficiency calibration

Development and certification of new calibration sources

- Dedicated holders
- Spent fuel plate sections
- Certified by radiochemical analysis of adjacent section
  - Flat plate: $8.29 \times 10^9$ Bq Cs-137 at 2010/10/19
  - Curved plate: $1.22 \times 10^{10}$ Bq Cs-137 at 2005/05/13

Efficiency calibration $\left[ \frac{counts}{\gamma \ mm^2} \right]$
ND-PIE gamma spectrometry - BU analyse

Mapping by line scans

Counts

Analyse of 600 $\gamma$ energy spectra:
Net peak area Cs-137 662keV (counts)
ND-PIE gamma spectrometry - BU analyse

Mapping by line scans

Counts

Efficiency calibration

\[ \frac{\text{counts}}{\text{mm}^2} \]

Calculate BU in

\[ \frac{N_f}{A} \]

[Fissions/mm\(^2\)]
ND-PIE gamma spectrometry - BU analyse

\[ \frac{N_f}{A} = I_{137\text{Cs}_{662\text{keV}}} \times \frac{C_{\text{decay o_pile}_{137\text{Cs}}} \times C_{\text{decay i_pile}_{137\text{Cs}}} \times C_{\text{absorption}_{662\text{keV}}}}{\varepsilon_{662\text{keV}} \times P_{137\text{Cs}_{662\text{keV}}} \times \lambda_{137\text{Cs}} \times FY_{\text{fuel flux composition}_{137\text{Cs}}}} \times \left( \frac{\text{fission}}{\text{mm}^2} \right) \]

- \( I_{137\text{Cs}_{662\text{keV}}} \): the intensity of the \(^{137}\text{Cs} 662\text{keV} \) gamma peak \([\text{counts/s}]\) 
- \( C_{\text{decay o_pile}_{137\text{Cs}}} \): \(^{137}\text{Cs} \) out-pile decay correction from the measurement date to EOI date \(1\%\)
- \( C_{\text{decay i_pile}_{137\text{Cs}}} \): \(^{137}\text{Cs} \) in-pile decay correction during irradiation \(1\%\)
- \( C_{\text{absorption}_{662\text{keV}}} \): the correction for gamma ray absorption in the fuel plate \(2\%\)
- \( \varepsilon_{662\text{keV}} \): the detection efficiency (detector and geometry) at 662keV in \([\text{counts.mm}^2/\text{γ}]\) 
- \( P_{137\text{Cs}_{662\text{keV}}} \): \(^{137}\text{Cs} 662\text{keV} \) gamma emission probability \([\text{γ desintegration}]\) 
- \( \lambda_{137\text{Cs}} \): \(^{137}\text{Cs} \) decay constant \([\text{Bq}/N_{137\text{Cs}_{\text{atoms}}}]\) 
- \( FY_{\text{fuel flux composition}_{137\text{Cs}}} \): \(^{137}\text{Cs} \) fission yield, based on fuel and flux composition \([N_{137\text{Cs}_{\text{atoms}}}/N_f]\) 

Estimated uncertainty \(2\sigma\) 7.6%
D-PIE Radio Chemical Analysis - BU analyse

Uncertainty 2σ

- $^{143}\text{Nd} + ^{144}\text{Nd}$
  - $N_f$ in the sample
  - 2%-3%

- $^{145}\text{Nd} + ^{146}\text{Nd}$
  - $N_f$ in the sample
  - 2%-3%

- $^{148}\text{Nd}$
  - $N_f$ in the sample
  - 2%-3%

- $^{150}\text{Nd}$
  - $N_f$ in the sample
  - 2%-3%

- $^{137}\text{Cs}$
  - In & out pile decay
  - 4%-5%

- $^{144}\text{Ce}$
  - In & out pile decay
  - 4%-5%

$<N_f>$ in the sample

Uncertainty 2σ

2% – 3%
Comparison BU

ND-PIE $\gamma$-spectrometry

\[ \frac{N_f}{A} \text{ [fissions/mm}^2\text{]} \]

D-PIE radiochemical analysis

\[ \frac{N_f}{m} \text{ [fissions/g]} \]

?? Surface A of the radiochemical sample ??

Not measured accurately for standard procedure
Comparison BU

ND-PIE γ-spectrometry

\[ \frac{N_f}{A} \text{ [fissions/mm}^2\text{]} \quad 2\sigma \quad 7.6\% \]

[%] FIMA ND-PIE \( \frac{N_f}{N_i} \) 9%

\[ \frac{N_f}{N_i} = \frac{N_f}{A} \cdot \frac{A_{fuel}}{N_{i,fuel}} \]

\( \frac{N_{i,fuel}}{A_{fuel}} \): initial heavy metal atoms per fuel meat surface 5%

D-PIE radiochemical analysis

\[ \frac{N_f}{m} \text{ [fissions/g]} \]

[%] FIMA D-PIE \( \frac{N_f}{N_i} \) 2% - 3%

\[ \frac{N_f}{N_i} = \frac{N_f}{N_f+N_e} \]

\( N_e \): heavy metal atoms at end of irradiation from radiochemical analysis
Comparison BU - Samples

- **Sample 1 & 2**
  - $U_3Si_2$ dispersion fuel
  - $^{235}\text{U}/\text{U}$: 27%
  - Estimated BU: 20% FIMA

- **Sample 3**
  - UMo dispersion fuel
  - $^{235}\text{U}/\text{U}$: 20%
  - Estimated BU: 10% FIMA

- **Sample 4**
  - $\text{UAI}_2$ dispersion fuel
  - $^{235}\text{U}/\text{U}$: 20%
  - Estimated BU: 1.5% FIMA

---

**DEVIATION [%] = \frac{\text{FIMA}_N\_\text{DPIE}}{\text{FIMA}_D\_\text{PIE}} - 1**

- FIMA_N_DPIE: Non-destructive gamma spectrometry
- FIMA_D_PIE: Destructive radiochemical analysis
Comparison BU - Results

Deviation ND-PIE gamma spectrometry towards D-PIE radiochemical analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>-4.3</td>
</tr>
<tr>
<td>4</td>
<td>-1.2</td>
</tr>
</tbody>
</table>
Comparison BU - Results

Deviation ND-PIE gamma spectrometry towards D-PIE radiochemical analysis

\[ \text{DEV} = \frac{\text{FIMA ND-PIE}}{\text{FIMA D-PIE}} - 1 \]

Estimated error +/- 9% (2s)

Deviation [%]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.2</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

+/− error (2s) D-PIE radiochemical analysis
Comparison BU - Results

Deviation ND-PIE gamma spectrometry towards D-PIE radiochemical analysis

Bias deviation: -0.6%
Spread deviation 2s: 7.5%

Estimated error +/-9% (2s) is a slightly over-estimation
Comparison BU – Results fuel rods

Deviation ND-PIE gamma spectrometry towards D-PIE radiochemical analysis

\[
\text{DEVIATION} [%] = \frac{FIMA_{ND\_PIE}}{FIMA_{D\_PIE}} - 1
\]

Estimated error +/- 5.8% (2s)
Comparison BU – Results fuel rods

Deviation ND-PIE gamma spectrometry towards D-PIE radiochemical analysis

Bias deviation: -0,6%
Spread deviation 2s: 5,3%

Estimated error +/-5,8% (2s) is a good estimation
Comparison BU – Conclusions

- Estimated error on the ND-PIE gamma spectrometry % FIMA:
  - $2s = 9\%$ slightly overestimated
  - $2s = 7.5\%$ new proposed estimated error (preliminary, only 4 samples)
- Largest sources of error which could be improved:
  - Certification of the standards: 5.8% ($2s$)
  - Fuel meat area determination, estimated error 5% ($2s$)
Comparison BU – Conclusions

- Results on MTR-fuel plates towards fuel rods:
  - Spread of the deviation towards radiochemical analysis:
    - MTR-fuel plates: 7.5% (2s), only 4 samples
    - Fuel rods: 5.3% (2s)
  - No significant bias towards radiochemical analysis

- For future validation samples and comparison study:
  - Measure the surface of the sample accurately after cutting the sample
  - Re-measure the sample after cutting, with ND-PIE gamma spectrometry prior to radiochemical analyses: no need for surface value determination, exclude the 5% error source
Acknowledgement

Many thanks to my colleagues

- Ivan Fets for the nice technical graphics
- Lesley Adriaensen & Mireille Gysemans for the support on the radiochemical analyses
- Ann Leenaers, Sven Van den Berghe & Marc Verwerft for the nice discussions and ideas on handling the data
ND-PIE on MTR fuel plates at SCK•CEN: a comparison with destructive analysis
Fuel qualification programs for low enriched MTR-fuel

BONAPARTE bench
(Bench for Non-destructive Analysis of Plate and Rod Type fuel Elements)

Fuel plate/meat swelling
by mapping plate thickness and outer oxide layer
Introduction

Fuel qualification programs for low enriched MTR-fuel

BONAPARTE bench

Fuel pin configuration
Content

- Basics of BU measurement by Fission Products (FP)
- Explanation of ND-PIE gamma spectrometry BU measurement system at LHMA
- Brief explanation of D-PIE radiochemical BU analysis
- Comparison of results of both techniques (validation purposes)
- Discussion and conclusions
Neodymium as burn-up indicator:

- Nd-143 + Nd-144, Nd-145 + Nd-146, Nd-148, Nd-150
- “Stable” radionuclides, non-volatile
- Fission yield (atoms/ fission) well known
- Nd-148 ASTM E321-69 reference for burn-up
  - But: Nd-147 (n,γ) Nd-148 is high for MTR with high flux
  - Nd-147 T1/2 only 10.98 days
  - Nd-148: 10% BU overestimation in case of BR2 irradiations
Basics of BU measurements by fission products

- Cs-137 as burn-up indicator,
  - $T_{1/2} = 30.17y$
    - Need for decay correction (in-pile, out-pile)
    - Suited for long irradiations over several years
  - $\gamma$-emission probability 0.852
  - $E_\gamma = 662\text{keV}$-easy measurable
  - Cs-137 is to a very good approximation ~ BU
  - But: volatile!
Basics of BU measurements by fission products

- Ce-144 as burn-up indicator,
  - $T_{1/2}=284.8 \text{d}$
    - Need for decay correction (in-pile, out-pile)
    - Not suited for long irradiations
  - $\gamma$-emission probability 0.1083
  - $E_\gamma = 80 \text{keV}-133.5 \text{keV}$-easy measurable
  - Ce-144 $\sim$ BU
ND-PIE gamma spectrometry - System

- Open channel through hot cell floor with Al-sealing at bottom
ND-PIE gamma spectrometry - System

- High purity Ge-detector
- 20% efficiency Cryo pulse cooling
ND-PIE gamma spectrometry - BU analyse

\[
\frac{N_f}{A} = I_{^{137}Cs_{662keV}} \cdot \frac{C_{\text{decay}_{o\_pile\_^{137}Cs}} \cdot C_{\text{decay}_{i\_pile\_^{137}Cs}} \cdot C_{\text{absorption}_{662keV}}}{\varepsilon_{662keV} \cdot P_{^{137}Cs_{662keV}} \cdot \lambda_{^{137}Cs} \cdot F_{Y_{fuel\_flux\_composition}}} \frac{fission_{mm^2}}{7.6\%}
\]

Estimated uncertainty 2 \( \sigma \)

Propagation of uncertainties

<table>
<thead>
<tr>
<th>Addition/Subtraction</th>
<th>( z = x \pm y )</th>
<th>( \Delta z = \sqrt{(\Delta x)^2 + (\Delta y)^2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplication</td>
<td>( z = xy )</td>
<td>( \Delta z =</td>
</tr>
<tr>
<td>Division</td>
<td>( z = \frac{x}{y} )</td>
<td>( \Delta z = \left</td>
</tr>
<tr>
<td>Power</td>
<td>( z = x^n )</td>
<td>( \Delta z =</td>
</tr>
<tr>
<td>Multiplication by a Constant</td>
<td>( z = cx )</td>
<td>( \Delta z =</td>
</tr>
<tr>
<td>Function</td>
<td>( z = f(x,y) )</td>
<td>( \Delta z = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial f}{\partial y}\right)^2 (\Delta y)^2} )</td>
</tr>
</tbody>
</table>

Addition/Subtraction: \( 3\% \)  
Multiplication: \( 1\% \)  
Division: \( 2\% \)  
Power: \( 6.3\% \)  
Multiplication by a Constant: \( 1\% \)  
Function: \( 1\% \)
\[ \varepsilon_{662\text{keV}} = I_{\text{surface}}^{\text{Cs}_662\text{keV}} \cdot \frac{C_{\text{decay}}^{\text{Cs}_{137}}} {P_y^{\text{Cs}_662\text{keV}}} \cdot \frac{C_{\text{absorption}}^{\text{Cs}_{662\text{keV}}}} {A_{\text{certificate}}^{\text{Cs}_{137}}} \left[ \frac{\text{counts.mm}^2} {\gamma} \right] \]

- \( I_{\text{surface}}^{\text{Cs}_662\text{keV}} \) the \( ^{137}\text{Cs} 662\text{keV} \) gamma peak intensity integrated over the surface of the standard [counts.mm\(^2\)/s]
- \( C_{\text{decay}}^{\text{Cs}_{137}} \) \( ^{137}\text{Cs} \) decay correction from the measurement date to certificate date 0,1%
- \( C_{\text{absorption}}^{\text{Cs}_{662\text{keV}}} \) the correction for gamma ray absorption in the standard 2%
- \( P_y^{\text{Cs}_662\text{keV}} \) \( ^{137}\text{Cs} 662\text{keV} \) gamma emission probability [\( \gamma \text{ desintegration} \)] 1%
- \( A_{\text{certificate}}^{\text{Cs}_{137}} \) \( ^{137}\text{Cs} \) activity of the standard at certificate date [Bq] 5,8%

Estimated uncertainty 2 \( \sigma \) 6,3%
D-PIE Radio Chemical Analyses - BU analyse

fuel+cladding

Dissolution sample 8 M nitric acid + Hg(II) reflux

Filtration I

Filtrate A

Dissolution residue 10 M nitric acid + hydrofluoric acid reflux

residue

Filtration II

Filtrate B

Vo solution for analyses
D-PIE Radio Chemical Analyses - BU analyse

Dissolution fuel $V_0$

Dilutions $V_0-V_1$

**ALIQUOT A**

- $\alpha$-spec
  - $^{244}$Cm
  - $^{242}$Cm
  - $^{238}$Pu, $^{241}$Am
  - $^{239}$Pu, $^{240}$Pu
  - $^{137}$Cs
  - $^{144}$Ce
  - $^{134}$Cs
  - $^{154}$Eu
  - $^{155}$Eu
  - $^{241}$Am

- $\gamma$-spec

**ALIQUOT B**

Isotopic analyses

3-column separation $U/Pu$

$Nd$

**ALIQUOT C**

Isotopic dilutions

+ spikes $^{233}$U, $^{242}$Pu, $^{146}$Nd

3-column separation $U/Pu$

$Nd$

TIMS

Isotopic composition

TIMS

Concentrations
Comparison BU - Results

Averaging, Errors and Uncertainty

Repeated measurements allow you to not only obtain a better idea of the actual value, but also enable you to characterize the uncertainty of your measurement. Below are a number of quantities that are very useful in data analysis. The value obtained from a particular measurement is \( x \). The measurement is repeated \( N \) times. Oftentimes in lab \( N \) is small, usually no more than 5 to 10. In this case we use the formulae below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ( (x_{\text{avg}}) )</td>
<td>The average of all values of ( x ) (the “best” value of ( x ))</td>
</tr>
<tr>
<td>Range ( (R) )</td>
<td>The “spread” of the data set. This is the difference between the maximum and minimum values of ( x ).</td>
</tr>
<tr>
<td>Uncertainty in a measurement ( (\Delta x) )</td>
<td>Uncertainty in a single measurement of ( x ). You determine this uncertainty by making multiple measurements. You know from your data that ( x ) lies somewhere between ( x_{\text{max}} ) and ( x_{\text{min}} ).</td>
</tr>
<tr>
<td>Uncertainty in the Mean ( (\Delta x_{\text{avg}}) )</td>
<td>Uncertainty in the mean value of ( x ). The actual value of ( x ) will be somewhere in a neighborhood around ( x_{\text{avg}} ). This neighborhood of values is the uncertainty in the mean.</td>
</tr>
<tr>
<td>Measured Value ( (x_m) )</td>
<td>The final reported value of a measurement of ( x ) contains both the average value and the uncertainty in the mean.</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
x_{\text{avg}} &= \frac{x_1 + x_2 + \cdots + x_N}{N} \\
R &= x_{\text{max}} - x_{\text{min}} \\
\Delta x &= \frac{R}{2} = \frac{x_{\text{max}} - x_{\text{min}}}{2} \\
\Delta x_{\text{avg}} &= \frac{\Delta x}{\sqrt{N}} = \frac{R}{2\sqrt{N}} \\
x_m &= x_{\text{avg}} \pm \Delta x_{\text{avg}}
\end{align*}
\]
ND-PIE gamma spectrometry - BU analyse fuel rods

\[
\frac{N_f}{L} = I_{137\text{Cs,662keV}} \cdot \frac{C_{\text{decay, o pile, 137Cs}} \cdot C_{\text{decay, i pile, 137Cs}} \cdot C_{\text{absorption, 662keV}}}{\epsilon_{662\text{keV}} \cdot P_{137\text{Cs,662keV}} \cdot \lambda_{137\text{Cs}} \cdot FY_{\text{fuel flux composition, 137Cs}}} \quad \left[ \frac{\text{fission}}{\text{mm}} \right]
\]

- \( I_{137\text{Cs,662keV}} \): the intensity of the \(^{137}\text{Cs}\) 662keV gamma peak \([\text{counts} / \text{s}]\)

- \( C_{\text{decay, o pile, 137Cs}} \): \(^{137}\text{Cs}\) out-pile decay correction from the measurement date to EOI date

- \( C_{\text{decay, i pile, 137Cs}} \): \(^{137}\text{Cs}\) in-pile decay correction during irradiation

- \( C_{\text{absorption, 662keV}} \): the correction for gamma ray absorption in the fuel rod

- \( \epsilon_{662\text{keV}} \): the detection efficiency (detector and geometry) at 662keV in \([\text{counts.mm} / \gamma]\)

- \( P_{137\text{Cs,662keV}} \): \(^{137}\text{Cs}\) 662keV gamma emission probability \([\gamma / \text{desintegration}]\)

- \( \lambda_{137\text{Cs}} \): \(^{137}\text{Cs}\) decay constant \([\text{Bq} / \text{N}_{137\text{Cs}\ \text{atoms}}]\)

- \( FY_{\text{fuel flux composition, 137Cs}} \): \(^{137}\text{Cs}\) fission yield, based on fuel and flux composition \([\text{N}_{137\text{Cs}\ \text{atoms}} / N_f] \)

Estimated uncertainty 2 \( \sigma \)

<table>
<thead>
<tr>
<th>Term</th>
<th>Estimated uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{137\text{Cs,662keV}} )</td>
<td>2%</td>
</tr>
<tr>
<td>( C_{\text{decay, o pile, 137Cs}} )</td>
<td>1%</td>
</tr>
<tr>
<td>( C_{\text{decay, i pile, 137Cs}} )</td>
<td>1%</td>
</tr>
<tr>
<td>( C_{\text{absorption, 662keV}} )</td>
<td>2%</td>
</tr>
<tr>
<td>( \epsilon_{662\text{keV}} )</td>
<td>4.6%</td>
</tr>
<tr>
<td>( P_{137\text{Cs,662keV}} )</td>
<td>1%</td>
</tr>
<tr>
<td>( \lambda_{137\text{Cs}} )</td>
<td>1%</td>
</tr>
<tr>
<td>( FY_{\text{fuel flux composition, 137Cs}} )</td>
<td>1%</td>
</tr>
</tbody>
</table>
ND-PIE gamma spectrometry - BU analyse fuel rods

Table 14-3: Bias and uncertainties on derived quantities using BUX efficiency

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured count rate</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
</tr>
<tr>
<td>Certificate</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>Efficiency BUX</td>
<td>+0% ±2.3%</td>
<td>+0% ±2.3%</td>
<td>+0% ±2.3%</td>
<td>+0% ±2.3%</td>
<td>+0% ±2.3%</td>
<td>+0% ±2.3%</td>
</tr>
<tr>
<td>透明性</td>
<td>-4% ±1%</td>
<td>-4% ±1%</td>
<td>-4% ±1%</td>
<td>-4% ±1%</td>
<td>-4% ±1%</td>
<td>-4% ±1%</td>
</tr>
<tr>
<td>Gamma emission probability</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
</tr>
<tr>
<td>Correction for decay between reference date and measurement date</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
</tr>
<tr>
<td>Convert activity at reference date to saturation activity</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
</tr>
<tr>
<td>Convert number of atoms at reference date to total number of atoms produced</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
</tr>
<tr>
<td>Conversion from activity to number of atoms</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
</tr>
<tr>
<td>Average number of atoms produced per fission</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
<td>+0% ±0.5%</td>
</tr>
<tr>
<td>Number of fission's to produce 1 eV</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
</tr>
<tr>
<td>eV to Joule conversion</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
</tr>
<tr>
<td>Joule to MWd conversion</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
<td>+0% ±0%</td>
</tr>
<tr>
<td>Atoms (Initial heavy element)</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
</tr>
<tr>
<td>Mass (Initial heavy element)</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
<td>+0% ±1%</td>
</tr>
<tr>
<td>Combined</td>
<td>-4% ±2.9%</td>
<td>-4% ±3.1%</td>
<td>-4% ±3.5%</td>
<td>-4% ±2.9%</td>
<td>-4% ±3.0%</td>
<td>-8% ±3.0%</td>
</tr>
</tbody>
</table>

(1) Included in the calculation.
(2) Uncertainty in decay constant included; irradiation history power uncertainties not included.
(3) Uncertainty in not included in actual calculation, bias is taken from R-3537 at 0.66166 MeV.