A Method of Measuring Decay Heat in Spent Nuclear Fuel using Gamma-ray Spectroscopy

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ABSTRACT

In this paper, a method is presented for determining the decay heat in spent nuclear fuel by using gamma-ray spectroscopy. Using this method, the decay heat may be determined within ten minutes per assembly i.e. it is well suited for industrial applications in, for example, an encapsulation facility. The method has been tested and evaluated in the wet Swedish Central Storage for Spent Fuel, CLAB. Although only tested in a wet storage, the method should also be applicable for dry storage.

The objective of developing the method was primarily to investigate possibilities to achieve a fast, robust and reasonable accurate determination of decay heat by gamma-ray measurements on fuel assemblies. Such a method could also be for verification of burnup and cooling time, for safeguard purposes prior to encapsulation, (1).

So far, measurements and calculations on 35 BWR- and 34 PWR-assemblies, with various nuclear data, have been performed. The test measurements, using preliminary measuring equipment, have shown that the decay heat may be determined within an uncertainty of 3%.

INTRODUCTION

The spent fuel from Swedish nuclear power plants is planned to be deposited in a deep geological storage, encapsulated in copper- and steel canisters and embedded in bentonite clay within the bedrock, (2). This approach requires that an upper limit for the maximum permissible temperature on the surface of the canisters is defined. As a consequence, the total thermal power developed in the spent fuel from radioactive decay is limited accordingly. In order to ensure that the limit is not exceeded, the need of a method to determine the decay heat of a spent fuel assembly has been identified. Such a method may be used alone or combined with calculations using suitable computer codes.

In this paper, a fast end reliable experimental method to determine the decay heat in spent fuel with a cooling time typically in the order of 40 years is presented. The method is based on gamma-ray measurements of the fission product $^{137}\text{Cs}$. In parallel an investigation has been performed in which the decay heat of fuel assemblies has been experimentally measured by calorimetry, (3,4). We show in the present investigation that the calorimetric data are strongly correlated with the intensity of the gamma radiation from decay of $^{137}\text{Cs}$. 
BASIC CONSIDERATIONS

SOURCES OF DECAY HEAT

After a nuclear reactor has been shut down and the fuel has been removed from the core, several nuclear processes continue to generate heat within the fuel matrix. Using the isotope generation and depletion computer code Origen-S, (5,6), the contributions to the decay heat from the various sources have been calculated as a function of cooling time and burnup. A number of nuclear fuel assemblies with different irradiation histories, burnups and cooling times, see table I, were calculated using this code. Some results are summarized in figures 1 and 2. A discussion on the various sources follows.

Table I: Span of fuel parameters used in the Origen-S simulations.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Burnup [GWd/tU]</th>
<th>Cooling time [y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWR 8x8</td>
<td>14 - 45</td>
<td>9 - 50</td>
</tr>
<tr>
<td>PWR 15x15</td>
<td>24 - 52</td>
<td>8 - 22</td>
</tr>
<tr>
<td>PWR 17x17</td>
<td>19 - 43</td>
<td>8 - 13</td>
</tr>
</tbody>
</table>

HEAVY ELEMENTS AND ACTINIDES

During irradiation of the nuclear fuel, various reactions such as (n,γ), (n,α) and (n,2n) reactions produce numerous heavy elements and actinides. Several actinides produced in reactor operation decay by means of spontaneous fission which contribute to the decay heat. This process releases neutrons that can further induce decay heat by neutron induced reactions. At the cooling times of interest (≈40y), the actinides contribute to about 40% of the total decay heat. This contribution increases slowly with time, see figure 1.

FISSION PRODUCTS

Some radioactive fission products are formed directly in the nuclear fission process, other nuclides may be produced as a result of neutron capture (n,γ) in the neighbouring isobar. After a cooling time of about 40 years, 30% of the total decay heat arises from the decay of ¹³⁷Ba+Cs. The rest of the fission products contributes with another 25%, see figure 1.

STRUCTURAL AND CLADDING MATERIALS

Neutron-induced reactions such as (n,α), (n,γ), (n,p) and (n,2n) in structural materials, e.g. in the fuel cladding, may produce radioactive elements. However, the contribution is relatively small at the cooling times of interest here. These contributions are therefore ignored in this paper.

DEPENDENCE ON VARIOUS FUEL PARAMETERS

An investigation was performed with regards to what extent the fuel parameters power history, initial ²³⁵U enrichment, burnup and cooling time influence the various contributions to the
Figure 1: Contributions to total decay heat calculated with Origen-S as a function of cooling time at a burnup of 37 GWD/tU and initial enrichment of 2.6%. The number of fuel cycles was 4. FP=Fission products, ACT=Actinides.

decay heat. This investigation was performed using the code Origen-S, (5). The contributions were first calculated for a standard case with a cooling time of 40 years, initial $^{235}$U enrichment of 2.6% and a burnup of 35 GWD/tU. Calculations were then made while varying the value of the fuel parameter of interest from the standard case. Also the number of power cycles was varied.

**COOLING TIME DEPENDENCE**

The cooling time dependence of the contributions to the total decay heat are shown in figure 1. The burnup was 37 GWD/tU in this case. The $^{137}$Cs+$^{137}$Ba contribution decreases about 15% relative when the cooling time increases from 20 years to 50 years. The corresponding $^{244}$Cm contribution increases by a factor of 2. In the region of around 40 years cooling time, the $^{137}$Cs+$^{137}$Ba contribution varies about two percent units for a change in cooling time of one decade.
Figure 2: Contributions to total decay heat calculated with Origen-S as a function of burnup at a cooling time of 40 years and initial enrichment of 2.6%. FP=Fission products, ACT=Actinides.

**BURNUP DEPENDENCE**

The influence of burnup of the fuel on various contributions to the decay heat is shown in figure 2. As seen in the figure, the contribution from $^{137}$Cs+$^{137}$Ba is constant within 14% relative for a change in burnup from 14 to 45 Gd/tU.

**OTHER DEPENDENCIES**

The initial $^{235}$U enrichment was varied between 1% and 4%. This span covers most LWR spent fuel in Sweden. The $^{137}$Cs+$^{137}$Ba contribution to the total decay heat changes from 28% to 33%, i.e. about 15% relative, in the enrichment range of 1 to 4%, corresponding to 1.7% per unit percent change in enrichment. The contribution of the actinide $^{244}$Cm changes about a factor of 10 for the same variation in the enrichment.

The change in power history of the spent fuel was made by changing the number of power cycles in the calculations. The initial enrichment was 3% in this case. The $^{137}$Cs+$^{137}$Ba contribution to the decay heat decreased with about 4% relative when the number of power cycles changed from 3 to 7. The small change is due to the relatively long half-lives of the isotopes of interest here.
EXPERIMENTAL METHOD

Non-destructive measurements of nuclear fuel are preferably performed by using either of two types of radiations: Neutrons or gamma radiation. As discussed above, gamma radiation from $^{137}$Cs is only weakly dependent on various fuel parameters and is thus well suited for measurements when information about the fuel is scarce or unavailable. The thermal power in the spent fuel may be determined using measurements of the $^{137}$Cs intensity as outlined below.

The heat produced in the decay of $^{137}$Cs is directly proportional to the activity ($A$) of $^{137}$Cs in the fuel: $^{137}P = k \cdot A$. $^{137}P$ may be written as $f \cdot P$ where $f$ is the fraction of the total decay heat ($P$) originating from the decay of $^{137}$Cs. Thus, $P = k \cdot A/f$. Further, assuming a homogenous $^{137}$Cs distribution, implying a proportionality between the total $^{137}$Cs activity and the measured $^{137}$Cs gamma intensity, the total decay heat can be expressed as

$$P = C \cdot \frac{I}{f}$$

where

- $P$ is the residual thermal power of the fuel assembly.
- $C$ is a calibration constant expressed in W/count/s specific for the measuring equipment used to measure the gamma intensity. This constant depends on the measuring geometry, fuel type and intrinsic detector parameters. $C$ includes the ratio between measured $^{137}$Cs intensity and the activity of $^{137}$Cs. It is determined in a calibration procedure is discussed in the results section.
- $I$ is the measured count rate in the $^{137}$Cs peak.
- $f$ is the fraction of the total thermal power in the fuel generated by the decay of $^{137}$Cs.

As can be seen in figures 1 and 2, the fraction of heat generated by the decay of $^{137}$Cs varies only weakly with cooling time and burnup for cooling times over about 12 years. This implies that for old fuel, the fraction of the heat generated from $^{137}$Cs may be approximated with a constant which can be corrected to first order using a linear interpolation using the declared values of the fuel parameters.

Figures 1-2 shows $f$ as a function of cooling time and burnup for BWR fuel and for various sources. From these figures, the assumption of linearity for $^{137}$Cs holds reasonably well for cooling times over 12 years and burnup over 15 GWd/tU for BWR fuel. 2-dimensional linear relations was established for $f$ as a function of burnup and cooling time. The relative standard deviation between the fitted plane and the points is 0.7% for cooling times between 12 and 20 years. The fit is expected to improve for spent fuel with longer cooling time than what was possible to measure in this study. For PWR fuel, both regarding a 15x15 and 17x17 pin lattice, simulations was performed in the same manner. Table II shows the resulting fitted planes for the three cases of BWR 8x8, PWR 15x15 and PWR 17x17 fuel. For simplicity, only the burnup and cooling time were considered as variables in this study. These parameters may be experimentally determined using the methods developed in (1).
Table II: Parameters and associated uncertainties of the fitted linear functions of \( f \) as a function of burnup (\( \beta \)) and cooling time (\( t \)). \( f = a + b \cdot \beta + c \cdot t \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BWR 8x8</th>
<th>PWR 15x15</th>
<th>PWR 17x17</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>4.32(2) ( \cdot 10^{-1} )</td>
<td>4.48(2) ( \cdot 10^{-1} )</td>
<td>4.48(4) ( \cdot 10^{-1} )</td>
</tr>
<tr>
<td>( b )  [( tU/MWd )]</td>
<td>( -2.73(3) \cdot 10^{-6} )</td>
<td>( -2.41(4) \cdot 10^{-6} )</td>
<td>( -2.43(8) \cdot 10^{-6} )</td>
</tr>
<tr>
<td>( c )  [1/y]</td>
<td>( 2.1(8) \cdot 10^{-4} )</td>
<td>( -1.35(8) \cdot 10^{-3} )</td>
<td>( -1.6(3) \cdot 10^{-3} )</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL PROCEDURES**

In this paper, the results from measurements on 69 spent nuclear fuel assemblies with cooling times ranging from about 5 to 20 years and burnups ranging from about 19 to 45 GWd/tU are reported. Table III summarizes the fuel parameters of the assemblies.

**GAMMA-RAY MEASUREMENTS**

The relative intensity of \( ^{137}\text{Cs} \) was measured using a high-resolution germanium detector with 40% relative efficiency. The system used for this measurement is described in detail in (1,7,8). The spectroscopy system consisted of the mentioned detector equipped with a transistor-reset preamplifier, a gated integrator main amplifier with a 1.5 \( \mu s \) or 3.0 \( \mu s \) integration time (Ortec 973U) and an analog-to-digital converter (ND 582) with fixed nominal conversion time of 1.5 \( \mu s \). The ADC was connected to a specially developed computer interface card (GammaData GC16BIV2) with a multi-channel analyzer. The system is capable of analysing data at rates exceeding 100 kcps. To correct for the dead time in the system, the pulser method was used. The pulser peak height was adjusted to correspond to a gamma energy of about 2 MeV, i.e. well above interfering gamma-ray transitions. In such a way, the pulser peak area could be determined with high accuracy. The dead time of the system during the measurements was typically 35%. It was shown in (8) that evaluation of the peak area is less sensitive to variations in irradiation of the detector if the detector is irradiated radially rather than axially. Therefore radial irradiation was used, as is also described in (1).

The gamma-ray measurements were conducted during five measurement campaigns, normalised to each other in the following way. It is well established (9,10) that the gamma-ray intensity of \( ^{137}\text{Cs} \) at a certain cooling time is to a large extent linearly correlated to the fuel burnup. By using the declared burnup (\( \beta \)) of the fuel and the measured gamma-ray intensities (\( I_i \), corrected for decay time to the end of the last fuel cycle) from the \( ^{137}\text{Cs} \) peak, a line \( I_i = k_i \cdot \beta \) was fitted to the data from campaign \( i \). The ratio \( (k_i/k_0) \), campaign \( i \) compared to a reference campaign, was used as normalisation constant. The measured intensity may be compared to intensities measured in the reference campaign using the normalisation constant: \( I_i = k_i \cdot \beta = k_i/k_0 \cdot k_0 \cdot \beta = I_0 \cdot k_i/k_0 \).

The peak area was evaluated using a linear background approximation. As shown in the section on uncertainties, the gamma ray intensities were evaluated with an uncertainty estimated to about 2% for all campaigns and fuel types.

More detailed data from the gamma-ray measurements can be found in refs. (11,12).
Table III: Parameters of the measured fuel assemblies. $t$ is cooling time [y] of the spent fuel at the calorimetical measurement, $\beta$ is burnup [GWd/\text{tU}] and $\varepsilon$ is initial $^{235}\text{U}$ enrichment [%].
The fuel types (F) are listed as follows: A = BWR, B = PWR-15x15, C = PWR-17x17.

<table>
<thead>
<tr>
<th>F</th>
<th>$t$</th>
<th>$\beta$</th>
<th>$\varepsilon$</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>14.9</td>
<td>21.3</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>12.0</td>
<td>22.2</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>14.9</td>
<td>22.3</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>12.9</td>
<td>22.6</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>12.8</td>
<td>23.2</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>8.8</td>
<td>37.2</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>14.9</td>
<td>34.0</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>13.9</td>
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</tr>
<tr>
<td>9</td>
<td>B</td>
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<td>B</td>
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</tr>
<tr>
<td>14</td>
<td>B</td>
<td>12.1</td>
<td>35.6</td>
</tr>
<tr>
<td>15</td>
<td>B</td>
<td>10.4</td>
<td>35.6</td>
</tr>
<tr>
<td>16</td>
<td>B</td>
<td>13.4</td>
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<tr>
<td>17</td>
<td>B</td>
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<td>36.3</td>
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<td>18</td>
<td>B</td>
<td>16.0</td>
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<td>14.9</td>
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<td>22</td>
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<tr>
<td>23</td>
<td>B</td>
<td>9.0</td>
<td>40.2</td>
</tr>
<tr>
<td>24</td>
<td>B</td>
<td>9.0</td>
<td>51.0</td>
</tr>
<tr>
<td>25</td>
<td>B</td>
<td>20.5</td>
<td>24.7</td>
</tr>
<tr>
<td>26</td>
<td>B</td>
<td>20.5</td>
<td>24.7</td>
</tr>
</tbody>
</table>

### CALORIMETRIC MEASUREMENTS OF THE DECAY HEAT

In a separate project reported in (3,13), the individual decay heat of all fuel assemblies considered in this paper was measured using a calorimeter. The calorimeter equipment is described in (3). Principally, it consists of a steel box enclosing the spent fuel assembly. The fuel assembly heats the water inside the calorimeter and the temperature difference between the interior and the exterior of the box is measured when thermal equilibrium is reached. This temperature difference is a simple function of the heat generated by the spent fuel. Using an electrically heated model of the spent fuel, a calibration curve was established between (electrical) power and the temperature difference. Using the calibration, the decay heat of the spent fuel assemblies were determined. (13) reports an uncertainty of about 6% (standard deviation) in the measured decay heat using this procedure.
RESULTS

The measured gamma-ray intensity \( I \), divided with the contribution to the decay heat \( f \), was compared to calorimetrically measured decay heat \( P \) in accordance with equation 1 in the section on the experimental method. The measured decay heat is from (3,13). Figure 3 shows a diagram of \( P \) versus \( I/f \). All measured gamma-ray intensities were corrected to correspond to the same measuring date as the calorimetric measurements. Values of \( f \) were determined by interpolation using the linear functions described in the section on the experimental method. Following equation 1, a least squares fit of a straight line was performed. From this fit the constant \( C \) of equation 1 was determined for the different types of fuel by using the expression of equation 2, (14).

\[
C = \frac{\sum_i (I/f)_i P_i \sigma_i^{-2} \pm \sqrt{\sum_i (I/f)_i^2 \sigma_i^{-2}}}{\sum_i (I/f)_i^2 \sigma_i^{-2}}
\]  

\((I/f)_i\) and \( P_i \) denote measurement point number \( i \) and \( \sigma_i \) is the uncertainty of the measured decay heat for point \( i \). Figure 3 shows the measured quantities together with the fitted lines. Fuel assemblies with a cooling time of less than 8 years were excluded from the analysis since the correction for \( f \) is according to previous discussions not sufficiently accurate for such short cooling time.

DISCUSSION ON UNCERTAINTIES

BWR core physics calculations involve more complexities than the case of PWR. BWR fuel is e.g. more heterogenous in terms of material content both radially and axially and the control procedures employed for BWR operation, e.g. varying the void content, result in larger spatial variations in the power and neutron spectrum profiles. This implies that the calculation of the isotopic content is generally accepted to result in larger uncertainties for BWR spent fuel than for PWR fuel. The use of the fitted linear function to calculate \( f \) only requires knowledge of burnup and cooling time.

The experimental method described by equation (1) determines the decay heat \( P \) with help of three factors \( I \), \( f \) and \( C \). The constant \( C \) is determined in a calibration procedure, such as the measurements reported in this paper in the section on the experimental procedure. Using the law of error propagation and ignoring covariances, the uncertainty in the measured decay heat can be written as eq. (3), using the same notations as in eq. (1) where \( \Delta X \) denotes the uncertainty in quantity \( X \).

\[
\left( \frac{\Delta P}{P} \right)^2 = \left( \frac{\Delta C}{C} \right)^2 + \left( \frac{\Delta I}{I} \right)^2 + \left( \frac{\Delta f}{f} \right)^2
\]  

UNCERTAINTY OF \( C \)

As shown in table IV, the relative uncertainty of the slope of the fitted line \( C \) was found to be in the order of 1% for both BWR and PWR spent fuel.

UNCERTAINTY OF \( I \)

Several contributions to the uncertainty in measured intensities can be identified as shown in the following list which is to a large extent based on the discussion of uncertainties for this
Figure 3: The correlation between the measured $^{137}$Cs gamma intensity, corrected to the time of calorimetric measurements and divided by the factor $f$, and measured decay heat. The lines are fitted using the least squares method. For clarity reason, the slope coefficients of the lines have been multiplied by factors 100, 1000 and 1500 for BWR 8x8, PWR 15x15 and PWR 17x17, respectively.

measuring system from (15).

1. Statistical error. The area of the $^{137}$Cs peak was evaluated with a statistical uncertainty of 0.17% on the average.

2. Peak area evaluation. The linear background subtraction method was used. As described in (15), this method introduces an uncertainty in the peak area evaluation of less than 1%.

3. The speed of the elevator system used for the spent fuel in the scanning process is not completely constant and depends on direction. This introduces an uncertainty of about 0.5%.

4. Uncertainty in the position of the fuel assembly relative to the detector introduces an uncertainty in the order 0.5%.

5. There is an uncertainty in the length of time that the spent fuel is seen by the detector. This introduces an error of about 0.5%.
6. Gamma radiation is attenuated within the fuel assembly before it is detected. If the activity distribution is non-homogenous, this introduces an uncertainty in measured intensities since the assumption of proportionality in equation 1 between activity and detected intensity is not valid for such cases. Using a computer calculation based on the line of sight point attenuation kernel method commonly used in gamma radiation shielding problems, the effect of realistic non-homogenous activity distributions was found to introduce errors of about 2% in measured intensities.

Using quadratic summation of these contributions, according to equation 3, the uncertainty in measured gamma-ray intensity \( I \), was estimated to about 2% for all fuel types.

**UNCERTAINTY OF \( f \)**

To estimate the uncertainty of the heat fraction \( f \), two scenarios may be discussed:

1. The fuel parameters burnup, cooling time and enrichment are known. In such a case, the burnup can be verified with an uncertainty in the order of 2%, (1). The uncertainty in cooling time is in this case negligible. Using the law of error propagation on the linear function used in this paper to estimate \( f \), the uncertainty in \( f \) was 0.7%, 0.9% and 1.8% for BWR 8x8, PWR 15x15 and PWR 17x17 fuel, respectively. A more detailed interpolation, i.e. using higher order interpolation or a calculation with Origen, may give smaller uncertainties.

2. No information on the fuel parameters is available. In this case, the gamma measuring technique developed in (1) may be used to determine the burnup and cooling time of the spent fuel assembly. (1) states that the burnup and cooling time may be determined with uncertainties in the order of 5% and 1 years, respectively, when no information is available but the fuel type. Error summation in this case results in uncertainties for the factor \( f \) of 1.2%, 1.6% and 2.2% for BWR 8x8, PWR 15x15 and PWR 17x17 spent fuel respectively.

The results for the two scenarios are summarized in table IV.

**UNCERTAINTY OF \( P \)**

As can be seen from table IV, the overall uncertainty in the determination of the decay heat, \( \Delta P/P \), is on the average 2.8% and 3.1% for the case when all information regarding the fuel parameters are known and not known, respectively. It must be emphasised however, that the use of the method presented here relies implicitly on the assumption that errors in the calorimetrically measured decay heats are negligible. These errors are not yet analyzed. This means that the total error in deduced decay heat is the sum of the errors from table IV and the possible, so far unknown, systematic errors.

**SUMMARY, CONCLUSIONS AND DISCUSSION**

**DECAY HEAT DETERMINATION**

In summary, the correlation between calorimetrically measured decay heat and intensity of the \(^{137}\text{Cs}\) gamma radiation has been established for 69 BWR and PWR fuel assemblies.
The method of using gamma-ray measurements to determine the decay heat takes about 10 minutes and is about a factor of 100 faster than the current calorimmetrical method. This implies that the decay heat can be determined with the method described in this paper on a routine basis when handling the spent fuel, for instance in a final repository.

The method used here of deducing the residual heat from the gamma intensity of $^{137}$Cs and the factor $f$ may be compared with the alternative way of obtaining the residual heat including the following steps:

1) Measure the gamma intensity of $^{137}$Cs and $^{154}$Eu. 2) Use the intensities to verify that the fuel parameters delivered by the operator are correct, (1). 3) Run Origen or a similar code for the fuel assembly to obtain the residual heat.

The two methods are similar in the respect that they depend on a measurement of the gamma intensities and they both depend on the accuracy of the code used. However, to calculate the total heat on an absolute scale is associated with uncertainties as discussed in (16,17,18). The method presented here offers the advantage that the decay heat is directly connected to an experimental quantity, i.e. the gamma intensity of $^{137}$Cs and it is calibrated to experimental measurements of the decay heat using calorimetry.

In a standard case, when all fuel parameters are considered as correct, the decay heat is obtained by a simple interpolation procedure to obtain the $f$-factor which requires no Origen calculation. This facilitates the handling procedure and makes it more robust to mistakes. In a case when the operators fuel parameters are missing or the verification does not come out right, the decay heat may still be obtained rather accurately from a determination of the cooling time and burnup from gamma measurements as indicated in ref. (1) and table IV. If the intensity of $^{154}$Eu for some reason cannot be measured, the decay heat may still be determined approximately using a 'standard' value of $f \approx 0.3$, which is valid with an accuracy of $\pm 10\%$ in the range of $15 \leq$ burnup $\leq 45$ GWD/tU and $20 \leq$ cooling time $\leq 50$ years.

Table IV: Overall results and uncertainties.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>#</th>
<th>$\Delta C/C$</th>
<th>$\Delta I/I$</th>
<th>No info exists</th>
<th>Info exists</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWR 8x8</td>
<td>35</td>
<td>0.91%</td>
<td>2.1%</td>
<td>1.2% 2.6%</td>
<td>0.7% 2.4%</td>
</tr>
<tr>
<td>PWR 15x15</td>
<td>20</td>
<td>1.1%</td>
<td>2.4%</td>
<td>1.6% 3.1%</td>
<td>0.9% 2.8%</td>
</tr>
<tr>
<td>PWR 17x17</td>
<td>14</td>
<td>1.3%</td>
<td>2.4%</td>
<td>2.2% 3.5%</td>
<td>1.8% 3.3%</td>
</tr>
</tbody>
</table>

BURNUP VERIFICATION

(1) gives a detailed account for determining the burnup and cooling time of the spent fuel using data from the gamma-ray measurement. In this paper, a more simple method was used to determine the uncertainty in the fuel burnup verification. First, a linear relationship between measured gamma-ray intensities from $^{137}$Cs was established by $I = K\beta$, see figure 4, where $\beta$ denotes burnup. Second, by using ordinary least squares fit analysis the uncertainty of $k$ was determined to 0.58%, 0.37% and 0.39% for BWR8x8, PWR 15x15 and PWR17x17 fuel respectively.

This implies that the burnup could be determined with an uncertainty of 2.2%, 2.5% and 2.5% for BWR8x8, PWR 15x15 and PWR17x17 fuel respectively using the uncertainty of $I$,
provided that knowledge of fuel cooling time is available. (1) reports that burnup and cooling
time can be verified within about 5% and 1 year from operator declared data, respectively,
without any prior knowledge of fuel parameters.

Figure 4: Plot of the correlation between measured gamma intensity and operator declared fuel
burnup for three types of fuel assemblies. The lines are fitted using the method of least squares.

OUTLOOK

Measurements will according to current plans be repeated in certain intervals in the future on
the same selected fuel assemblies. New fuel designs as well as reconstructed assemblies are
also planned to be investigated in order to confirm the accuracy and reliability of the method.
In this work, CLAB provides a unique opportunity to follow up the decay heat of individual
fuel assemblies during several decades to come. This also means that the data from gamma
scanning measurements at the facility can be used to improve the fuel verification method
described briefly in this paper.

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