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Determination of the rod-wise fission gas release fraction in a complete fuel assembly using non-destructive gamma emission tomography

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A B S T R A C T

A gamma tomography instrument has been developed at the Halden Boiling Water Reactor (HBWR) in cooperation between the Institute for Energy Technology, Westinghouse (Sweden) and Uppsala University. The instrument is used to record the gamma radiation field surrounding complete fuel assemblies and consists of a shielded enclosure with fixtures to accurately position the fuel and detector relative to each other. A High Purity Germanium detector is used for acquiring high-resolution spectroscopic data, allowing for analysis of multiple gamma-ray peaks. Using the data extracted from the selected peaks, tomographic reconstruction algorithms are used to reproduce the corresponding spatial gamma-ray source distributions within the fuel assembly. With this method, rod-wise data can be can be deduced without the need to dismantle the fuel.

In this work, the tomographic device has been experimentally benchmarked for non-destructive rod-wise determination of the Fission Gas Release (FGR) fraction. Measurements were performed on the fuel-stack and gas-plenum regions of a complete fuel assembly, and quantitative tomographic reconstructions of the measurement data were performed in order to determine the rod-wise ratio of ^{85}Kr in the gas plenum to ^{137}Cs in the fuel stack. The rod-wise ratio of ^{85}Kr/^{137}Cs was, in turn, used to calculate the rod-wise FGR fraction. In connection to the tomographic measurements, the fuel rods were also measured individually using gamma scanning in order to provide an experimental benchmark for the tomographic method.

Fuel rods from two donor driver fuel assemblies were placed into a nine-rod HBWR driver fuel assembly configuration. In order to provide a challenging measurement object and thus an appropriate benchmark for the tomographic method, five rods were taken from an assembly with a burnup of 51 MWd/kgUO_2, and four rods were from an assembly with a burnup of 26 MWd/kgUO_2. At the time of the measurements, the nine rods had cooled for approximately 22 years. All fuel rods had operated at high linear heat rates (around 70 kW/m), thus leading to relatively high FGR fractions. Here, the FGR fraction was determined to be ~24% in the high-burnup rods, and ~17% in the low-burnup rods. The tomography measurement results were in good agreement with the results from individual rod scanning, demonstrating the feasibility of tomography for this application. The capability of tomography to assess individual fuel rods without the need to dismantle the assembly can be particularly valuable in cases of fuels that do not allow disassembly, such as experimental HBWR fuel fitted with extensive instrumentation.

1. Introduction

A gamma tomography instrument has recently been developed at the Halden Boiling Water Reactor (HBWR) in cooperation between the Institute for Energy Technology (IFE), Westinghouse (Sweden) and Uppsala University. The instrument is designed to be able to non-destructively characterize fuel irradiated in the HBWR by measuring the gamma radiation field surrounding the fuel and using tomographic reconstruction techniques to determine the rod-wise distribution of radioactive isotopes in the fuel. The method and instrument thus allow for characterization of fuel assemblies without the need to disassemble the fuel. In

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comparison, conventional single-rod gamma-ray spectroscopy characterization requires that the fuel rods are removed from their parent assemblies for individual measurement.

The novel tomography capability at the HBWR may enable the characterization of a range of objects that have previously not been assessable, such as instrumented fuel rods in assembly designs that do not allow disassembly in between test irradiations. Furthermore, the tomographic technique offers a simplified, less hazardous and potentially faster procedure for fuel characterization. However, the tomographic technique must be properly evaluated and benchmarked for the intended measurement applications to ensure that the results are reliable.

One measurement application that is of interest is determining the rod-wise fission gas release fraction, i.e. the fraction of gaseous fission products produced in each fuel rod that have been released to the fuel rod gas volume. This phenomenon, referred to as *fission gas release* (FGR), has negative implications on fuel rod behavior and in the worst case, excessive FGR can result in failure of the fuel rod cladding. The mechanisms behind FGR are complex, but at a basic level, higher temperatures, higher linear heat rates, and higher burnups result in higher levels of FGR. The mechanisms and consequences of FGR with regard to fuel behavior are described extensively in e.g. [1–4].

In order to demonstrate and evaluate the tomographic device for determination of fission gas release fraction (usually presented in terms of percentage, as %FGR), a set of fuel rods have been measured using both the tomographic setup and the rod-wise gamma-scanning technique. In this demonstration, nine HBWR driver fuel rods were first characterized using the conventional single-rod method in order to determine the rod-wise fission gas release fraction by measuring ^{85}Kr and ^{137}Cs in the gas plenum and fuel stack, respectively, of each of the rods. These nine fuel rods were subsequently assembled into a HBWR driver fuel assembly configuration and characterized using the gamma tomography system. In this work, the measurements are described and results of the two methods are compared, thus providing an experimental benchmark for tomographic measurement of %FGR.

2. Background

2.1. Gamma scanning

Gamma scanning is a well proven technique for characterizing nuclear fuel, whereby fuel properties can be deduced by measuring and mapping the distribution of gamma-rays emitted from the fuel [5]. Common applications of single-rod gamma scanning in Halden are for determination of the axial burnup and power profiles in experimental fuel rods, while it is also occasionally used for measuring fission gas release.

2.1.1. Experimental setup and procedure

Gamma scanning measurements in Halden are performed using a collimated High Purity Germanium (HPGe) detector to measure the gamma rays emitted from selected regions of the fuel. The use of the high-resolution HPGe detector enables analysis of the collected gamma-ray energy spectra for different peaks, which are typically characteristic of a specific emitting isotope. By mapping the distribution of the emitted gamma ray(s), and thus the distribution of the emitting isotope(s), various fuel characteristics may be investigated.

In order to determine rod-wise fuel characteristics by gamma scanning, individual fuel rods must be removed from the fuel assembly and measured one at a time. The process of removing fuel rods from a fuel assembly is time consuming, involves the risk of causing damage from handling and the procedure exposes personnel to dose. Experimental fuel assemblies at the HBWR also typically employ extensive instrumentation that precludes the removal of individual fuel rods for single-rod gamma scanning until the End of Life (EOL), when the instrument cables can be (permanently) severed for the fuel rods to be removed.

2.1.2. Determining rod-wise %FGR using single-rod gamma scanning

Single-rod gamma scanning has previously been demonstrated and used as a conventional non-destructive method of determining %FGR in individual fuel rods [6–8]. This method is based on measuring the 662 keV gamma rays emitted by ^{137}Cs in the fuel stack region of a fuel rod and the 514 keV gamma rays emitted by ^{85}Kr in the gas plenum (with the same measurement geometry). The content of ^{137}Cs in the fuel is proportional to the burnup of the fuel and therefore the ^{137}Cs content is also proportional to the amount of fission gasses, including ^{85}Kr, that have been produced in the fuel. The fission gas release fraction is determined by taking the ratio of the amount of ^{85}Kr measured in the gas plenum to the amount of ^{85}Kr produced in the fuel. This method of determining % FGR has been benchmarked against destructive examination results (i.e. rod puncturing, volume measurement, and mass spectrometry analysis of the gasses contained within the fuel rods) [9].

Eq. (1) is used for calculating %FGR for single rods based on measurement of ^{137}Cs in the fuel stack region and ^{85}Kr in the gas plenum. For a more elaborate description of this equation, we refer to [10].

$$\%FGR = 100 \cdot \frac{A_5}{A_7} \cdot F_n(z) \cdot \frac{\ell \cdot k_k}{L} \cdot \frac{Y_7 \cdot \varepsilon_7 \cdot \eta_7}{Y_5 \cdot \varepsilon_5 \cdot \eta_5} \cdot \frac{\left(1 - e^{-\lambda_7 \cdot t_B}\right) \cdot e^{-\lambda_7 \cdot t_D}}{\left(1 - e^{-\lambda_5 \cdot t_B}\right) \cdot e^{-\lambda_5 \cdot t_D}} \cdot \frac{\alpha_{\mu 7}}{\alpha_{\mu 5}} \cdot P_\mu \cdot Q_\mu \cdot K_e \quad (1)$$

where index “5” refers to ^{85}Kr, index “7” to ^{137}Cs

%FGR: Fraction of produced ^{85}Kr released into the free rod volume [%]
A: Net count rate in full energy peak (514 and 662 keV, respectively)
$F_n(z)$: Axial burnup form factor at position of reference ^{137}Cs measurement for rod n for measurement performed at axial position z
ℓ: Plenum length [mm]
L: Fuel column length [mm]
k_k: Compression factor taking the fuel rod internal volume distribution into account including the pellet-cladding gap and plenum compression spring volume
Y: Fission yield [atoms per fission]
ε: Gamma emission yield [photons of the characteristic energy emitted per disintegration]
λ: Decay constant [years^{-1}]
t_B: Irradiation time [years]
t_D: Decay time [years]
α_μ: Photon attenuation from plenum or fuel to detector (including absorption in cladding)
P_μ: Attenuation of 662 keV gamma rays in fuel
Q_μ: Attenuation of 662 keV gamma rays in additional absorber typically used when measuring the fuel stack
η: Detector full peak efficiency at the characteristic energy
K_e: Calibration factor (equal to 1 in this report)

One notable challenge associated with performing these measurements is the relative weak 514 keV peak from ^{85}Kr. Since ^{85}Kr has a low fission yield and 514 keV gamma rays are emitted in only 0.434% of ^{85}Kr decays, the Compton background and interfering peaks at 511 keV and 512 keV (from positron annihilation and ^{106}Rh, respectively) may make it difficult to observe and/or resolve