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Inspection of a LOCA Test Rod at the Halden Reactor Project using Gamma Emission Tomography

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Abstract. The LOCA test series IFA-650 conducted at the OECD Halden Reactor Project (HRP) has provided unique data on the performance of fuel rods during LOCA transients. One focus of the current investigations is the performance of the fuel in the ballooning stage of the LOCA transient. In this stage, relocation of fuel material is a possibility, in which case pellet fragments fall down to fill the void introduced by the increased volume of the ballooned cladding. This increases the heat load in that region, further promoting corrosion of the cladding. A special concern in the case of high-burnup fuels is the increasing number of small fuel fragments, which may be expected to cause a higher packing fraction in the ballooned region.

In this work, a novel technique is presented for assessing the average density of the fuel material in the ballooned region of LOCA test rods. The investigation is based on non-destructive gamma emission tomography measurements, using the dedicated instrument recently developed at the HRP in collaboration with Westinghouse (Sweden) and Uppsala University. In this approach, the gamma radiation field surrounding the test rod has been measured with a narrowly collimated HPGe detector. Tomographic reconstruction of the data was performed, providing the radial gamma-ray source distribution within the measured volume, which reveals the fuel fragment distribution. From this, the density of the fuel in the measured volume (i.e., the packing fraction) may be calculated.

The technique has been used to investigate a LOCA test rod of the Halden Reactor Project LOCA series. The LOCA experiment was carried out about one month prior to the gamma tomography examination. The results show that the distribution of the relocated fuel can be imaged using gamma rays from fission products. The reconstructions of the 662 keV rays from $^{137}$Cs and 1596 keV from $^{140}$Ba/La are demonstrated. In addition, the peaks of activation products offer valuable information on the location of the test rig structures, which may be utilized in a quantitative tomographic reconstruction to assess the spatially resolved packing fraction.

Keywords: LOCA, Gamma Emission Tomography, Fuel Fragmentation, Fuel Relocation

INTRODUCTION

The ongoing IFA-650 test series at HRP has provided unique data on fuel rod behavior under LOCA transient conditions. In this test series, single test rods of medium to high burnup have been instrumented with pressure sensors, thermocouples and cladding elongation detectors and mounted in a special flask which allows for the simulation of a LOCA transient, including the blow down and the subsequent temperature rise due to decay heating. The fuel rod may undergo cladding ballooning causing the possibility of fuel relocation, and a separate water loop allows for the progression to cladding burst and the dispersal of fuel to the coolant [1].
One of the main objectives of these tests is to study the fragmentation and relocation of the fuel. Fuel pellets and fragments may fall down from above into the balloon formation, or may be pressed there by gases following a cladding rupture. Previously, the fragmentation and relocation of the test rods have been studied using various PIE techniques such as two-dimensional (2D) gamma scanning performed at HRP as well as sifting, ceramography and neutron radiography performed at IFE Kjeller. Recently, it was proposed to use the new gamma emission tomography instrument at HRP to investigate relocation of fuel, and in this article the first results are presented.

The gamma emission tomography instrument in Halden was developed in a joint effort by HRP, Uppsala University and Westinghouse Sweden. The instrument was optimized for use on irradiated nuclear fuel, e.g., it has thick shielding to allow for the studies of highly radioactive objects. In addition, to enable the exploitation of the multitude of radioisotopes typically present in irradiated nuclear fuel, a spectroscopic high-purity Germanium (HPGe) detector is used. The instrument and the first results were presented in 2015 [2].

For LOCA rod analysis, tomographic reconstruction with spatial resolution on the mm scale can provide information about the presence or absence of fuel within spatially-resolved cross-sectional maps of the LOCA rod. The information yielded from such an investigation may be used to:

1. Indicate the relocation of fuel pellets or fragments to the fuel balloon.
2. Obtain the packing fraction in the balloon.

For the first of these objectives, qualitative tomographic reconstructions are required, indicating the locations in the LOCA fuel rod where fuel material is present. For this purpose, some idealizations can be made that make the analysis simpler and faster, such as neglecting the strongly inhomogeneous self-attenuation of the test rod and rig structures. For the second of the objectives, quantitative reconstructions may be required (i.e., the reconstructed image should have pixel values that accurately correspond to their emission intensity). Quantitative reconstructions require treatment of the self-attenuation of the object, which in turn may require accurate localization of the fuel material and rig structures in the object.

The objective of this report is to present a first experimental evaluation the applicability of the gamma emission tomography technique for characterizing LOCA test rods. Qualitative tomographic reconstructions of the fuel in selected axial locations are presented as well as results of the localization of the attenuation structures of the LOCA rig, which may be used to obtain quantitative reconstructions of the fuel material distribution in LOCA test rods.

**METHOD**

Prior to the LOCA test, the investigated rod was exposed to a conditioning irradiation in the HBWR at 110 W/cm adding an additional burnup of 0.07 MWd/kg. This produced an inventory of short lived isotopes for gamma spectroscopy in the fuel and (by activation) also in the rig structure. Due to the high accumulated burnup of the test rod, long-lived radioisotopes such as $^{137}$Cs were also available for gamma spectroscopy measurements.

The LOCA test rod was examined using the gamma tomography instrument at several axial elevations starting about one month after the execution of the LOCA simulation test. Prior to the tomographic assessment, 2D gamma scanning of the rod was performed, which aided in the planning of the tomography measurements by localization of axial positions of interest. During all transportations of the LOCA flask from the reactor, to the gamma scanning station and to the tomography instrument, the LOCA flask was maintained in a vertical orientation in order to, as much as possible, conserve the spatial distribution of relocated fuel in the rod.
The gamma emission tomography system at HRP has a motorized fixture allowing for elevation and rotation of the fuel relative to a narrow collimator forming a beam to a gamma detector. In addition, the collimator-detector system has a motorized fixture that allows for horizontal translation. The elevation/rotation fixture positions the fuel for investigation at the axial elevations of interest, where the fuel is rotated 360°. In this set of measurements, the fuel was rotated in steps of 3°, and at each angular position the detector-collimator system was translated laterally in 1 mm steps and the gamma spectrum was recorded at each position. The principles of the operation are shown in Figure 1.

Two collimators were used; one with a slit opening of 1 mm wide and 22 mm tall, and one with a slit opening of 1 mm wide and 2 mm tall. The taller collimator was used to produce images which are effectively averaged over an axial range of approximately the same size as the collimator height, while having mm-scale resolution in the lateral direction of the fuel, due to the orientation of the narrow dimension of the slit. This collimator was used to scan over a 61 mm lateral range, which included the heater cylinder, the flask and a flow tube located outside the flask, see Figure 1.

To achieve additional reconstructions of the local emission distribution in a smaller axial range, a 1x2 mm² collimator was manufactured and used to perform measurements in the region of the fuel balloon. The 1x2 mm² collimator was used in scans ranging laterally over 21 mm, covering only the LOCA rod and the heater cylinder. For both collimators, the measurement time was selected in order to obtain adequate measurement statistics primarily in the 662 keV peak from 137Cs, while also keeping the measurement time short enough to enable collection of data from several axial positions during the measurement campaign. The typical duration of the inspection of a single elevation was about 1-2 days. In total the measurements took place during about 1.5 months.

The resolution of the instrument is limited by the motion control stepping interval and the width of the collimator slit. These are both 1 mm.

**FIGURE 1.** Schematic illustration of the LOCA rig and the motion of the tomographic setup. In addition, the fuel is elevated to the axial locations of interest. The measured object consists of the LOCA rod (gray), a Zircaloy heater cylinder (blue) including Inconel heater cables (red) and thermocouple cables (yellow), the steel flask (brown) and a steel flow tube (green). The illustration is not to scale.
ANALYSIS

The raw data consist of gamma-ray spectra collected at thousands of unique positions surrounding the fuel. The number of counts in selected peaks at each investigated position was extracted from the collected spectra (including background subtraction, and dead-time correction), and used as input for tomographic reconstructions.

Tomographic reconstructions were made to obtain the 2D gamma emission distribution in the investigated cross-sections. For this purpose two reconstruction methods were used.

- **Filtered Back-projection (FBP):** The FBP method [3] is an analytical technique which allows for the rapid reconstruction of qualitative images that show the location of the selected gamma-emitting isotope. In the FBP reconstructions performed in this work, a ramp filter was applied and no method of attenuation compensation was utilized.

- **An algebraic reconstruction technique:** This method solves the equation \( I = WA \), where \( I \) is a column vector of the recorded intensities, \( A \) is a column vector with the emission intensities of each pixel and \( W \) is a system matrix, where the elements express the probability of a gamma ray emitted in each pixel to reach the detector at each position. In this work, a Least-Squares (LS) solution was implemented with Total Variation (TV) regularization, which is known to prevent image degrading by noise while preserving edge locations [4].

To enable quantitative reconstruction, i.e., providing accurate emission intensities for each pixel of the reconstructed image, the spatially dependent attenuation values of gamma rays inside the investigated object must be known. To determine this, the localization of rig structures by template matching [5] in the reconstructed images of activation products was tested.

In the template matching method, a template is created with the same size and shape as the structure object of interest, e.g., the LOCA flask, the heater cylinder and the heater cables. The template has unit value inside the structure searched for, and zero outside. It is used to produce a combined image with the reconstruction by multiplying the pixel values in overlapping pixels. By alternating the position of the mask, an estimate of the position is provided by the highest sum of the pixels in the combined image.

RESULTS

Peak Selection and Extraction

The recorded spectra contained numerous peaks available for extraction of count rates and subsequent tomographic reconstruction. Figure 2 shows example spectra from the fuel and structure regions respectively. Five peaks were selected for extraction and tomographic reconstruction; the 662 keV peak from \(^{137}\text{Cs}\) and 1596 keV from \(^{140}\text{Ba/La}\), which are fission products in the irradiated fuel, and in addition three activation products; the peak at 320 keV from \(^{51}\text{Cr}\) produced by neutron capture in stainless steels, 811 keV of \(^{58}\text{Co}\) from activation in nickel and 1099 keV of \(^{59}\text{Fe}\) from activation in iron. The activation products were reconstructed to provide the position of rig structures, while the fission product reconstructions provided images of the fuel.
FIGURE 2. Gamma spectra collected from the LOCA test rig. The Channel number corresponds to the energy [keV]. Upper spectrum: Spectrum collected with collimator directed toward the fuel. Lower spectrum: Spectrum collected from structures in a collimator orientation that is directed outside the fuel rod.

Tomographic Reconstruction

Based on 2D gamma scans performed prior to the transport of the LOCA flask to the tomography instrument, seven axial positions were selected for the investigations using the 1x22 mm² collimator. These locations are marked in the 2D scan in Figure 3, and the corresponding reconstructions of the $^{137}\text{Cs}$ content are added for comparison. The reconstructions all show a non-uniform, yet relatively smooth distribution of $^{137}\text{Cs}$ in the fuel. This is not unexpected due to the large collimator slit size in the axial orientation (22 mm). This tall collimator opening results in the reconstructions representing an axially averaged emission distribution over the tall axial field of view of the collimator.

The large-collimator reconstructions show a visible increase of the fuel diameter in the location of maximum ballooning to about twice its original size. In the closest reconstruction above that position (ca. 25 mm above), the area covered by fuel is substantially smaller, and clearly non-circular.

In the reconstructions of the data collected with the 1x2 mm² collimator, details appear that are indistinguishable with the 1x22 mm² collimator, resolving several separate fragments in the fuel cross section, or possibly aggregations of fragments. The results from the 1x2 mm² collimator measurements and their corresponding axial locations are shown in Figure 4. The spatial distribution of the fuel is visibly distorted from the nominal rod shape.
FIGURE 3. Left and below: Images of $^{137}$Cs from the 7 measurements using the 1 mm wide x 22 mm high collimator. Center: 2D gamma scans collected at rotational positions separated by 90°. Right: Axial scan performed in tomography setup with the collimator in the horizontal orientation (i.e. 22 mm wide x 1 mm high).
FIGURE 4. Left and right columns: Tomographic reconstructions of $^{137}$Cs collected with the 1x2 mm$^2$ collimator. Second and third columns: 2D gamma scans collected at rotational positions separated by 90°. Fourth column: Axial scan performed in tomography setup with the collimator in the horizontal orientation (i.e. 22 mm wide x 1 mm high) with indications of the axial positions of the tomographic scans in red.
The extracted data from the 1596 keV peak of $^{140}$Ba/La was reconstructed at one sample location for comparison of the $^{137}$Cs reconstructions. As seen in Figure 5, the reconstructed images of these two isotopes are in good agreement.

**FIGURE 5.** Reconstructed images of 662 keV gamma rays from $^{137}$Cs (left) and 1596 keV gamma rays from $^{140}$Ba/La (right) in the intact fuel region at the upper end of the rod, using the 1 mm wide x 22 mm high collimator.

The resolution was experimentally determined by examination of the reconstruction at 991 mm. Here the resolution was examined at the four edges at horizontal and vertical directions from the rod center. On average, the 10 % to 90 % edge response was 1.3 mm.

**Rig Structure Localization**

The peaks selected from the structures were used to identify and localize the rig structures that surround the LOCA rod. As shown in Figure 6, the FBP reconstructions of the isotopes $^{51}$Cr, $^{58}$Co and $^{59}$Fe give clear indications of the presence of 316L stainless steel in the LOCA flask, and the lower flow tube (downcomer), thermocouple cables, and the Inconel heater cables.

The Zircaloy heater cylinder in which the heater cables are inserted did not emit gamma rays at the investigated peak energies from the activation products mentioned above; however it is noteworthy that it is still fully possible to localize it in the reconstructions of low energy gamma from activation in the surrounding steel, due to shadow effect [5], i.e., the gamma attenuation appears as a negative source intensity due to the attenuation of gamma rays in this structure. The heater cables were localized using the 811 keV peak, the LOCA flask and the flow tube were localized using both the 320 keV and 1099 keV peaks, and the heater cylinder was localized by applying the template matching algorithm to the negative image (shadow) of the 320 keV peak. The results of the TV reconstructions of the activation products and the template matching are shown in Figure 7. Note that the shadow of the fuel rod is also visible in these images, and its position is observed to be off-center in the flask. For comparison, a drawing of the test rig cross section is shown in Figure 8.
FIGURE 6. FBP reconstructions with LOCA flask components labelled. The reconstructions are from the uppermost scan shown in Figure 3 (elevation ca. 90 mm below the top of the fuel stack).
FIGURE 7. Localization of structures using gamma rays emitted by activation products and template matching. The position of the template is marked in red. A) Inconel heater cables localized using $^{56}$Co, B) Steel flask localized using $^{59}$Fe, C) Flow tube localized using $^{51}$Cr and D) Zircaloy heater cylinder localized using the shadow effect in the reconstruction of $^{51}$Cr. The reconstructions were produced from the uppermost scan shown in Figure 3 (elevation ca. 90 mm below the top of the fuel stack).
FIGURE 8. Cross section drawing of IFA-650.15 test rig. The heater with cables, the test flask, the rod with its instrumentation and lower flow tube are inserted into the tomography station for the investigations presented here.

CONCLUSIONS

A LOCA test rod was examined for the first time using the recently installed gamma emission tomography system at HRP. The test rod was investigated in several axial locations, and cross sectional maps of the $^{137}$Cs and $^{140}$Ba/La contents were produced. The tomographic images provided detailed (qualitative) information on the fragmentation and relocation of the fuel.

The instrument was used with two collimators with significantly different axial slit sizes (2 mm vs. 22 mm). Measurements using the narrow collimator were used to produce high-resolution images where separate fuel fragments could be resolved in the ballooned part of the fuel. Measurements using the larger-slit collimator were used to produce images that correspond to the average fuel distribution over an axial range similar in size to the collimator height. The images produced using the larger-slit collimator may be useful for the calculation of the average packing fraction in a larger region of the test rod.

It was shown that rig structures can be localized in the reconstructions using the gamma rays emitted by the activation products $^{51}$Cr, $^{58}$Co and $^{59}$Fe in the materials of the flask, heater cables and the flow tube on the side of the flask. In addition, the Zircaloy heater cylinder was easily visible from the shadow effect caused by its attenuation of the 320 keV gamma rays from $^{51}$Cr. Localization of the rig structures allows for accurate compensation for gammaray attenuation in the structures which is necessary for obtaining a quantitative map of the fission product inventory in the fuel. Algebraic reconstruction methods, which take the gamma-ray attenuation into account, may be used for accurate calculation of the packing fraction.

The spatial resolution was examined at 991 mm where the fuel has maintained a rod-like shape. The 10 % to 90 % edge response was 1.3 mm, which is in good agreement with the expectations.
DISCUSSION AND OUTLOOK

The investigation of a LOCA using the gamma emission tomography system was successful as a means of observing the fragmentation and relocation of the fuel. Still, the analysis is preliminary (and qualitative in nature) and the development of the new PIE technique is ongoing.

One of the proposed uses of these data is to investigate the packing fraction in the fuel balloon. In such investigations, a fission product that is evenly distributed in the fuel material should be reconstructed, such that the fuel density may be assumed to be proportional to the concentration of that fission product. $^{137}$Cs, which is volatile at high temperatures, may not be the best choice, and instead, the other demonstrated example, $^{140}$La/Ba, may be a better option. However, $^{140}$La/Ba has a shorter half-life that makes it unavailable for measurement several weeks after the end of irradiation. This may need to be considered in the scheduling of future LOCA rod tomography inspections. As seen in the fuel spectrum of Figure 2, there are also many other candidate peaks corresponding to various isotopes that may be useful for inspection of the fuel, corresponding to isotopes such as $^{95}$Zr, $^{95}$Nb, $^{103}$Ru and $^{154}$Eu.

For the purpose of packing fraction measurements, the self-attenuation of the fuel rig should be properly taken into account in the tomographic reconstructions in order to prevent a bias in the results. If this is not taken into account, the fuel concentration in regions with high attenuation (such as in the center of the fuel and in elevations with a high accumulation of fuel) could be underestimated. The self-attenuation was neglected in the qualitative FBP reconstructions presented in this article. Since both fuel and structure materials were able to be successfully localized from these images, further work has already begun with implementation of the attenuation compensation in the tomographic reconstruction methods in order to be able to obtain unbiased packing fractions.

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