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FEASIBILITY OF IDENTIFYING LEAKING FUEL RODS USING GAMMA TOMOGRAPHY

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Abstract

In cases of fuel failure in irradiated nuclear fuel assemblies, causing leakage of fission gasses from a fuel rod, there is a need for reliable non-destructive measurement methods that can determine which rod is failed. Methods currently in use include visual inspection, eddy current, and ultrasonic testing, but additional alternatives have been under consideration, including tomographic gamma measurements.

The simulations covered in this report show that tomographic measurements could be feasible. By measuring a characteristic gamma energy from fission gasses in the gas plenum, the rod-by-rod gamma source distribution within the fuel rod plena may be reconstructed into an image or data set which could then be compared to the predicted distribution of fission gasses, e.g. from the STAV code. Rods with significantly less fission gas in the plenum may then be identified as leakers.

Results for rods with low fission gas release may, however, in some cases be inconclusive since these rods will already have a weak contribution to the measured gamma-ray intensities and for such rods there is a risk that a further decrease in fission gas content due to a leak may not be detectable. In order to evaluate this and similar experimental issues, measurement campaigns are planned using a tomographic measurement system at the Halden Boiling Water Reactor.

Key words: Gamma Tomography, Leaking Fuel, Nuclear Fuel

1 INTRODUCTION:

1.1 LEAKING FUEL

A typical commercial power reactor contains tens of thousands of fuel rods which have been manufactured to stringent requirements to ensure that they remain intact over the lifetime of the fuel assembly for normal as well as accident conditions. Although modern fuel assemblies have a robust design and are more resistant to fuel failures than previous generations of fuel, there are still occasional fuel rod failure events. A fuel failure is said to occur when the cladding is breached such that fission products enter the reactor coolant.

Fuel may fail for a variety of reasons, including manufacturing defects, excessive fretting, or as a result of conditions of the operating environment experienced by the fuel in the core. When fuel rods fail during reactor operation they are detected by

reactor operators through detection of fission products in the reactor coolant or steam systems, i.e. failed fuel rods release radioactive fission gasses and other fission products into the primary loop.

While fuel failures are not an issue in terms of controlling or operating the reactor, the release of fission products into the steam or coolant loop may increase the radiation dose to plant workers and may lead to increased operating costs as a result of protecting against the elevated dose. The occurrence of a fuel leaker causes power plant operators to take costly actions to prevent degradation of the fuel leaker while it continues to operate, and to investigate the cause of the leaking fuel in order to prevent further fuel failures from occurring.

According to (IAEA, 2010) the world average fuel failure rates for Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) for the period 1994-2006 were 13.8 respectively 4.4 failed fuel assemblies per 1000 discharged fuel assemblies. The number of leaking fuel assemblies per 1000 discharged assemblies for the period 1994-2006 is shown in Figure 1. This information is based on 417 Light Water Reactors (LWRs) which in total reported nearly 800 failed fuel assemblies during this time period.

Figure 1, World average fuel assembly failure rates for BWRs and PWRs during the period 1994-2006, according to (IAEA, 2010). This information is based on 417 LWRs which operated during the given time period and which in total reported nearly 800 failed fuel assemblies.

Occasionally, a failed fuel assembly contains more than one leaking rod. The average number of failed rods per failed assembly, according to (IAEA, 2010), was 1.6 for PWRs and 1.1 for BWRs. Whereas typical PWR and BWR fuel assemblies contain approximately 250 and 100 fuel rods, respectively, and since the majority of the fuel rods are still intact and may be used further to produce energy in the reactor, it is often desirable from an economic perspective to repair a leaking assembly by removing and replacing the leaking rod(s) so that the repaired assembly may be returned to the reactor for further irradiation.

1.2 EXISTING METHODS FOR LEAKER ROD IDENTIFICATION

The fuel assembly containing the leaking rod must first be identified. This is typically accomplished after shutdown using a technique called fuel sipping (IAEA, 2010), after which the leaking assembly is moved to a spent fuel storage pool. After the leaking assembly has been identified, the individual leaking fuel rod has to be identified in order to fully investigate the cause of the fuel failure and to allow for eventual replacement of the leaking rod(s). While fuel sipping can identify an assembly which contains leaking rods, it cannot identify which rod is leaking within an assembly.

Existing methods for identifying leaking rods include visual inspection, eddy current testing, and ultrasonic testing (IAEA, 2010). Visual inspection is effective only in detecting failed rods on the periphery of the assembly, eddy current investigation requires removing the fuel rod(s) from the assembly to be individually measured, and ultrasonic testing has success rates estimated to be only 80-90% (IAEA, 2010).

When a leaking fuel assembly is repaired, it is important to be sure that *all* failed rods are replaced, should there be more than one, since a leaking rod reinserted into the core has a relatively high probability for degradation during an additional cycle. Fuel sipping may be used for this purpose; however, it is not a reliable method for detecting leaking fuel rods in repaired fuel assemblies which have been contaminated by other leaking rods.

Alternative methods of identifying leaking fuel rods within a fuel assembly are of interest, including gamma tomography which has previously been proposed as a method for leaker rod identification (Enokido et al., 1995). The gamma tomography method is especially attractive since it does not require removal of the fuel rods for individual inspection. Gamma tomography is investigated in this work for its feasibility as a leaker rod identification method.

2 GAMMA TOMOGRAPHY FOR LEAKER ROD IDENTIFICATION

Tomography is a technique, where external measurements are used to reconstruct information about an objects interior (such as an image). The principle of this method for leaker-rod identification is that the gamma radiation field surrounding the fuel assembly at the axial position of the gas plenum region is recorded, and tomographic reconstruction techniques are used to obtain an image of the gamma-ray source distribution within the fuel assembly cross section at this axial position. Fuel rods which have expelled their radioactive fission gasses (i.e. those that are leaking) are expected to be indicated in the resulting rod-by-rod activity distribution by their relative low activity.

2.1 THE GAMMA TOMOGRAPHIC METHOD

Gamma tomography, specifically Single Photon Emission Computed Tomography (SPECT), of nuclear fuel assemblies involves two basic steps: (1) recording the gamma-ray flux distribution in a number of points surrounding the fuel, and (2) performing a tomographic reconstruction of the source distribution, based on the measured data.

In the first step, a gamma-ray spectroscopy system records the gamma radiation field surrounding the fuel using one or several detectors, which are collimated to ensure that they record gamma rays emitted from a well-defined volume of the fuel. The detectors are translated and rotated relative to the fuel at a selected axial location and gamma-ray spectra are collected at each detector location. Analysis of selected peaks in the collected gamma-ray spectra, allows for specific attributes of the fuel to be characterized.

In the second step, tomographic reconstruction techniques are applied to the recorded data to produce an image or data set describing the spatial distribution of the gamma-ray source within the fuel assembly. There are many different tomographic reconstruction techniques which have been developed since the basic principles were first described by Radon in 1917. In medical applications, analytic techniques are primarily used, but for heterogeneous objects such as nuclear fuel assemblies, algebraic techniques may be a better choice (Jacobsson Svärd, 2005).

Gamma tomography has been previously demonstrated for quantitative measurement of rod-by-rod activity contents in irradiated nuclear fuel assemblies (Jacobsson Svärd, 2005). Here, the technique was applied to BWR fuel assemblies for determining their internal rod-by-rod power distribution. The analysis was based on analysis of the 1596 keV gamma rays emitted in the decay of ^{140}La (a daughter of ^{140}Ba), representative of the power in the last weeks of operation, and algebraic reconstruction techniques were used.

Gamma tomography has also been investigated as a safeguards verification method, whereby missing rods may be detected in irradiated fuel assemblies (Jacobsson Svärd, 2006; Lévai et al, 2002). In (Jacobsson Svärd, 2006), the method relied on spectroscopic analysis of selected gamma peaks, while in (Lévai et al, 2002), the method is based on the gross gamma activity above a selected energy threshold. In both cases, missing rods may be identified by the relative low activity in a fuel rod location which should otherwise contain higher activity if the fuel rod were present.

2.2 FISSION GAS ISOTOPES AVAILABLE FOR LEAKER ROD IDENTIFICATION USING GAMMA TOMOGRAPHY

In order for the tomographic reconstructions to be useful, there must first be adequate data available from the gamma-ray spectroscopy measurements. For the purpose of identifying leaking rods, it is desired to identify rods which do *NOT* contain fission gasses. This implies that some radioactive fission gas must be present in the gas plenum of intact fuel rods, and that during its decay this gas must emit gamma rays suitable for measurement. Specifically, the fission gas isotope must have a suitable half-life, and the emitted gamma-rays must be within the operating range of the detector and must be able to be resolved in the collected gamma-ray spectra.

Several fission gas isotopes have been measured in the gas plena of fuel rods using gamma ray spectroscopy (Holcombe et al 2009; Holcombe et al 2011). Measurement of the long-lived ^{85}Kr has been used to investigate fission gas release behavior over the lifetime of individual fuel rods (Holcombe et al 2009), and some short-lived isotopes, such as ^{133}Xe , and ^{135}Xe have been shown to be measurable a short time after reactor shutdown (Holcombe et al 2011).

Some properties which are crucial for the isotopes' suitability for use in tomographic measurements include their production and decay properties and the resulting attenuation coefficients for their emitted gamma rays in the various structural materials encountered in a tomographic measurement. Selected production and decay properties of some relevant isotopes are shown in Table 1, while the linear attenuation coefficients for selected materials and gamma-ray energies are presented in Table 2.

Table 1, Production and decay properties of three fission gas isotopes that may be used in tomographic measurements.

Isotope	Half-life	γ -ray energy [keV]	Branching ratio [%]*	Fission Yield [%]*
^{133}Xe	5.24 days	81	38	6.6991
^{135}Xe	9.14 hours	250	90	6.5385
^{85}Kr	10.8 years	514	0.434	0.2834

*from ENDF/B VII.1

Table 2, Linear attenuation coefficients for selected gamma-ray energies and typical materials encountered in nuclear fuel assemblies and measurement set-ups.

γ -ray energy [keV]	Linear attenuation coefficients [cm^{-1}] †				
	Water	Stainless Steel	Zircaloy-4	Air (1 atm)	Helium (30 atm)
81	0.183	4.538	11.01	0.00020	0.00022
250	0.127	0.976	1.068	0.00014	0.00016
514	0.096	0.659	0.560	0.00011	0.00012

† Deduced from data obtained from National Institute of Standards and Technology, XCOM, Photon Cross Sections Database

As can be seen from the properties summarized in Table 1 and Table 2, each of the isotopes and their respective gamma rays have both favorable and unfavorable properties with regard to leaker rod identification measurements using gamma tomography. Table 3 lists the main advantages and disadvantages of the selected isotopes.

Table 3, Advantages and disadvantages of the selected isotopes.

Isotope	Half-life	γ -ray energy [keV]	Advantages	Disadvantages
^{85}Kr	10.75 y	514	<ul style="list-style-type: none"> - long half-life - high γ-ray energy 	<ul style="list-style-type: none"> - low fission yield - low gamma emission yield - interfering peak (annihilation at 511 keV)
^{133}Xe	5.24 d	81	<ul style="list-style-type: none"> - high fission yield - high gamma emission yield - intermediately long half-life - no interfering peaks 	<ul style="list-style-type: none"> - low γ-ray energy
^{135}Xe	9.14 h	250	<ul style="list-style-type: none"> - high fission yield - high gamma emission yield - high γ-ray energy - no interfering peaks 	<ul style="list-style-type: none"> - short half-life

In case leak identification is to be performed at longer cooling times, the long-lived ^{85}Kr may be an attractive choice, provided that high-resolution gamma-ray spectroscopy can be used to separate the 514 keV ^{85}Kr peak from the annihilation peak at 511 keV. At shorter cooling times, its intensity is expected to be too low to be accurately measured in the presence of more short-lived isotopes.

Of the more short-lived isotopes, ^{133}Xe , has high activity, but the low energy gamma rays are strongly attenuated in structural materials such as fuel rod cladding. ^{135}Xe has high activity and a suitable gamma energy; however, its short half-life means that it must be measured very soon after reactor shutdown.

In order to further investigate the usefulness of these isotopes for gamma-tomographic leak identification measurements, simulation studies have been performed, as described in the following section.

3 SIMULATION STUDIES

The established Monte Carlo code, MCNP (Pelowitz, 2005), was used to simulate gamma-ray transport from fission gasses in the plenum region of an example Halden Boiling Water Reactor (HBWR) fuel assembly through a set of collimator slits at selected locations surrounding the fuel. This simulated measurement data was subsequently reconstructed into images of the gamma-ray source distribution within the fuel assembly.

3.1 FUEL MODEL AND SOURCE

The fuel assembly modeled was consistent with the dimensions of HBWR fuel. Whereas the number of fuel rods in HBWR fuel may vary, the modeled fuel contained 18 fuel rods with one leaking rod in the inner ring of fuel rods. The leaking rod was simulated by defining a weaker gamma-ray source content, having a factor of ten less activity than the intact rods. The channel surrounding the fuel is part of the measurement equipment under development at the HBWR (Holcombe et al, 2012) and was accordingly simulated as stainless steel, consistent with the design of the

HBWR device. However, for the simulations using the 81 keV gamma rays an Aluminum channel was used in order to minimize the attenuation of these gamma rays in the channel.

The volume inside the channel and surrounding the fuel rods was modeled as either air or water. The gamma tomography device under development at the HBWR is planned to allow for measurements in air, but in the case of measuring fuel with short cooling time, it may be necessary to cool the fuel by flooding the channel with water. The cross sectional geometry is shown in Figure 2.

Figure 2, MCNP model of an example HBWR fuel assembly. The material filling the volume between the fuel rods was either water or air (depending on the simulation, as described in the text). The inner structure was stainless steel and the surrounding channel was stainless steel or Aluminum (depending on the simulation). The image to the right illustrates the simulated source particle distribution; the failed rod having ten times less activity than the intact rods, which all have equal source content.

Full-energy gamma-ray transport was of primary interest since an HPGe-based detection system with high energy resolution is planned to be used. Accordingly, the source was mono-energetic with an energy of 81 keV, 250 keV or 514 keV depending on the simulation. The internal gamma-ray source distribution in each fuel rod was simulated to be uniform. In order to save simulation time, source biasing was used to preferentially direct source gamma rays towards the detectors.

3.2 MODELLED INSTRUMENTATION

The modeled instrumentation was based on the gamma tomography instrumentation currently under development at the HBWR (Holcombe et al, 2012). In order to reduce the simulation time, some simplifications were made; (1) an ideal collimator was assumed, i.e. no gamma rays were allowed to pass through the collimator material, only through the collimator slits, and (2) no detector was simulated and the analysis was based on all gamma rays passing through the collimator slit with their full energy preserved.

These simplifications allowed many collimator/detector positions to be modeled simultaneously. Here, 41 collimator slits were modeled, each with its own recorded data (MCNP surface current tally). Each collimator had a slit width and height of 1 mm and 20 mm respectively. The collimator length was 50 cm, and the distance from the center of the fuel to the detectors was 55 cm.

3.3 SIMULATED MEASUREMENT SEQUENCE

In the simulations, the detector/collimator package was rotated relative to the fuel at angular steps of 3° . At each angular step, MCNP calculated the non-perturbed flux of gamma rays to pass through the collimator slits, i.e. the fraction of gamma rays reaching the detector without interacting, in order to produce a projection corresponding to each of the angular steps. A sample projection at 0° is shown in Figure 3. The projections were scaled such that the number of counts in the measurement position with the highest simulated intensity was assumed to be 2500. Finally, statistical uncertainties were superimposed upon this simulated data, based on simple Poisson statistics. Additional uncertainties based on e.g. background subtraction were not taken into account and intensities of zero, for which Poisson statistics is undefined, were kept at zero.

Figure 3, Sample projection from the 0° rotation angle.

For symmetry reasons, only 180° rotation was simulated and used twice to depict the entire 360° rotation.

3.4 SIMULATED MEASUREMENTS AND TOMOGRAPHIC IMAGE RECONSTRUCTIONS

The following measurements and corresponding construction materials were simulated in this work:

- a) Detection of 81 keV gamma rays from ^{133}Xe .
Because of the low gamma-ray energy, a measurement setup with the smallest possible gamma-ray attenuation was modelled, i.e. with air inside the fuel channel, surrounding the fuel rods, and with the fuel channel itself constructed of Aluminum.
- b) Detection of 250 keV gamma rays from ^{135}Xe .
 - i. A fuel channel in stainless steel with water inside
 - ii. A fuel channel in stainless steel with air inside
- c) Detection of 514 keV gamma rays from ^{85}Kr
A fuel channel in stainless steel with water inside

Tomographic image reconstruction of the simulated measurement data was performed using a filtered back-projection algorithm (Kak and Slaney, 1999). This method, while not optimized to take attenuation into account, is adequate for obtaining images of the source distribution, in which failed rods may be visually discerned. The resulting images are presented in Figures 4-7.

Figure 4, Reconstructed image based on the 81 keV source (^{133}Xe) simulations. The simulated measurement scenario here has used materials with minimum attenuation to allow for the best possible conditions for the low energy source gamma rays to reach the detectors. Still, the inner rods are not discernible.

Figure 5, Images obtained using the 250 keV source (^{135}Xe). On the left with a stainless steel fuel channel with water inside, surrounding the fuel rods, and on the right, with a stainless steel fuel channel with air inside. The inner rods are visible in both images, and the failed rod is easily identifiable.

Figure 6, Image obtained using the 514 keV source (^{85}Kr), simulating a stainless steel fuel channel with water inside, surrounding the fuel rods. The inner rods are visible and the failed rod is easily identifiable.

It is clear from the simulations based on the ^{133}Xe source that the 81 keV gamma rays are not useful for discerning inner fuel rods. The strong attenuation of this low gamma-ray energy results in almost no transmission from the inner fuel rods to the detectors. Thus, 81 keV gamma rays from ^{133}Xe are deemed unsuitable for leaker rod identification in tomographic measurements.

Using the simulated 250 keV energy from ^{135}Xe , the inner rods are clearly visible in both images. Furthermore, the leaking rod is easily discerned with either water or air surrounding and filling the fuel channel.

The image obtained for the ^{85}Kr source (514 keV) is similar in quality to the images obtained for the 250 keV gamma-ray source. The inner rods are clearly visible in the image and it is easy to discern the leaking rod.

4 CONSIDERATIONS FOR THE PRACTICAL APPLICATION OF THE METHOD

For the case of the 250 keV and 514 keV simulations, it appears at first glance that leaker rod identification using gamma tomography is feasible either under water or in air; however, there are other practical issues which must be considered and/or overcome in order for this technique to be successful.

4.1 AVAILABILITY OF FUEL AT SHORT COOLING TIMES

Because ^{135}Xe has a half-life of only 9.14 hours, tomographic measurements for leaker rod identification using this isotope must be performed very soon after the end of irradiation, before its inventory has disappeared. Fuel with such short decay times may require cooling in the measurement fixture. Being able to perform measurements within a short time after shutdown may not always be possible due to fuel handling constraints, especially at commercial power reactors.

4.2 EXPERIMENTAL CHALLENGES FOR ^{85}Kr MEASUREMENTS

^{85}Kr is a long-lived fission gas isotope, which is abundantly present in the fuel and in the potentially released fission gasses. There is much experience with measuring ^{85}Kr

to determine the fission gas release fractions within individual fuel rods. Challenges associated with measuring the 514 keV peak include the low emission rate of these gamma rays, and the proximity of the peak to the positron-annihilation peak (511 keV). In order to be able to resolve the 514 keV peak in the measured spectra from irradiated fuel, it is generally necessary to allow the fuel to decay for at least six months. These same challenges will be present in tomographic measurements.

4.3 RODS WITH LOW FISSION GAS CONTENTS

These simulations were based on a uniform fission gas release concentration in each of the fuel rods, with the failed rod containing 10% of the amount contained one of the intact fuel rods. However, fission gas release distributions in actual irradiated fuel assemblies are not necessarily uniform, and the rod-to-rod variations in the fission gas release fraction within a fuel assembly may make it difficult to visually discern which rod is failed. Furthermore, when a fuel rod fails, it is not guaranteed that it will expel such a large portion of its fission gas inventory. Factors affecting how much fission gas is expelled include e.g. the location of the failure on the fuel rod, the size of the failure, and the burnup of the fuel.

Additional information may be needed to determine if one or more rods contain a smaller-than-expected amount of fission gas. It is suggested to use an established code for calculating the fission gas content and release to the plenum, such as the STAV code (Zhou, 2008).

Furthermore, one has to define the operational limits of a gamma tomography leaker rod identification system with regard to fuel burnup. Fuel with low burnup will have correspondingly low fission gas production and low fission gas release. In this case there may not be sufficient fission gas inventory in intact fuel rods to distinguish them from failed fuel rods in the reconstructed image. Further investigations are required to determine the burnup range for which the proposed method is feasible.

4.4 TIME REQUIRED FOR MEASUREMENT

The time required for measurement is expected to be crucial for the applicability of tomographic leaker identification measurements. The relatively low emission rates of gamma rays from fission gases require long measurement times to yield statistically accurate data, and tomographic measurements require data from a large number of measurement positions. Predominantly, the measurement time will depend on the number of detectors used and on the achievable count rate in the detector.

As a first estimate, the time required for the tomographic measurement equipment currently under construction at the Halden BWR (Holcombe et al, 2012) has been considered. This device comprises only one detector, and thus the time required for leaker identification measurements depends dominantly on the achievable count rate in that detector. In order to estimate the expected count rate, data from previously performed measurements have been considered, according to the following:

- (Holcombe et al, 2011) accounts for a measurement of the 250 keV peak from ^{135}Xe , recorded from the plenum region of a single fuel rod which had cooled for approximately three days. The collimator had a horizontal slit 1.5 cm wide and 0.5 mm high, and the detector was approximately 85 cm from the fuel rod.

The fuel rod was measured in air and the count rate in the 250 keV peak was 12 counts per second (cps). If adjusted for the dimensions of the measurement system simulated in this work, it is estimated that the corresponding count rate would be approximately 80 cps.

- Many measurement campaigns have been conducted where 514 keV gamma rays emitted in the decay of ^{85}Kr have been measured in single rods in the spent fuel pools of commercial nuclear reactors, see e.g. (Holcombe et al, 2009; Andersson, 2003). The count rates in the 514 keV peak for the measurements performed in (Andersson, 2003) ranged from 2 cps to 28 cps, depending on the amount of fission gas release. Accordingly, the count rates can be expected to be of the same order of magnitude as for the ^{135}Xe measurements.

Assuming that the number of counts in the measurement position with the highest intensity is 2500 (corresponding to a statistical uncertainty of 2% (1σ), background subtraction contributions excluded), each data point would have to be recorded for approximately 30 s. Using 120 angular and 41 lateral positions, i.e. using the number of data points simulated in section 3.4, a measurement time of more than 40 hours would be required, which is unacceptably long.

However, there are several ways that the required measurement time may be reduced, including:

- Increasing the number of detectors,
- increasing the exposed area of the detector (i.e. increase the collimator width and/or height),
- decreasing the distance between the detector and the fuel,
- increasing the angular step size (i.e. reducing the number of projections),
- utilizing a gamma ray detection system with the highest possible absolute efficiency for the measured gamma-ray energy.

In order to evaluate the effect from reducing the number of projections, with the same level of counting statistics in each data point as in section 3.4, a simulation has been performed for the 250 keV energy from ^{135}Xe , comprising 40 angular and 41 lateral positions. Just as in section 3.4, Poisson statistics were added to the data, corresponding to 2500 counts in the position with the highest count rate. The reconstructed image based on these simulations is presented in Figure 7.

Figure 7, 250 keV measurements using only 40 projection angles and with counting statistics included corresponding to maximum 2500 counts in any position. The image is of lower quality than Figure 5, but the failed rod may still be discerned.

While the reconstructed image in Figure 7 is of lower quality than the image shown in Figure 5, the failed rod may still be discerned. One should notice that the expected measurement time for this data and the equipment described in (Holcombe et al, 2012) is almost 15 hours. As a means to further reduce the measurement time, one may consider doubling the collimator slit area and reducing the distance to the detector to 30 cm, which would reduce the measurement time to around 2 hours. However, altering the measurement geometry by widening the collimator slit or placing the detector closer to the fuel should be carefully evaluated since changes in the measurement geometry may result in an increased total count rate and degradation of the image resolution. These types of time-limiting issues will be further investigated experimentally using the measurement device soon to be completed at the HBWR (Holcombe et al, 2012).

For other measurement set-ups, one may also consider the use of a large number of detectors to reduce measurement time.

5 CONCLUSIONS, DISCUSSION AND OUTLOOK

A technique for identification of leaking rods in a nuclear fuel assembly based on tomographic measurements of fission gasses in the plenum region has been proposed. The technique is based on the assumption that failed fuel rods contain much less fission gasses than intact fuel rods, and that a reduction in gas content may be identified. No dismantling of the fuel would be required.

The simulations in this work indicate that gamma tomography may be a feasible technique for leaker rod identification, and that the isotopes ^{135}Xe and ^{85}Kr are the best candidate isotopes for measurement. However, measurement of the gamma rays emitted by these isotopes presents a number of experimental challenges; the 250 keV gamma rays from the short-lived ^{135}Xe must be measured within the first few days after the end of irradiation; the 514 keV gamma rays from the more long-lived ^{85}Kr may not be measured until the fuel has cooled for approximately six months or more, and its detection requires a high-resolution spectroscopic detection system to discern it from the 511 keV annihilation peak.

Furthermore, the non-uniform rod-by-rod fission gas release distribution within actual assemblies will increase the uncertainty associated with the technique since it may lead to difficulty in determining whether a rod is failed or if it has low fission gas release due to its operation history. Neither is it clear whether all failed rods will expel enough fission gasses such that their gas inventory will be small enough to be detected using this method.

When the measured fuel has low burnup there will be low fission gas inventory and low fission gas release, leading to a scenario where there may not be sufficient fission gas inventory in intact fuel rods to distinguish them from failed fuel rods in the reconstructed image. In order to define the operational limits of this technique, it is recommended to perform additional investigations of assemblies with a wide range of burnups.

Finally, it has been acknowledged that the measurements may be very time consuming due to the low emission rates of the 250keV and 514 keV gamma rays, and accordingly, efforts must be made to maximize the count rates by carefully designing a dedicated measurement system.

At present, a gamma tomography measurement system is under development for use at the HBWR (Holcombe et al, 2012). Tomographic measurements of the contents of fission gasses in the gas plenum region of HBWR fuel assemblies are planned and further investigations of the feasibility of leaker rod identification using this technique will be performed, covering issues such as detectability and time required for measurement.

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