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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.

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 Fig. 1. This information is based on 417 Light Water Reactors (LWRs) which in total reported nearly 800 failed fuel assemblies during this time period.

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.

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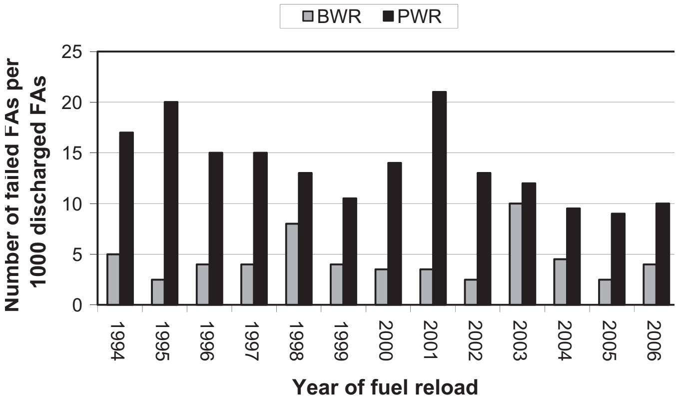

Fig. 1. World average fuel assembly failure rates for BWRs and PWRs during the period 1994–2006, according to (IAEA, 2010). This information is based on 417 LWRs which operated during the given time period and which in total reported nearly 800 failed fuel assemblies.

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, 2011). Measurement of the long-lived ^{85}Kr has been used to investigate fission gas release behavior over the lifetime of indi-