Development of a Limited Angle Gamma Ray Emission Tomography System for In-Situ Spatially-Resolved Measurement of Fuel Burn Up and Pre-Shutdown Power

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INTRODUCTION

It is recognized that spatially-resolved assessment of fuel burn up provides useful data for the validation of core physics models that subsequently allow fuel management strategies to be improved, plant lifetime extension requests to be made, and confidence in through-life safety cases to be increased. However, whilst there exist a number of suitable destructive and non-destructive techniques that can be used to determine the spatial distribution of radioactive fission products within nuclear fuel assemblies, they all share a common limitation: they can only be used at end-of-cycle (EOC), or end-of-life (EOL), once the reactor core has been de-fueled. Given that many proposed small modular reactor (SMR) designs are fueled-for-life, useful data to substantiate designs would not be available for many years, if at all. In-situ measurements made at time-points through-life could be highly beneficial.

In-situ imaging measurements of neutron and gamma ray fields in an operating nuclear reactor have been performed [1]. These measurements, whilst proportional to the reactor power, did not provide a spatially-resolved measure of burn up and only a qualitative (>6 mm resolution) understanding of fuel element power distribution. No measurements whilst shutdown were reported. Whilst non-invasive imaging based on single photon emission computed tomography (SPECT) can be used to produce high resolution maps of the internal distributions of burn up indicator isotopes such as ^{137}Cs, and pre-shutdown power indicator isotopes such as ^{140}Ba [2], they can only do so for single fuel assemblies because of the necessity for rotation of detectors relative to them.

Even if access could be provided to a shutdown reactor core, for fuel assemblies positioned within it, it would not be possible to map indicator radioisotopes in a meaningful way (e.g. with fuel element resolution) using conventional gamma ray emission tomography due to the mechanical uncertainties resulting from the large travel distances and the attenuation due to the surrounding fuel assemblies. However, one special type of computed tomography, computed laminography, can be used where access is limited [3]. Computed laminography is similar to computed tomography, however, projections are taken over a limited angular range to produce a partial three dimensional image of the object. In the absence of an external source, for a nuclear fuel assembly the image will show the internal radioisotope source distribution. If appropriate indicator radioisotopes are selected, the imaging system is sufficiently precise, and a suitable, validated, method of reconstruction is chosen, the activity of a given radioisotope as a function of position can be deduced to with a few %.

LATIMER: LIMITED ANGLE TOMOGRAPH FOR IN-SITU MEASUREMENT OF GAMMA EMISSION FROM REACTORS

Obviously in most power reactors the reactor vessel will lack the external penetrations necessary to conduct computed laminography of fuel assemblies whilst in-situ and will, along with other support structures, attenuate emitted gamma rays. Therefore, to develop a proof-of-principle, limited-angle tomograph for SPECT of nuclear fuel assemblies, a suitable reactor at which measurements could be taken was chosen. Due to a longstanding collaboration between the Defence Academy of the United Kingdom and the Czech Technical University (CTU) in Prague, the VR-1 training reactor at the Department of Nuclear Reactors was selected. The VR-1 is a pool-type light water reactor that uses low enriched IRT-4M fuel assemblies [4]. These assemblies are placed in an 8×8 Cartesian grid to make the reactor core. One side of the core abuts a 250 mm diameter horizontal radial channel that spans the entire width of the primary shield. The LATIMER system has been designed to fit within this channel as shown in Figure 1.

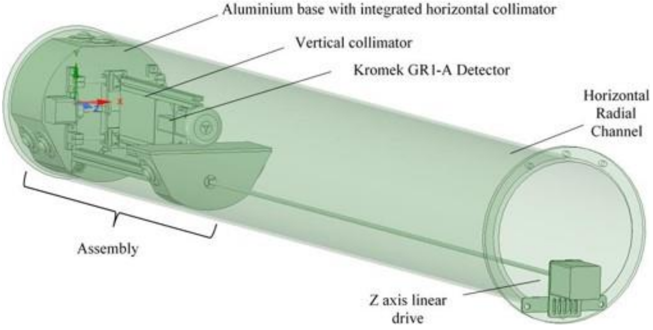

Fig. 1. CAD drawing of the LATIMER system design.

Collimated Detector Assembly (CDA)

Like the EGRET system [5], LATIMER makes use of a crossed slit collimator configuration to constrain gamma rays from a source. It is built on a 240 mm diameter, 300 mm long aluminum cylindrical base through the middle of which a 150 mm wide, 1 mm high horizontal slot is cut. This slot provides collimation of gamma rays in the axial plane. A 200 mm long stainless steel vertical collimator with a 1 mm wide aperture is fixed on the rear of the cylinder (relative to the core). This collimator is hung off of a position-encoded precision hinge, itself mounted on a stepper motor actuated, x-axis linear slide. The vertical collimator can be moved through a 30° angular range by a stepper motor actuated wheel that is driven across a hemi-cylinder located to its rear. This step mimics traditional rotation about a source. Once a full angular sweep is made, the vertical collimator is returned to its mid-range position (where the drive wheel is parallel to the direction of travel of the linear slide) and incremented in the lateral direction. This process is repeated until the full x-theta space has been covered. The whole CDA is then incremented in the z-direction (further down the radial channel from the core) by a stepper motor driven ball screw, and the process is repeated. Gamma rays are detected by a Kromek GR1-A, 1 cm thick cadmium zinc telluride (CZT) detector that is mounted at the end of the vertical collimator. It is estimated that a spatial resolution of <4 mm in the radial plane is achievable.

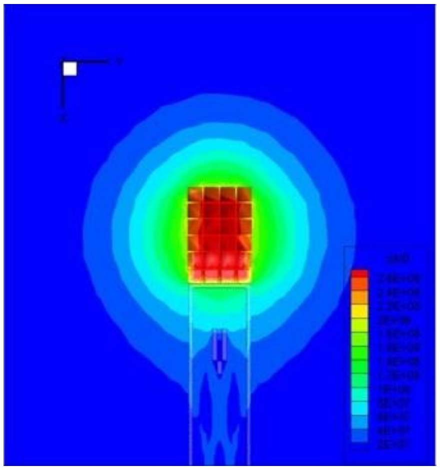

Fig. 2. Calculated gamma ray flux in the VR-1 core and radial channel.

Optimization of the size and shape of the vertical collimator has been undertaken using the Attila code (Varex Imaging). Due to high aspect ratio of the collimator and the resultant large mesh, a 3D model was set up as a 1 mm high rectangular slice in the plane of the horizontal collimator, encompassing both the VR-1 core and radial channel. Using ^{140}Ba (1.6 MeV) as the upper bound energy for shielding purposes, a monoenergetic source term within the fuel assemblies was produced and gamma ray flux in the energy group >1.5 MeV in the GR1-A detector flux was calculated and compared to the expected line-of-sight flux. This process was repeated for different collimator designs and angles.

Data acquisition, post-processing and reconstruction

The LATIMER data acquisition and control, and post-processing and reconstruction systems are based on those previously developed for EGRET [5]. Like in EGRET, once all projections are acquired, MCA spectra are post-processed; background removal is performed using the SNIP algorithm and required gamma ray peaks fitted using the Levenberg-Marquardt (LM) approach. The point-by-point measured flux in each peak is then passed to the TORPOINT (TOmographic Reconstruction of POINTs) reconstruction code. TORPOINT implements a forward transport model for gamma rays through 'ideal' fuel assemblies in the core in order to determine a system matrix that is then used to solve the inverse problem via an implementation of the Algebraic Reconstruction Technique (ART) or the conjugate gradient least squares (CGLS) approach. Due the incomplete number of projections, whilst the fidelity of the reconstruction is high towards the image center, it falls off towards the periphery.

CONCLUSIONS

LATIMER is the first SPECT laminograph designed for spatially-resolved, in-situ measurement of fuel burn up and pre-shutdown power. The basic system design has been completed and the size and shape of the vertical collimator is being optimized through Attila modelling. Once this step is complete, manufacture and build will commence. As the data acquisition, post-processing and reconstruction software is common to the EGRET system developed previously by the Defence Academy of the United Kingdom, it is expected that testing will commence in summer 2018. Investigations into whether LATIMER can be used whilst the reactor is at power will be undertaken in the near future.

ACKNOWLEDGMENTS

The authors acknowledge support from Jan Rataj, Tomas Bily and Ondrej Huml at the Czech Technical University.

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