Proof-of-Concept for Safeguards of Spent Nuclear Fuel Using Passive Fast Neutron Emission Tomography

Nuclear Science & Security Consortium

Mairead E. Montague[1], P. A. Hausladen[2], J.P. Hayward[1,2]

mmontag1@vols.utk.edu [1]University of Tennessee, Knoxville [2]Oak Ridge National Laboratory

Abstract

IAEA goals include preventing the proliferation of nuclear weapons, developing surveillance techniques for nuclear materials, and pursuing the continuity of knowledge over nuclear materials.[1] Reactor fuel assemblies can individually produce over half of a significant quantity of special nuclear material. Extensive research has gone into determining methods to prevent diversion of the spent nuclear fuel. Passive fast neutron tomography using a modified parallel slit collimator is one such method. Using spontaneous fission from the build up of ^{244}Cm, spent fuel can be imaged, potentially at the level of individual fuel pins. In this experiment, a ^{252}Cf neutron source is used to demonstrate the viability of Passive Fast Neutron Emission Tomography (NET). After measuring 5 source locations at varying pin spacing, the measured data is combined to represent 5 closely spaced fuel rods. The reconstruction of this data demonstrates the imager's ability to differentiate between individual fuel pins.

Introduction

Neutron Sources in Spent Nuclear Fuel:

Spent nuclear fuel has a high neutron emission rate of 10^7 - 10^8 n/s.

- Many of these neutrons come from decays of transuranic isotopes that are formed during reactor operation: ^{244}Cm, ^{242}Cm, ^{240}Pu, ^{238}Pu, ^{242}Pu

Typically, measuring neutrons from spent nuclear fuel means measuring the ^{239}Pu content in fuel.

Drawbacks include:

- Pu saturates with increased burnup
- Minimally sensitive to rod replacements

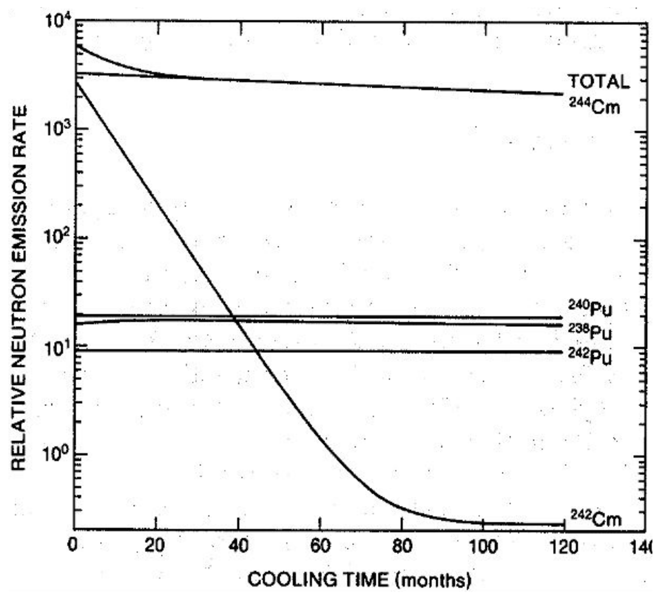

Figure 1: Relative neutron emission rates per isotope from spent fuel at a burnup of 31.5 GWd/tU over the course of 10 years.[2]

The relative contribution to the neutron emission rate of a spent fuel assembly from ^{244}Cm is higher than from other transuranic isotopes.

- At a burnup of 31.5 GWd/tU, ^{244}Cm neutron emission dominates neutron emission[2]
- ^{244}Cm has neutron production rate of 1.64×10^7 neutrons/s/g
- Does not saturate as a function of burnup

NET proposes using the spontaneous fission rates of ^{244}Cm to monitor and image spent nuclear fuel by detecting the fast neutron emissions.

Neutron Source in this Experiment:

^{252}Cf used instead of ^{244}Cm

- More accessible source
- Identical Watt fission spectrum[3]
- Emission Rate: 67780 ± 1356 n/s/cm[3]
- Neutron source was placed along the vertical centerline of the neutron detectors

Imager Design

Modified Parallel Slit Collimator:

72 Tapered Slits arranged around a 35.5 cm diameter inspection volume

- Inner Slit Diameter: 0.3 cm
- Outer Slit Diameter 0.8 cm

Collimator Components

- **(a)** Inner 10 cm of stainless steel to reduce gamma dose to the detectors
- **(b)** 29.22 cm of borated polyethylene (5% by weight boron) to collimate neutrons

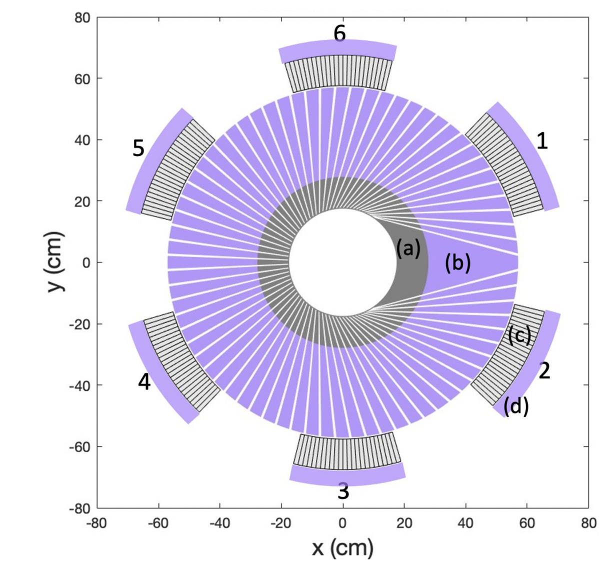

Figure 2: The 72 slit collimator consists of 10 cm of stainless steel (a), 30 cm of borated polyethylene (b). The detector ring is 6 detector modules (c) with a 5 cm thick layer of HDPE behind the detectors (d).[4]

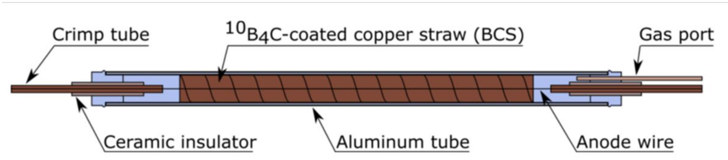

Figure 3: Drawing of a Boron-Coated Straw detector.[4]

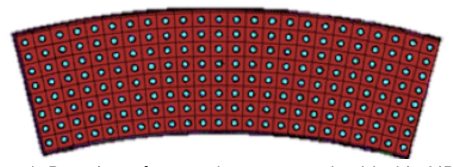

Figure 4: Drawing of straw detectors embedded in HDPE[4]

Neutron Detector Modules:

One detector module consists of 24 rows of 8 boron coated straws embedded in high density polyethylene

- Each row of 8 straws has single readout channel
- Located 0.5 from collimator to allow the collimator to rotate

Detector Components

- **(c)** 6 detector modules to moderate and detect fast neutrons
- **(d)** 5 cm of borated polyethylene to prevent background neutrons from scattering into the system

Full Detector Measurement:

A full measurement would require 12 detector modules but only 6 were constructed

- Every other detector position is a spacer made of aluminum and polyethylene
- The detector ring could be rotated by 1 detector module spacing to get the missing 6 detector positions
- Each measurement would need to be taken twice, once in each position, to get the full view

Figure 5: The fully constructed imager assembly.

Experiment

Mock PWR Grid:

17 x 17 pressurized water reactor fuel assembly grid created to hold mock source rods

- Centered in the inspection volume and coordinate system assigned where the center fuel pin is (0,0)
- Fuel pin hole diameter: 0.96 cm
- Fuel pin pitch: 1.27 cm

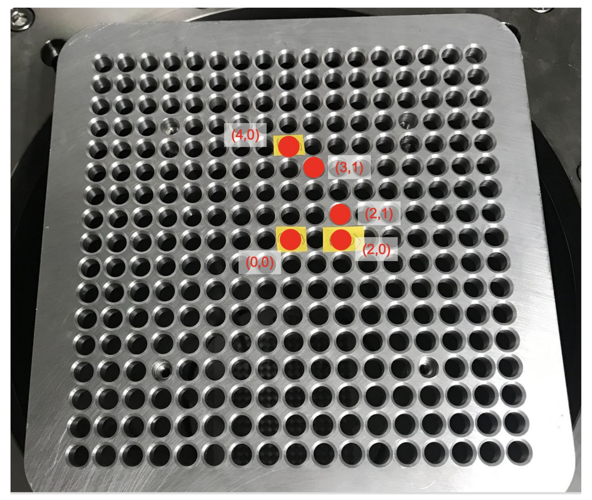

Figure 6: The grid with red labels on each fuel pin where a source measurement was taken.

Experimental Procedure:

1. Initial Background measurement taken with no source present
2. Source rod was then placed into the fuel assembly mock grid at 5 separate locations to examine the spatial resolution.
   - Rod positions measured: (0,0), (0,4), (2,0), (1,3), and (2,1)
   - Fuel pin coordinate distances: 1, √2, 2, and 4
   - Determine if individual pins can be differentiated
3. Collimator rotated at a constant speed while recording data for one full rotation

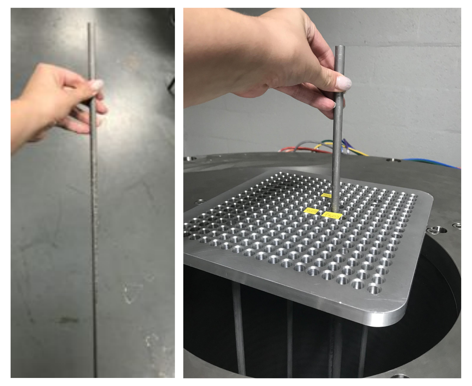

Figure 7: Neutron source rod by itself (left) and in the grid fixture (right).

4. Bin neutron counts by collimator position
   - 72 collimator positions or projections
   - Detected neutrons per projection are the neutrons detected in a time period defined by the total measurement time divided by the number of positions
5. Create a sinogram
   - Organize neutron counts by detector number and projection number and subtract off the background measurement
   - The individual measurement data were summed to represent a single measurement with 5 identical sources in various locations

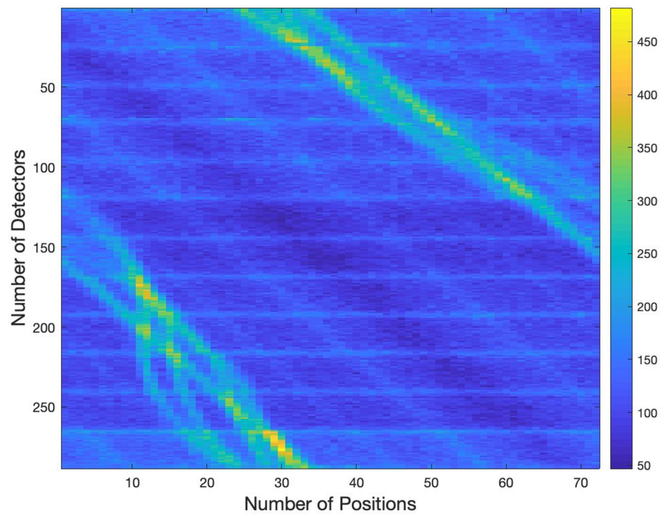

Figure 8: The experimentally generated sinogram for all 5 sources.

Table 1: Summary of initial measurements performed

Source slot	Date of Measurement	Measurement time (s)	Total detected neutrons	Detected neutrons per projection
(0,0)	6/28/21	4520	545119	7571
(0,4)	7/1/21	4641	537167	7460
(2,0)	7/1/21	4518	536682	7454
(1,3)	7/12/21	4593	536396	7450
(2,1)	7/2/21	4606	538943	7485

Results

Iterative Reconstructions:

The experimental data is then reconstructed using a Maximum Likelihood Expectation Minimization reconstruction.

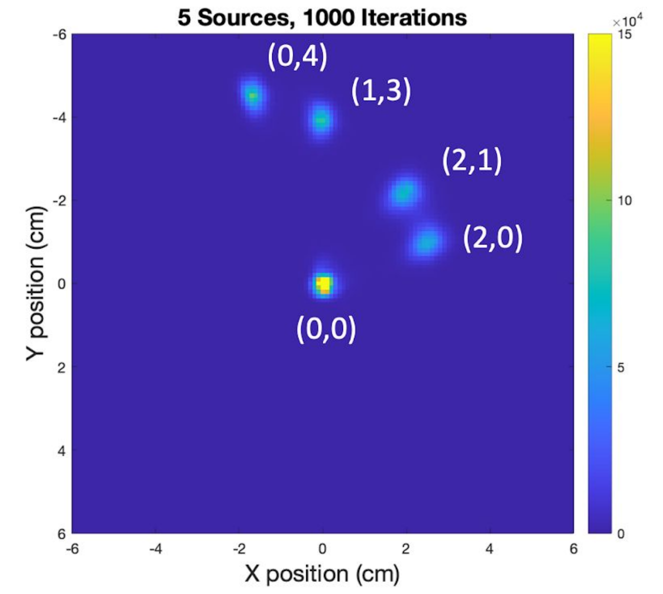

Figure 9: A zoomed in reconstructed image of all 5 sources after 1000 iterations.

The imager demonstrates sufficient spatial resolution to resolve individual fuel pins at 1 fuel pin pitch apart (1.27 cm).

- Sources at (2,1) and (2,0) are visibly separate sources.

Issues with spatial reconstruction

- Sources, except the one at the origin, are oblong-shaped, rather than circular
- Intensities of each source should be similar, but the image shows a much greater intensity for the source at the center
  - Source intensity at (0,0) is 3.85×10^6 emitted neutrons
  - Source intensity at (0,4) is 2.28×10^6 emitted neutrons
  - 59% difference in the emitted neutron intensity
- Total integrated source intensity in the image is accurate but overly weighted toward the center

Conclusion

An experiment was performed using a proof-of-concept passive fast neutron emission tomography imager to determine the ability of the imager to resolve individual fuel pins. Using five source measurements to represent spent nuclear fuel pins at different pin spacing, the imager was used to detect fast neutrons from Cf-252. The imager exhibits sufficient spatial resolution to differentiate between individual fuel pins spaced at 1, √2, 2, and 4 fuel pin gaps. More work must be performed to improve the source (pin) intensity distribution and source localization. The initial testing of the imager demonstrates its potential as a nondestructive verification tool for SNF exceeding the IAEA's guidelines for partial defect detection in spent fuel assemblies.

References

[1] *International Safeguards in the Design of Nuclear Reactors*. International Atomic Energy Agency, 2014.

[2] J. R. Phillips, "Irradiated Fuel Measurements," in Passive Nondestructive Assay of Nuclear Materials, 1991

[3] Radev R, McLean TD. Characterization of ^{244}Cm neutron sources. Appl Radiat Isot. 2020 Sep;163:109225. doi: 10.1016/j.apradiso.2020.109225. Epub 2020 May 20. PMID: 32561061.

[4] Hausladen, P. A., et. al. "Initial Measurements with the Prototype Parallel-Slit Ring Collimator Fast Neutron Emission Tomography System" 4, 2021

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