Modelling Passive Fast-Neutron Emission Tomography of Spent Nuclear Fuel

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Project Goal

• ORNL is developing a passive fast neutron emission imager for the purpose of verifying the completeness of spent fuel assemblies

• Why not measure plutonium content?
  – The plutonium content is insufficiently known (only known to a few percent using burnup codes), so plutonium measurements will never be able to verify the completeness of a fuel assembly at the single pin level
  – Pu content saturates, so it is less sensitive to some diversion scenarios

• Present and near-term verification performed by both bulk measurements (Fork Detector) and imaging systems (Digital Cherenkov Viewing Device and Passive Gamma Emission Tomography)
Neutron Imaging Approach

Why imaging?
• Would you attempt to detect the absence of a single star by measuring the total brightness of the night sky?

Why fast neutrons?
• May be more sensitive to defects at the center of large fuel assemblies
• May be more sensitive to fuel that was replaced and subsequently irradiated
• May be able to separately measure pin-by-pin fissile mass in addition to exposure (burnup)
Challenges

• **Fundamental question**: Can we make a fast neutron emission imager capable of resolving individual fuel pins in large (17 × 17) assemblies that is usable (reasonable size, measurement times)?

• **Primary challenges** come from the need to reconcile largely incompatible demands:
  – **High efficiency** to use modest neutron activity
  – **Usable size** (assume facilities can handle something up to the diameter of a fuel cask)
  – **Gamma tolerance** to extremely high activity
  – **High resolution** to respond to individual fuel pins
  – **Effective modulation** of fast neutrons to achieve line of response
Conventional Imager Designs

- Due to propensity of neutrons to scatter, need large detectors
- Conventionally, two options:
  - Compact, scanning geometry with few detectors
  - Large geometry with many detectors
ORNL Parallel-Slit Ring Collimator Concept

- Make space for large detectors by rotating each slit to distribute endpoints evenly over outer diameter.
- Enables detectors that are large and close to the source in a compact design, slits spaced far enough to effectively modulate.
- Equivalent to a parallel slit collimator, but eliminates need to scan.

20 slits shown (actual number is ~100)
ORNL Parallel-Slit Ring Collimator Concept

• Parallel-slit ring collimator acquires same data as the parallel-slit collimator, but in a different order

• Enables compact, efficient imager without needing to scan
Baseline Design

Description:

- Stainless steel and borated polyethylene collimator with 100 slits to isolate lines of response
- Stainless steel for structural integrity and shielding detectors from gammas
- Annulus of 100 detectors that wrap around the fuel detects neutrons
- Fuel and detectors remain stationary, collimator rotates to perform tomography
- Annular design gives compact size

Radiation Resistant:

- Boron straw detectors tolerate gamma fields of hundreds of R/h

Efficient:

- Large detectors positioned close to source
- No scanning, all lines of response measured simultaneously
What Design is Best?

• The “best” design minimizes the time to resolve individual fuel pins
  – Identifies best compromise between efficiency, resolution, and gamma dose management in a package of acceptable size

• Computationally, how do we find this?

**Gamma Dose Rates**
1. Compute dose rates for survey of parameter space
2. Understand how dose rates scale with parameter changes
3. Identify limits of ability of neutron detector to reject gamma rays
4. Identify configurations that are acceptable

**Neutron Response**
1. Understand complicated neutron response
2. Estimate response for all positions in FOV from relatively few simulations
3. Define estimated SNR that identifies “good data”
4. Perform survey of collimator parameter space
Gamma Ray Dose Rates (Examples)

- Expect dose rates in hundreds of R/hour, largest where collimator is thinnest (due to slits)
- Depends primarily on stainless steel thickness
- Increases with slit width because of streaming of radiation and lowering average collimator density
Gamma Dose Rate Summary

- Simulated dose rates for 512 collimator configurations with slit widths between 1 and 5 mm (including tapering), steel thicknesses between 5 and 10 cm, and borated polyethylene thicknesses between 30 and 45 cm.
- For each thickness of steel, dose rates for different collimators fall exponentially with collimator areal density.
- For all collimators, dose rate per cm of steel falls approximately exponentially with collimator areal density.
Prototype Detector Characteristics

Straws viewed from end

Measurement in Cs irradiator facility

Fast shaping (minimizes pileup)

Is response dominated by pileup or sampling of large-amplitude signals?

Detector output as a function of dose rate

0 R/hr 22 R/hr 105 R/hr 430 R/hr

Time (µs)

Amplitude (V)

Amplitude (V)

0 0.2 0.4 0.6 0.8 1 1.2

Time (ns)

110 cm

Modelling Passive Fast-Neutron Emission Tomography
• Detectors are at or close to fundamental limitation is set by low-probability gamma interactions that deposit a large fraction of energy in a straw
Emission tomography works by using a collimator (pinhole, parallel hole) to associate detector counts with lines of response in the inspection area.
Response Modified by Inter-Detector Scattering

- Line of response limited by inter-detector scattering where neutrons traversing neighboring slits can also be detected
- Complicated response; to estimate SNR, need to know response for ~ 100,000 points in field of view for each detector of each configuration

Response of marked detector to each point in inspection area (counts/source neutron) for 3 mm slits
Approach for Parametric Study

1. Use MCNP to simulate 2 points per configuration: one to estimate “direct” component, one to estimate collimator penetration

2. Use analytical calculation to extrapolate to other ~100,000 points in field of view (FOV)

3. Use collimator response to estimate SNR
Extrapolating Slit Simulations to the Full FOV

- Each point represents an MCNP simulation
- After subtracting collimator penetration, response across a single slit is predictable in terms of the projected slit width
- Linear combination of slits gives cross talk, then add collimator penetration
Signal to Noise Ratio (SNR) and Optimizing the Collimator

- Effective SNR needs to capture both efficiency (counting statistics) and resolution.
- In this context, we define “signal” as the magnitude of the difference between the calculated response to a single pin and the same activity attributed to the “halo” around it.
- SNR compares this “signal” to the fluctuations in the total counts.

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\text{SNR} = \sum \frac{\text{Response to pin} - \text{Response to halo}}{\text{Response to assembly}}
\]
Neutron SNR Summary

- The performance of the collimator (in terms of SNR) scales roughly with the geometric mean slit width, $\sqrt{W_{id}W_{od}}$.
- Because inter-detector scattering is the primary limitation on resolution, SNR increases with increasing slit width.
- Tapered slits have similar performance to parallel slits with the same geometric-mean width.
Parametric Study Results

- The “best” collimator has the highest SNR at a gamma dose rate that is tolerable.
- Steel is a poor neutron collimator, but steel portion lowers the gamma dose rate sufficiently to enable the use of wider, more efficient slits.
- Tapered slits preserve areal density and efficiency.
- This calculation is for fuel having exposure of 40 GWd/MTU and 1 year cooling.
- The best collimator for older fuel would have wider slits and (likely) less steel.
Next Steps

- Simulation of tomographic measurement of spent fuel using realistic distribution of neutron intensities (factor of ~3 from highest to lowest)
- Development of image reconstruction software
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