Spent Fuel Characterization Through Nondestructive Assay (NDA) Measurements

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Purpose: Why are we interested in spent fuel?

- Understanding the heat content/radioactivity of spent fuel
  - Designing constraints for a repository.
  - Determining when material can be handled/moved between facilities safely.
- Positioning within a repository or interim storage facility.
  - Determining which fuel assemblies can be safely located next to each other.
  - Estimating how much fissile content exists within an assembly.
- Verifying characteristics through measurement
  - Comparing to declarations can assess initial enrichment, burnup, and cooling time.
  - Inconsistent information could indicate missing pins/diversion of fissile material.

Red = Repository objective
Green = Verification of declarations
Purple = Transportation
The spent fuel nondestructive assay (NDA) project researched methods from 2009-2019 to develop and test integrated technologies to improve NDA measurements of spent fuel assemblies with the following technical goals:

1. Verify initial enrichment, burn-up and cooling time of declaration,
2. Detect diversion or replacement of pins,
3. Estimate fissile mass,
4. Determine multiplication, and
5. Estimate heat emitted from assembly.

Objective was to provide safeguards inspectors techniques for verifying characteristics of spent fuel more effectively.

This presentation focuses on research performed as part of the spent fuel NDA project through the DOE/NNSA NA-241 Safeguards Technology office.
NDA Techniques Examined

**Passive:**
- **Comparison of high and low multiplying sections** [Passive Neutron Albedo Reactivity (PNAR)] – deployed in Japan
- **Spectral/resonance effects** [Self-Integration Neutron Resonance Densitometry (SINRD)] – deployed in Republic of Korea (ROK)
- **Time correlated neutrons from coincidence counting** [Differential Die-away Self-Interrogation (DDSI)] – field tested in Sweden

**Active:**
- **Continuous neutron interrogation** [Californium Interrogation with Prompt Neutron (CIPN)] – deployed in ROK and then instrument went to Armenia
- **Time-varying neutron interrogation** [Differential Die-away (DDA)] – fabricated and field tested in Sweden
Deployment of Passive Neutron Albedo Reactivity (PNAR) in Japan

- Primarily neutron instruments were chosen because they estimate multiplication.
- PNAR uses ratio of fission chamber (FCs) counts in high vs. low multiplying regions.
- $^{244}$Cm is main passive source, but many detected $n$ come from induced fission.

By J. Eigenbrodt
Concept:
- CIPN measures total neutron count rate with/without Californium (Cf) source present.
- Difference in counts arises from multiplication of Cf neutrons, which is proportional to multiplication/fissile content (shown axially in figure to right).

Measurements:
- Occurred September/October 2013 at KAERI, Post Irradiation Examination Facility (PIEF).
- Examined 4 PWR assemblies, burnups ranging from 17 to 38 GWd/tU, cooling times > 20 years.
Concept: Window in energy the resonance absorption from specific isotopes in transmitted neutron flux. Measured signal is proportional to isotope present/multiplication (see below). The size of water gap between assembly and instrument impacts measurement.

Measurements: 2 ROK assemblies, 12/2013

Geometry comprises 4 $^{235}$U fission chambers:

- one wrapped in 3 mm Cd,
- one wrapped in 0.1 mm Gd,
- one “bare” (thermal FM), and
- one fast flux monitor located behind 1 cm of $B_4C$ and embedded in polyethylene.

By A. LaFleur
Large Field Test Campaigns Conducted in Sweden.

- Through collaboration with Euratom and the Swedish company SKB, we measured 25 Pressurized Water Reactor (PWR) and 25 Boiling Water Reactor (BWR) spent nuclear fuel assemblies at the Swedish central interim storage facility Clab.
  - Passive gamma (PG) detectors (LaBr$_3$ and HPGe),
  - Passive neutron (total counts plus die-away) with the DDSI instrument,
  - Active neutron (total plus die-away) with the DDA instrument for a subset of assemblies, and
  - Calorimetry (to be completed in the near future).
The principle of the DDSI technique is that a passive neutron source from spontaneous fission and (α, n) neutrons induces more fission in spent fuel.

Neutrons are detected in time intervals indicative of assembly characteristics (neutron coincidence and list mode counting).

Such list mode data are converted to Rossi-alpha distributions, which are histograms of times between neutron detections.

The fit is well approximated by a double exponential at early, fast, and slow times.

25 PWRs and 25 BWRs were measured during field tests in Sweden.
• Single exponential fit to early time domain of RAD yields tau parameter, i.e. early die-away time, which is proportional to net multiplication (regardless of assembly type)
• This was demonstrated first in simulation space, then confirmed with experimental data from Sweden field trials
DDA Technique

• DDA comprises a neutron generator on one side of the assembly, and neutrons that both travel through the assembly and are created though induced fission go to detectors on the other sides.

• Fission chains within the assembly and time-dependent behavior increases knowledge of the spent fuel.

• DDA can be portable on only two sides of an assembly or large in which an assembly is inserted in the middle (see below example).
Passive gamma-ray spectra were analyzed and the reactor conditions of the spent fuel assembly, BU, IE and CT, were determined.

*A.Favalli et al., Nuclear Instruments and Methods A, 2016*
Through machine learning of data, we assess the ability of each technique/combination to predict parameters of interest. Lower fractions (<0.25) show best fits.
• Five integrated NDA instruments demonstrated their ability to measure spent fuel through field tests.

• No technique can provide all parameters of interest by itself.

• Combinations of multiple NDA techniques provide the best integrated approach to predicting spent fuel characteristics.
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