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"The State of the Art of the Nondestructive Assay of Spent Nuclear Fuel Assemblies"

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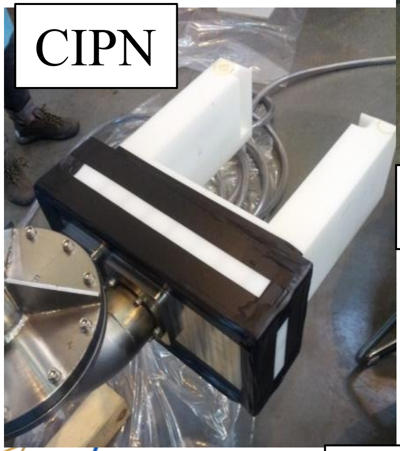
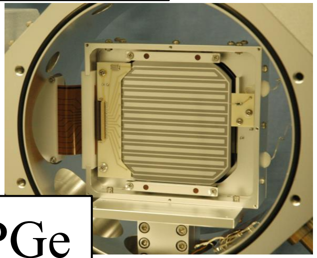
Introduction

- The purpose of this Nondestructive Assay (NDA) research is to develop and test technologies to improve NDA measurements of spent fuel assemblies (SFA).
- One effort being researched for this purpose is the Next Generation of Safeguards Initiative – Spent Fuel (NGSI-SF) project with technical goals:
  1. Detect **diversion or replacement of pins**,
  2. Verify **initial enrichment, burn-up and cooling time** of declaration,
  3. Estimate **Pu mass** in spent fuel,
  4. Measure **reactivity** (multiplication) of each assembly, and
  5. Estimate **heat** emitted from assembly.
- Other projects have also developed spent fuel NDA technology.
- Missing pin detection and other goals support the IAEA Department of Safeguards Long-Term R&D Plan, 2012-2023.

New Technologies for Spent Fuel NDA

Developed as part of NGSI-SF
Developed by other projects





Passive:

Comparison of high and low multiplying sections [Passive Neutron Albedo Reactivity (PNAR)]

Spectral/resonance effects [Self-Integration Neutron Resonance Densitometry (SINRD)]

Guide tube neutron and gamma detection [Partial Defect Verification of Spent Fuel (PDET)]

High count rate detectors [new HPGe and $LaBr_3$ gamma detector hardware; ^{10}B-based neutron detectors]

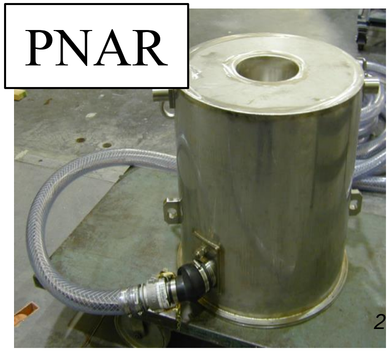
Time correlated neutrons from coincidence counting [Differential Die-away Self-Interrogation (DDSI)]

Active:

Continuous neutron interrogation [Californium Interrogation with Prompt Neutron (CIPN)]

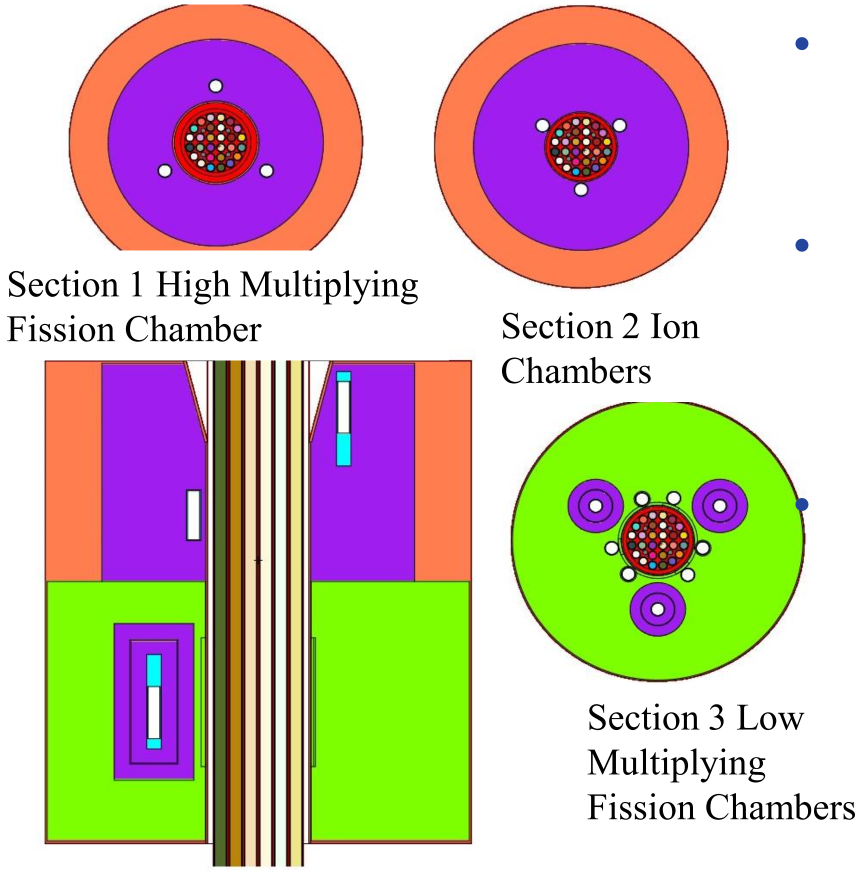
Active neutron coincidence counting [Advanced Experimental Fuel Counter (AEFC) for research reactors]

Time-varying neutron interrogation [Differential Die-away (DDA) – not built yet]



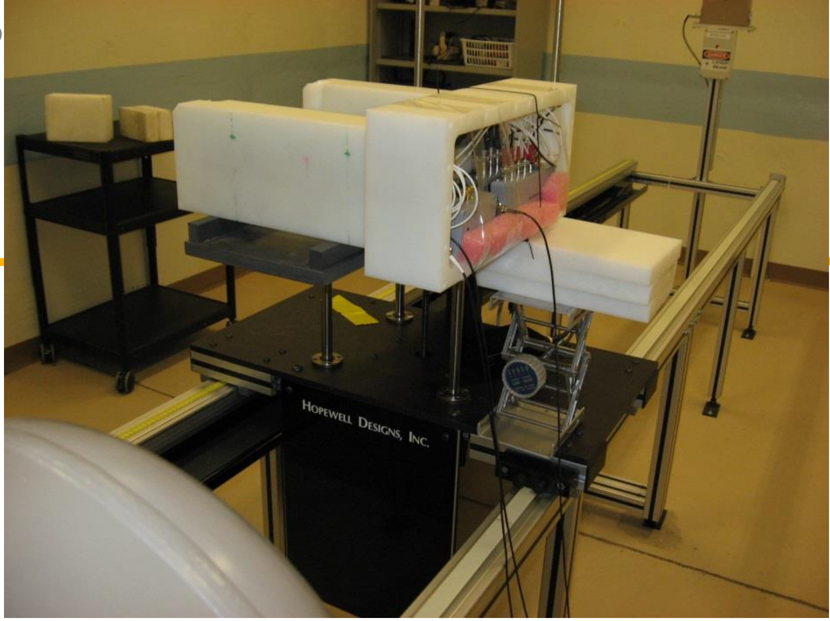
Passive Neutron Albedo Reactivity (PNAR) Detector Deployed at FDEC

- PNAR uses ratio of fission chambers (FCs) in Section 1 (high multiplying) to FCs in Section 3 (low multiplying).
- PNAR measurements of FUGEN assemblies made at Fukushima Daiichi D&D Engineering Company (FDEC) in Tsuruga-shi in West Japan from June 17-27, 2013.
- ^{244}Cm is main passive source, but many detected neutrons come from induced fission.



By J. Eigenbrodt

Deployment of CIPN in Republic of Korea (KAERI)



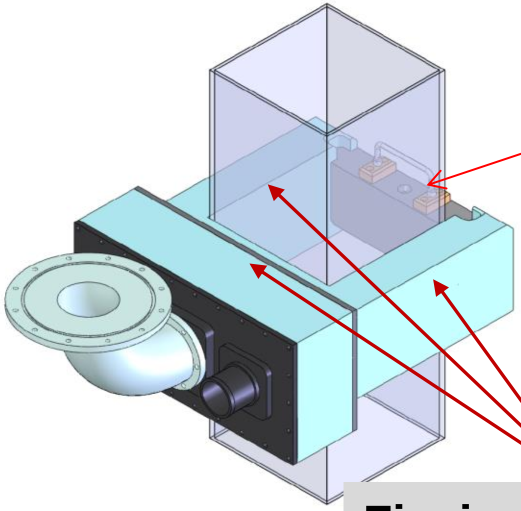
By D. Henzlova and P. Polk

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 fissile content.

Measurements:

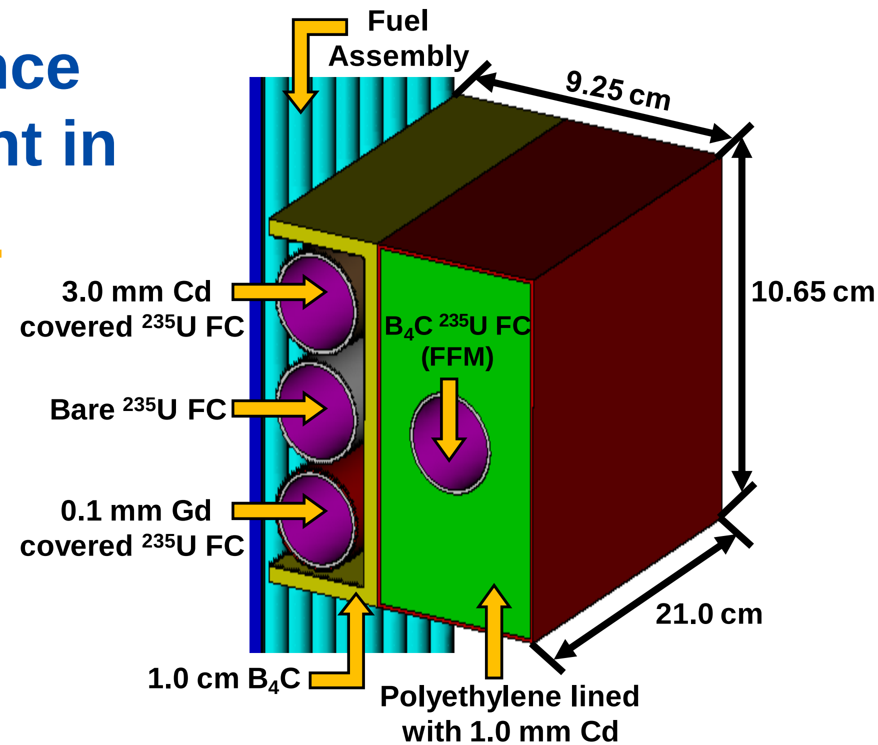
- Occurred September/October 2013 at KAERI, Post Irradiation Examination Facility (PIEF).
- Examined 4 PWR assemblies, burnups ranging from 17 to 38 GWd/tU, cooling times > 20 years.



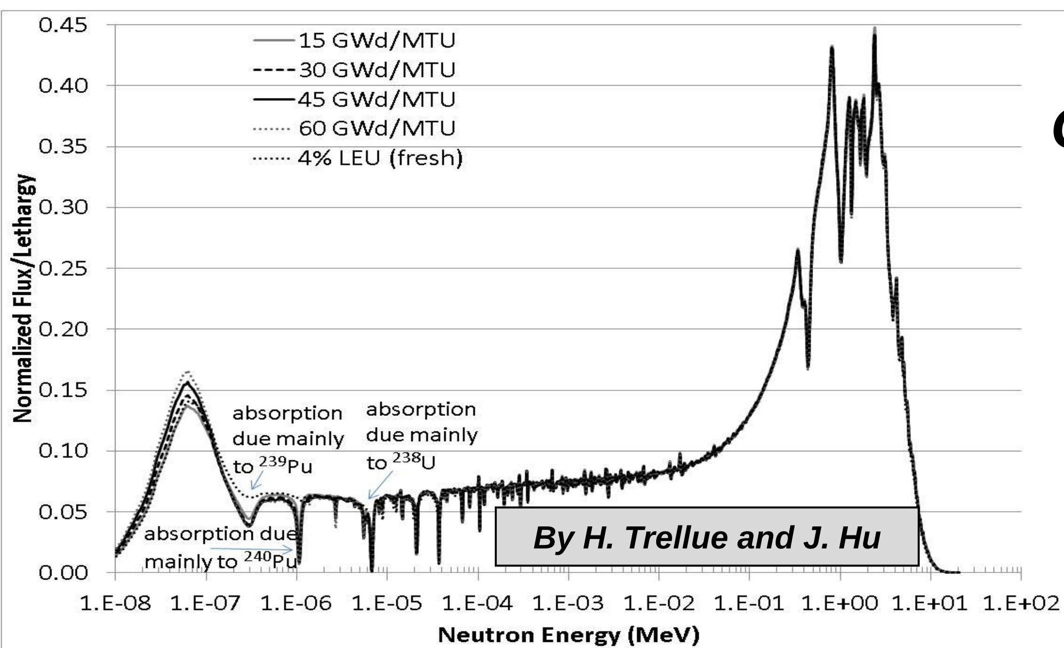
Self-Integration Neutron Resonance Densitometry (SINRD) Deployment in Republic of Korea (ROK)

Concept: The relative neutron flux among parts of the neutron energy spectrum are indicative of the isotopes present. The size of water gap between assembly and instrument is significant.

Measurements: 2 ROK assemblies, December 2013



By A. LaFleur



By H. Trellue and J. Hu

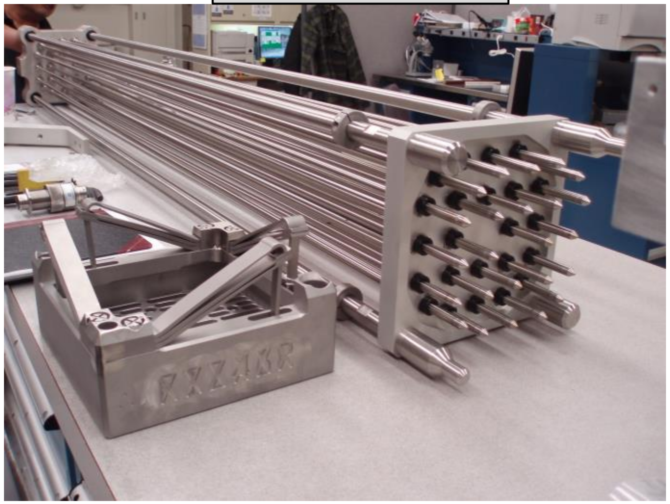
Geometry comprises 4 ^{235}U fission chambers:

- one wrapped in 3 mm Cd,
- one wrapped in 0.1 mm Gd,
- one “bare” (thermal FM), and
- one embedded in Cd lined borated polyethylene (fast flux).

Partial Defect Verification (PDET) Instrument Deployed in ROK and Sweden.

- Normalized gamma-to-thermal neutron ratios are obtained at each measurement/guide tube position.
- The data are arranged sequentially by the quadrant.
- Individual neutron and gamma counts are measured for additional information.
- The shape of counts with location is fairly invariant as long as no pins were missing or replaced with dummy fuel pins.
  - Insensitive to fuel burnup, initial fuel enrichment, and cooling time.
  - Less sensitive to fuel burnup gradient and boron content in pond water.

By Y. Ham, LLNL



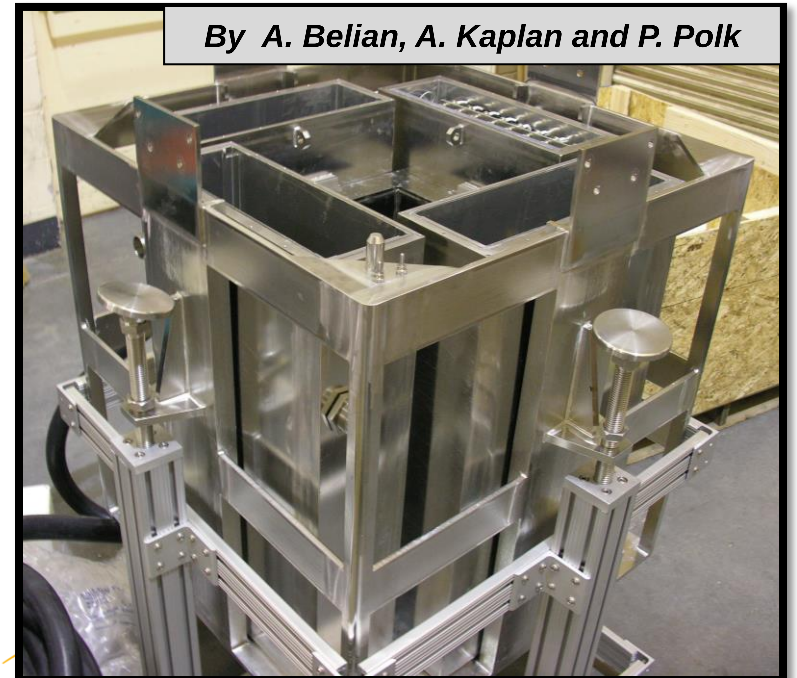
Advanced Experimental Fuel Counter

By K. Miller, H. Menlove

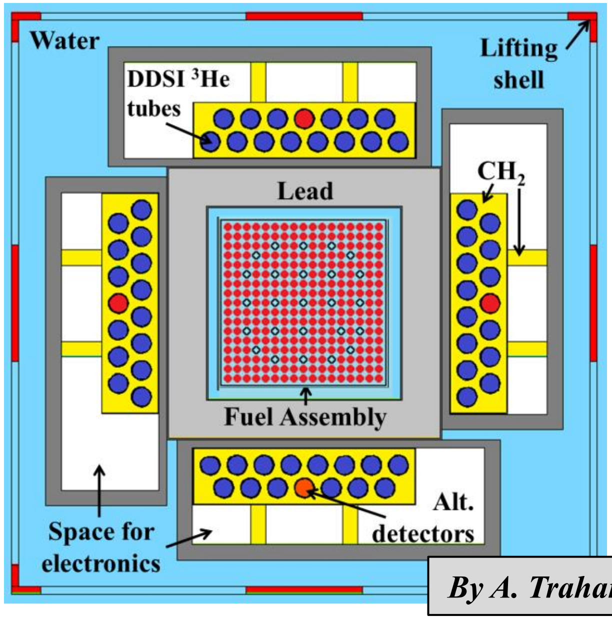
- Designed for research reactors only.
- System uses:
  - Active and passive neutron coincidence counting;
  - An ion chamber for gross gamma-ray counting.
- Measurement objective is to verify residual fissile mass (i.e., ^{235}U + ^{239}Pu) using active neutron interrogation.
- Extended analysis of passive neutron and gamma-ray count rates helps verify declared burnup, cooling time, and initial enrichment.
- Field trials have occurred as follows:
  - 2006 High Flux Australian Reactor (HIFAR), Australia,
  - 2011 Institute of Nuclear Physics (INP), Uzbekistan, and
  - 2014 Institute of Nuclear Physics (INP), Uzbekistan.

Differential Die-away Self-Interrogation (DDSI)

- Comprises ^{3}He tubes, 40-cm length.
- Interrogating source is spontaneous and (α,n) passive neutrons from the spent fuel itself.
- Swedish deployment planned in near future.



By A. Belian, A. Kaplan and P. Polk



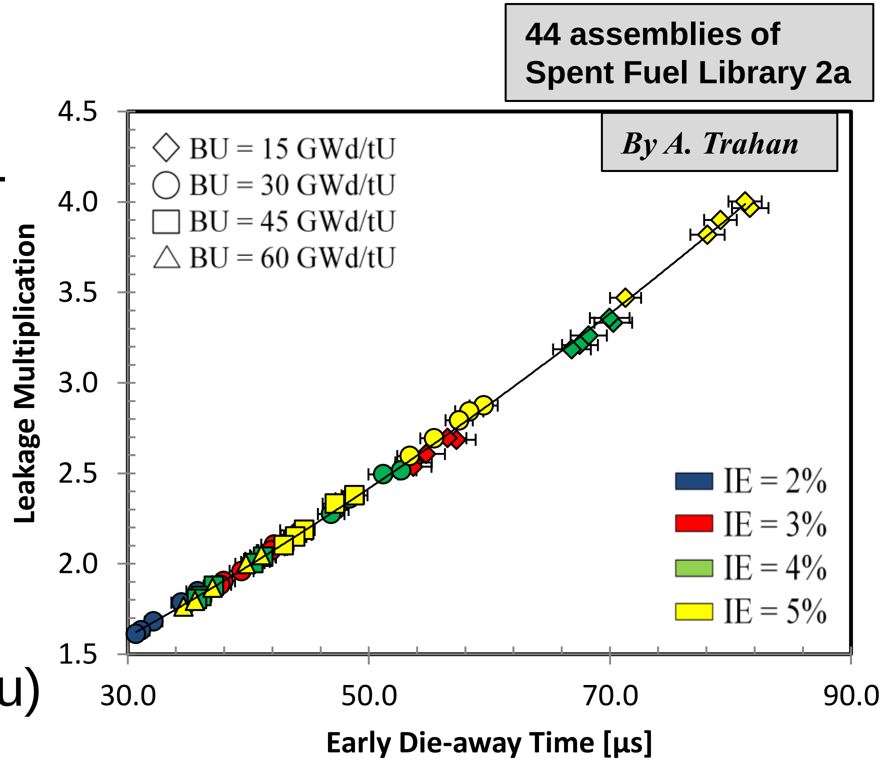
By A. Trahan

Concept:

- Time correlated neutron coincidence counting on small time scales where every detected neutron acts as a trigger event.
- Key point: **early time domain of neutron coincidences contains information about assembly multiplication.**

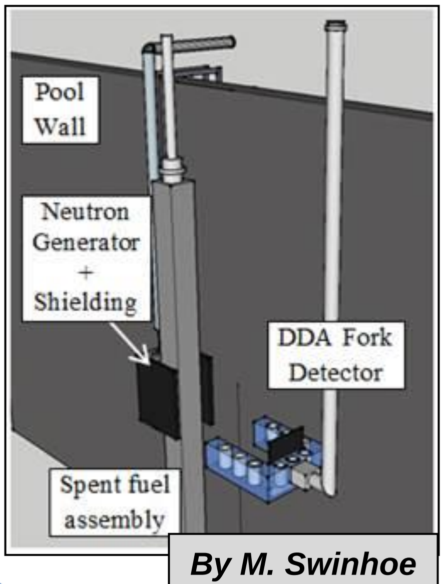
DDSI Applications

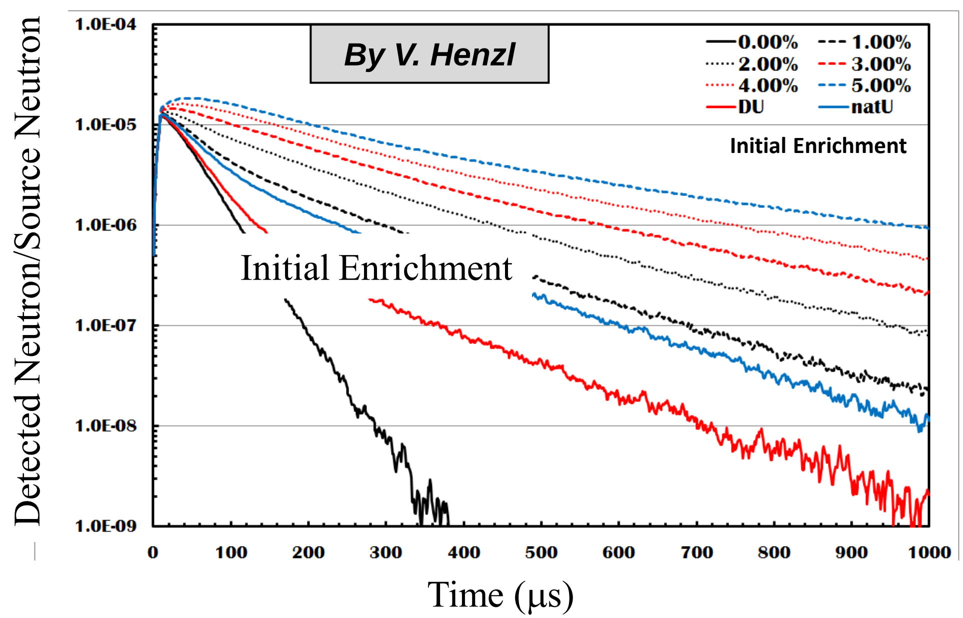
- Early time-domain measured by a Rozzi Alpha Distribution (RAD) can be fit with single exponential function; decay constant is nearly linearly proportional to leakage multiplication.
- Plutonium (Pu) mass determined using singles count rate and multiplication obtained from early die-away analysis.
- Pin diversion can be detected detection with Pu mass or reference assembly approach and fast/slow magnitude.
- DDSI can be applied to fresh MOX samples to measure both fertile (^{240}Pu) and fissile (^{239}Pu) components.



Differential Die-Away (DDA)

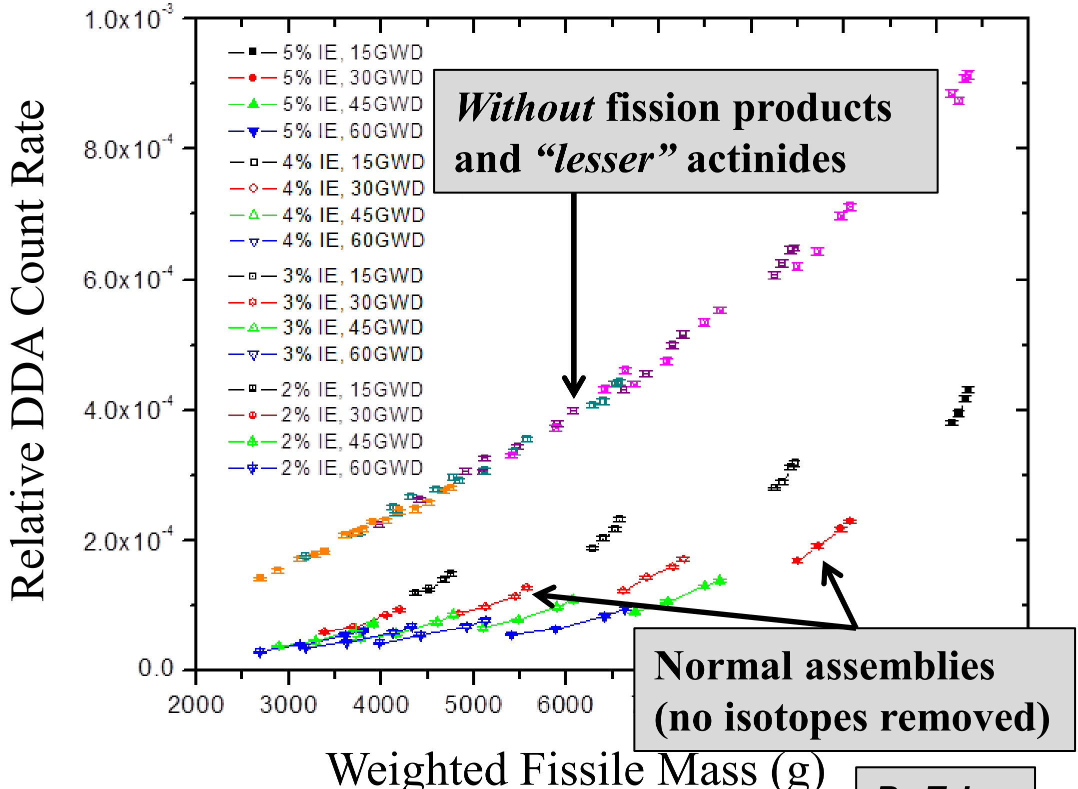
- Active source is a commercial-off-the-shelf 14 MeV Deuterium-Tritium generator (~2 x 10^8 n/s).
- Neutrons transported and multiplied through assembly and detected in ^{3}He tubes vary with fissile material.
- May provide fast estimation of plutonium in spent fuel with low uncertainty; higher precision than passive techniques achieve.





Another illustration of the complexity of the fuel using differential die-away (DDA) simulations

- 64 assemblies were simulated two ways:
  - All isotopes included, and
  - With ^{238}U, ^{235}U, ^{239}Pu, ^{241}Pu, and Oxygen only (fission products and most actinides missing).
- Count rate without absorbers is proportional to mass; absorbers can be estimated from burnup simulations.
- Count rate depends on Initial Enrichment (IE) and burnup (GWD/MTU).

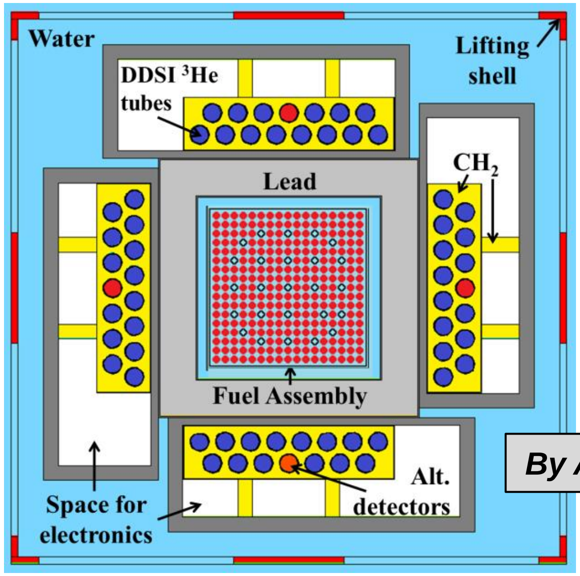


By T. Lee

Four new instruments proposed for deployment at Clab facility in Sweden as two hardware units

(1) Differential Die-Away Self-Interrogation &
(2) Passive Neutron Albedo Reactivity

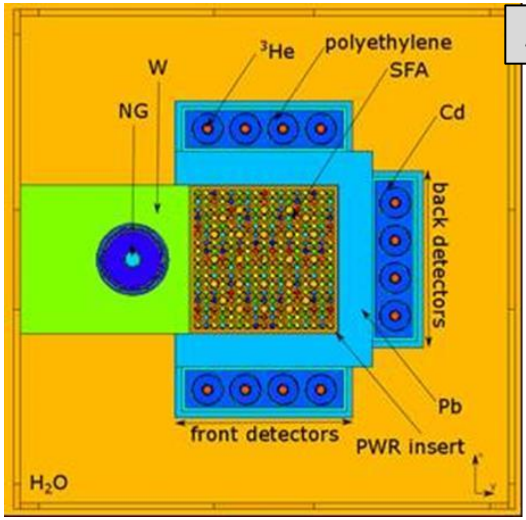
- **Passive**
- DDSI - correlated neutron coincidence counting
- PNAR - with and without a Cd liner



By A. Trahan

(1) Differential Die-Away &
(2) Californium Interrogation Prompt Neutron

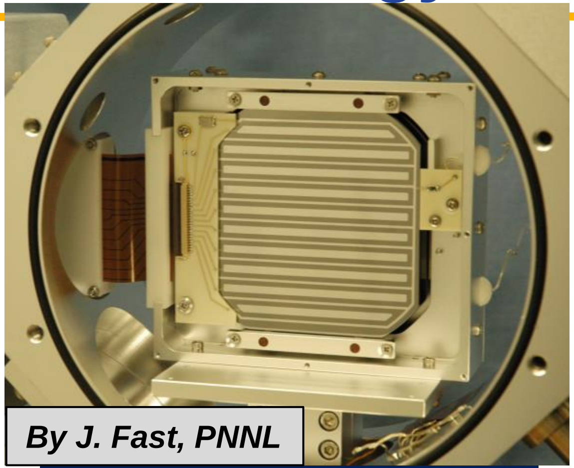
- **Active**
- DDA – time correlated counts after a burst of neutrons
- CIPN - change in count rate from continuous neutron source



By T. Martinik

Improved High Count Rate Gamma Technology

- Ultra-high rate HPGe spectroscopy is researched.
  - Gamma counts of interest are a small fraction of the passive backgrounds.
  - Extreme counting rate (<u>events to the energy spectrum</u>) is critical to keep measurement times under control.
- High count rate commercial-off-the-shelf LaBr-based scintillation detectors can be improved using:
  - Preamplifiers with rise time correction, and
  - External pile-up rejecters.
- Gamma ray mirrors enhance signal-to-noise by
  - Directing narrow band around signal of interest to detector, or
  - Reflecting dominant background gamma rays away from detector.



LBNL Strip Detector

Gamma-ray optic with 5 mirrors

Conclusions

- Many new NDA instruments have been deployed as part of the NGSI-SF project: CIPN, PNAR, and SINRD.
- Our team is in the process of measuring **25 PWR and 25 BWRs** at Clab in Sweden with DDSI and DDA as part of NGSI-SF project.
- Other instruments of interest that have been built and deployed for spent fuel NDA measurements recently include PDET and AEFC.
- Promising new gamma and neutron detector technologies have also been developed.

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- Members of NGSI-Spent Fuel Team 2014-15: G. Baldwin[4], A. Belian[1], T. Burr[1], P. De-Baere[5], A. Favalli[1], M. Fensin[1], M. Fugate[1], J. Galloway[1], I. Gauld[6], S. Grape[3], B. Grogan[6], Y. Ham[7], J. Hendricks[1], V. Henzl[1], J. Hu[6], K. Ianakiev[1], G. Ilas[6], P. Jansson[3], H. Liljenfeldt[6], T. Martinik[1,3], H.O. Menlove[1], D. Meyers[9], V. Mozin[7], M. Newell[1], P. Polk[1], S. Pozzi[8], C. Rael[1], P. Santi[1], P. Schwalbach[5], A. Sjöland[2], S. Jacobsson Svärd[3], M.T. Swinhoe[1], S.J. Tobin[1], A. Trahan[1,8], T.J. Ulrich[1], S. Vaccaro[5], D. Vo[1], A. Worrall[6]

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