IPNDV Working Group 3: Technical Challenges and Solutions
Nuclear Material (5) Technology Data Sheet

June 16, 2017

Nuclear Material (NM) Technology Name: Pulsed Neutron Interrogation (with Detection of Time Sequence of Prompt Fission Neutrons)

Physical Principle/Methodology of Technology:

Interrogation by a pulsed (D-D) or (D-T) neutron generator embedded in a substantial Lead (Pb) or tungsten (W) filter producing a pulse of source neutrons of wide energy spectrum (see Figures 1 and 2). The intention is to tailor the neutron source to include a large component of low energy neutrons (not purely 14 MeV) in order to induce fission almost exclusively in fissile isotopes (e.g., ^{235}U and ^{239}Pu) and allow to clearly distinguish the response from that of non-fissile isotopes (e.g., ^{238}U) if present in bulk amounts.

Induce fission mainly in fissile isotopes (such as ^{235}U, ^{239}Pu). Some amount of moderator/reflector material (if allowed) surrounding the object to measure would be useful for the purpose of extending the lifetime of the source neutrons within the object to measure.

Prompt fission neutrons are detected in fast neutron detectors, or fast neutron detector modules, surrounding the object to measure. As the fission neutrons escaping the object are emitted isotropically, the detectors should preferably surround the object.

Record the time histogram of detected prompt fission neutrons. The only recorded signal is the time histogram of detected prompt fission neutrons, e.g., in a multi-channel scalar triggered (time zero) at the time of the n-pulse from the generator. Repetition rate of the generator pulses can be 50 to 1,000 Hz.

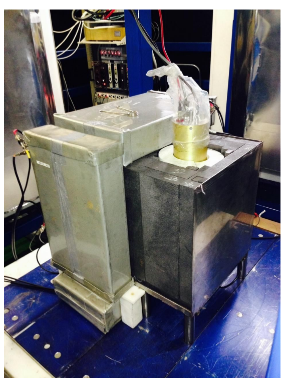

Figure 1: Experimental Setup Showing the Neutron Generator Enclosed within Tungsten, 3He-3 Detectors and Various Shielding and Moderators (Graphite, Cadmium, Polyethylene)

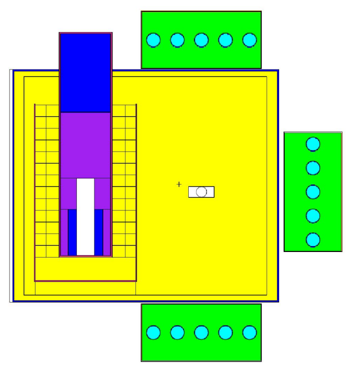

Figure 2: Monte Carlo Simulation Model of the Experimental Setup

Potential Monitoring Use Cases (pre-dismantlement, dismantlement, post-dismantlement, storage stage):

Any case/step where the nuclear material component is included.

For detection technologies, what does the method determine/measure (e.g., presence of nuclear material, isotopics, mass, etc.):

Confirmation of presence of large and dense object composed of fissile isotopes (such as ^{235}U, ^{239}Pu). Unable to separate parameters such as mass, density, shape, fissile isotope(s).

The prompt fission neutrons, induced by the source neutrons, will induce further fission events with subsequent prompt neutron emissions (self-multiplication). A fraction of the prompt fission neutrons in each generation will be detected. The length and shape of the time sequence of detected fission neutrons depends on the mass, density, shape, and fraction of fissile isotopes present in the object. In other words, a (relatively) long time sequence is evidence of a large, dense fissile object. A long time sequence of fission neutrons cannot be obtained from an object of a small fast fission probability, i.e., of an object of low fissile mass, or low density, or a spatially distributed fissile object.

The time sequence of detected fission neutrons (shorter than the neutron pulse repetition period) can be characterized by fitting the curve with a sum of decaying exponential functions. These fitting parameters are the only recorded measurement data and they will uniquely identify a fissile weapon component.

Physical Description of Technology (e.g., approximate size, weight):

Trolley size assembly (1 × 1.6 m) composed of three parts: neutron source assembly composed of neutron generator and neutron spectrum filter (Pb or W) adjacent to the object to measure, cavity for placing the object to measure surrounded by neutron reflector/moderator (if permitted), and fast neutron detector banks also surrounding the object to measure. A frame structure surrounding the object can conveniently support both the detector arrangement and the moderator/reflector.

A separate rack with power supplies, generator control, analyzer: multi-channel scalar, laptop with instrument control software, and data interpretation software/interface.

Total weight 300–400 kg.

Time Constraints (e.g., measurement times including distance from object, time to install the equipment):

Measurement time 600–1,000 seconds for a standard neutron generator of 10^7/s neutron emission rate, or longer depending on generator source strength, and type (D-D) or (D-T).

One hour for setup, warm up, and system check.

Measurement time to measure 500 g of Pu (0.1 ^{239}Pu /^{240}Pu) or 500 g of ^{235}U at 1 m from the surface of the container (order of magnitude: seconds, minutes, hours, days):

Measurement at one meter distance from object in the sense of removing the detector (and the neutron source) from the object is not recommended. The generator assembly should be in a dedicated location in contact with the sample cavity. The detector banks should preferably surround the object in a permanent frame structure.

Will this method work in the presence of shielding? If so, what is the maximum amount of shielding that will still allow the method to work?

Yes. A certain fraction of the fast source neutrons will penetrate the shield. A fraction of the fast prompt fission neutrons will escape the object to measure. The method does not depend on knowing neither the probability of source neutrons to induce fission, nor the detection probability of the fission neutrons. A substantial shield will only require longer measurement time to be applied.

Technology Complexity (e.g., hardware, software, and ease of use by personnel):

The operator needs to be trained in the use of the neutron generator including training in radioprotection and use of high voltage components.

Infrastructure Requirements (e.g., electrical, liquid nitrogen, etc.):

Standard radiation safety is required when the system is operating. The operator must be at a minimum distance from the n-generator, preferably in separate room with door interlock and shielding toward the instrument. Standard electrical requirements are needed for powering the system.

Technology Limitations/Variations (e.g., detection limits for nuclear material, operational temperature range, differences in technology detector materials):

The lower limit of detection, i.e., the smallest mass for which the fitting parameters of the time sequence can be distinguished from the time sequence of benign materials is expected to be several hundred grams of weapons material, but depends also on the size of the container to be measured and instrument parameters, e.g., neutron detection probability.

A special license is normally required to operate a neutron generator.

Information Collected by the Technology (used to help determine if an information barrier is required for use):

The recorded signal is the time distribution of detected prompt fission neutrons using standard MCS (multi-channel scalar) electronics. The data interpretation is simple and does not rely on specific determination of the fissile mass or isotopic composition. Only dedicated fast neutron detector assemblies are used. The method acquires a signal directly from the fissile constituents (self-multiplication) but is unable to separate variables such as fissile mass, density, shape, and type of fissile isotope (no information barrier is required).

The analysis can consist of comparison of measured time sequence (fitting) parameters to pre-established Monte Carlo simulated ones. The observation of a certain range of fitting parameter will positively identify the presence of a large dense object of fissile material, but will not be able separate into individual values of mass, density, shape, and isotopic composition. The Figures 3 and 4 below, of similar methods, although different in technology and scope, show time sequences of induced fission neutrons.[1] In this case the time sequence is initiated with a ^{252}Cf source and not a neutron generator, but the principle is relatively similar. The right-hand figure shows time sequences as function of uranium enrichment (for known reference standards as in the legend). Similar graphs could be shown as function of fissile mass, or as function of (to some extent) density. In other words, the slopes could not yield the values in the legend. This inability to separate parameters of the sample is considered a strength of the method.

[1] T.E. Valentine, L.G. Chiang, and J.T. Mihalczo, *Preliminary Evaluation of NMIS for Interrogation of Pu and HEU in AT400-R Containers at Mayak*, ORNL (January 2000), ORNL/M-6648 R4.

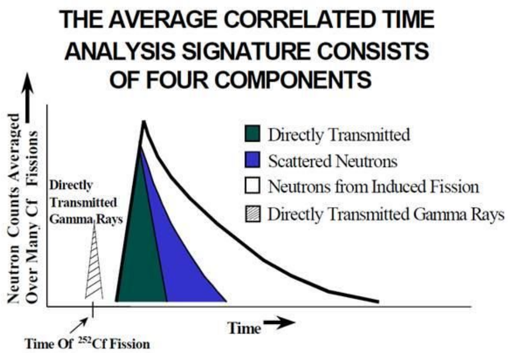

Figure 3: Simplified Conceptual Sketch of Correlation between a Detector and Source

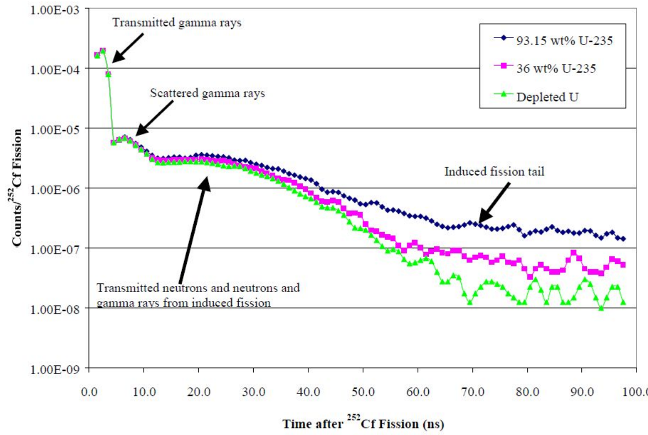

Figure 4: Time Distribution of Correlated Counts per ^{252}Cf Fission for Various U Enrichments

Interpretation models such as neutron coincidence counting and neutron multiplicity counting, which aim at determination of the spontaneous fissile mass, are not applied. The neutron detection probability can be limited physically so that these interpretation models cannot be applied.

Also the standard Differential Die-Away technique, which uses an external pulsed and thermalized neutron source to determine a signal proportional to the fissile mass, cannot be applied directly due to the absence of a large external moderator.

Safety, Security, Deployment Concerns:

Standard radiation safety requirements, safety in relation to use of high voltage, safety in relation to use of neutron generator.

Technology Development Stage (Technology Readiness Level, TRL):

Similar technologies have been applied successfully under field conditions, e.g., differential die-away (DDA) systems. Figures 5 and 6 give the principle of pulsed neutron interrogation device such as used for DDA at the JRC for the detection of prompt fission neutrons as a function of time, and the experimental raw data obtained for Uranium (U) samples. A detailed Monte Carlo study is required to confirm performance, i.e., sensitivity study for mass, shape, density, and isotopic content. Figures 1 and 2 above are examples of a pulsed source device (for a different purpose) being investigated both experimentally and by Monte Carlo simulations respectively.[2]

[2] Bent Pedersen, “New Applications of Active Neutron Interrogation in Nuclear Safeguards and Security,” Presented at Workshop on Scanning the Horizon: Novel Techniques and Methods for Safeguards (IAEA: Vienna, Austria, January 21–24, 2014).

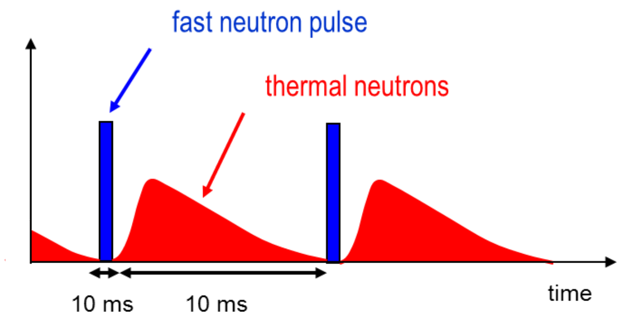

Figure 5: Principle of Pulsed Neutron Interrogation Device Such as Used for DDA

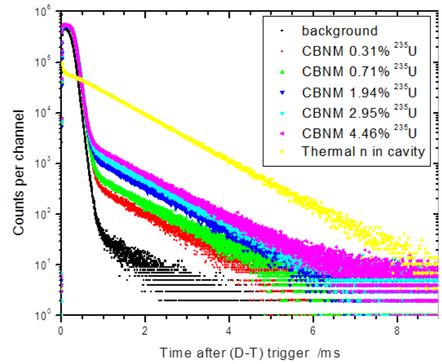

Figure 6: Raw Experimental Data for a series of ^{235}U Standards

Cost Estimate:

About €300,000: Neutron generator - €120,000, analyzer + electronics + detectors - €120,000, mechanical structures - €60,000.

Additional System Functionality (e.g., outside the monitoring use case):

A pulsed neutron generator can be used to confirm the presence of chemical explosives. But this may require the use of a substantial neutron moderator assembly (which may not be acceptable in the presence of bulk nuclear materials).

The same instrumentation can be configured to identify if the fissile material is U or Pu by observation of the delayed neutrons. The technique uses the fact that the delayed neutron fraction (beta) for ^{235}U and ^{239}Pu are a factor 2.3 different. For this purpose, a different measurement regime is applied, i.e., repetitions of 30 seconds irradiation and 30 seconds measurement. The method aims at estimating the ratio of delayed to prompt fission neutrons. In addition to the proposed generator-detector configuration, monitors for estimating the number of induced fissions would be required.

Where/How the Technology Is Currently Used (e.g., international safeguards, border protection):

Similar technologies, applying a neutron generator, are commercially available for nuclear waste characterization, and in nuclear safeguards for mass assay of small fissile quantities.

Examples of Equipment:

The Valentine et al. ORNL reference is a good example of similar technology,[3] and similar data recording and analysis.

[3] T.E. Valentine, L.G. Chiang, and J.T. Mihalczo, *Preliminary Evaluation of NMIS for Interrogation of Pu and HEU in AT400-R Containers at Mayak*, ORNL (January 2000), ORNL/M-6648 R4.