IPNDV Working Group 3: Technical Challenges and Solutions
Nuclear Material (7)—Technology Data Sheet

October 27, 2017

Nuclear Material (NM) Technology Name: Fast Neutron Imaging

Physical Principle/Methodology of Technology:

The term "neutron imaging" may refer to any one of a number of diverse imaging techniques, including *transmission* imaging, *emission* imaging, and *stimulated emission* imaging.

- *Fast neutron transmission imaging*, or radiography, is an active imaging technique performed by passing fast neutrons from an interrogating neutron source through an inspected object to measure its geometry.
- *Fast neutron emission imaging* is a passive imaging technique that forms an image using the spontaneous neutron emissions of an item.
- *Stimulated emission imaging* is an active imaging technique that forms an image of the induced neutron emissions of an item. This imaging is performed when an interrogating neutron source is used to induce fissions and the resultant fission neutrons detected in such a way that the position and direction of either the incident or emitted neutrons can be used to form an image of the spatial distribution of special nuclear material (SNM) in the object.

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

Fast neutron imaging techniques can be used as high-confidence methods for confirming the presence and configuration of SNM to support nuclear warhead monitoring and verification activities. These techniques, alone or in combination with other confirmation measurements, can be used to achieve high-confidence methods for confirming that an item presented for inspection is a warhead or component, a warhead or component of a particular type, or that it has not changed over time.

Used to measure U, Pu, or U and Pu:

Fast neutron transmission imaging: U and Pu

Fast neutron emission imaging: Pu

Stimulated emission imaging: U

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

Fast neutron transmission imaging: Measures the geometry of an object via the fraction of fast neutrons that transmit through it. This technique can provide highly detailed two- or three-dimensional images of the geometry, but it cannot identify specific materials, elements, or isotopes.

Fast neutron emission imaging: Measures the spatial distribution of SNM by passive detection of spontaneous neutron emissions. This technique is only practical for Pu assay because of the low spontaneous emission rate for uranium.

Stimulated emission imaging: Measures the spatial distribution of SNM by actively stimulating fissions with an external source. This technique is intended for U assay.

Physical Description of Technology (e.g., approximate size, weight): Transportable instruments using fast neutron imaging techniques have been successfully developed and deployed to characterize bulk quantities of shielded SNM. *Fast neutron transmission imaging:* Imager needs to be at least a meter longer and wider than the object it needs to measure. For example, an imager intended to inspect containers approximately 1 m on a side, requires a footprint at least approximately 2 m on a side. A transmission imager of this type is comparable in size, cost, and complexity to a clinical imager for nuclear medicine. *Fast neutron emission imaging:* The imager can fit through a standard personnel doorway. *Stimulated emission imaging:* This technique can be performed using either the transmission-type imager or the emission-type imager.
Time Constraints (e.g., , measurement times including distance from object, time to install the equipment): *Fast neutron transmission imaging:* Transmission images require a few minutes per view, or a total of tens of minutes for tomography, using commercial portable neutron sources. Tomography combines transmission data collected from a number of views from several angles to provide a slice through the inspected object. As long as the object fits within the field-of-view, the object is typically placed as close to the source as possible. *Fast neutron emission imaging:* Images can take from tens of minutes to more than an hour to accumulate. Individual sources can easily be identified at a distance of a few meters. *Stimulated emission imaging:* Stimulated emission imaging can be performed using either the transmission-type imager or the emission-type imager. In the case of the transmission imager, no change to the hardware is needed. The interrogating 14 MeV neutrons used to measure transmission also stimulate fissions. The stimulated emission imaging measurements is performed simultaneously with transmission tomography. As long as the object fits within the field-of-view, the object is typically placed as close to the source as possible. In the case of the emission imager, the imager needs to be supplemented by a pulsed interrogating neutron source and measurements of inspected objects are taken using the delayed multiplication technique. The imager is operable at a distance of a few meters away from the inspected object. **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):** The fast neutron emission imaging technique can detect 500 g of Pu at 1 m with a measurement time on the scale of minutes. The stimulated emission imaging technique is intended for bulk quantities of SNM that exhibit self-multiplication. Placing such samples close to a commercial portable neutron source enables detection on the scale of minutes. In both instances, more time will be needed if the SNM is shielded by low Z material. **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?**

These techniques excel when the SNM is shielded by high Z material and can still be used when the SNM is shielded by low Z material. As low Z shielding attenuates source neutrons as well as fission neutrons escaping the SNM, the neutron images can be blurred due to scatter phenomena and require more measurement time. The maximum amount of shielding depends upon self-imposed image resolution and measurement time limits.

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

Fast neutron transmission imaging: The imager is comparable in size, cost, and complexity to a clinical imager for nuclear medicine. For instance, the imager shown in the Appendix (Figure 1) contains 33 segmented plastic scintillator neutron detectors each with four photomultiplier tubes (PMTs). These detectors must be gain matched, time aligned, and their position responses calibrated, requiring a fair degree of automation. The present Thermo-Fisher API-120 D-T neutron generator needs to be run approximately monthly as part of its preventive maintenance.

Fast neutron emission imaging: A (1) schematic diagram and (2) photograph of an example emission neutron imager is shown in the Appendix (Figure 3). The imager consists of an aperture and a position sensitive fast-neutron detector whose relative positions are set with a linear stage to adjust the magnification of the pattern on the detector, and thus the field of view. The detectors are essentially the same as those in the transmission imager, but in this case forming a detector plane consisting of a 40×40 array of pixels.

Stimulated emission imaging: Stimulated emission imaging can be performed using either the transmission-type imager or the emission-type imager described above. In the case of the transmission imager, no change to the hardware is needed. In the case of an emission-type imager, the imager needs to be supplemented by a pulsed interrogating neutron source.

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

Embodiments of fast-neutron imaging systems using transmission, emission, or stimulated emission that can be reasonably transported and used in relevant industrial facilities can run off of a single 10A 110 VAC circuit.

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

Fast neutron transmission imaging:

- Although all materials can be imaged with this technique, it cannot identify specific materials, elements, or isotopes.
- Image contrast can be degraded when neutrons must penetrate a significant amount of material.

Fast neutron emission imaging:

- This technique is only practical for plutonium assay.
- Images are much less detailed than those produced by transmission imaging.

Stimulated emission imaging:

- This technique can be used to assay uranium in the presence of plutonium or other neutron emitter, but the characterization may be more challenging.

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

These techniques can be used to achieve high-confidence for confirming that an item presented for inspection is a warhead or component, a warhead or component of a particular type, or that it has not changed over time. This high confidence is achieved at the cost of revealing considerable sensitive information that may not be shareable with the operator of the equipment. It may be necessary to develop either an automated analysis that can extract meaningful attributes of the SNM and its configuration or compare to a stored template without revealing imaging data to the operator.

Safety, Security, Deployment Concerns:

It is desirable for imaging systems to have minimal footprint and to operate within the requirement of either minimal shielding or only the reduction in radiological dose to personnel naturally provided by industrial construction and modest standoff. As a practical matter, for transmission or stimulated emission measurements, general area dose rates of 0.02 mSv/hr with modest standoff limits can be achieved with neutron source intensities to the neighborhood of 10^8 neutrons s^{-1}.

Technology Development Stage (Technology Readiness Level, TRL):

These techniques are in the early stage of development; however, transportable instruments using fast neutron imaging techniques have been successfully developed and deployed to characterize bulk quantities of shielded SNM (TRL 6). Nevertheless, these techniques are relatively new such that the information protection and certification and authentication requirements associated with the current implementations have yet to be investigated.

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

Systems that use these techniques are designed to only have as much functionality as needed to generate the images.

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

These techniques have been demonstrated in facilities that manage bulk quantities of SNM. Deployment for regular use in such facilities has not yet been realized.

Examples of Equipment:

Refer to the Appendix for examples of fast neutron imaging systems and the imaging data. Examples of systems that use fast neutron transmission imaging are the Fieldable Nuclear Materials Identification System (FNMIS) and the Advanced Portable Neutron Imaging System (APNIS) (Figure 1). An example of a fast neutron tomographic image is shown in Figure 2. Both systems were developed by Oak Ridge National Laboratory. An example of a system that uses fast neutron emission imaging is the Fast Neutron Coded Aperture Imager (FNCAI) (Figure 3). Imager data for the fast neutron emission system are shown in Figures 4 and 5. This system was developed jointly by Oak Ridge National Laboratory and

Sandia National Laboratory. Examples of the stimulated emission imager data that employs the transmission-type imager or the emission-type imager are shown in Figures 6 and 7.

Appendix

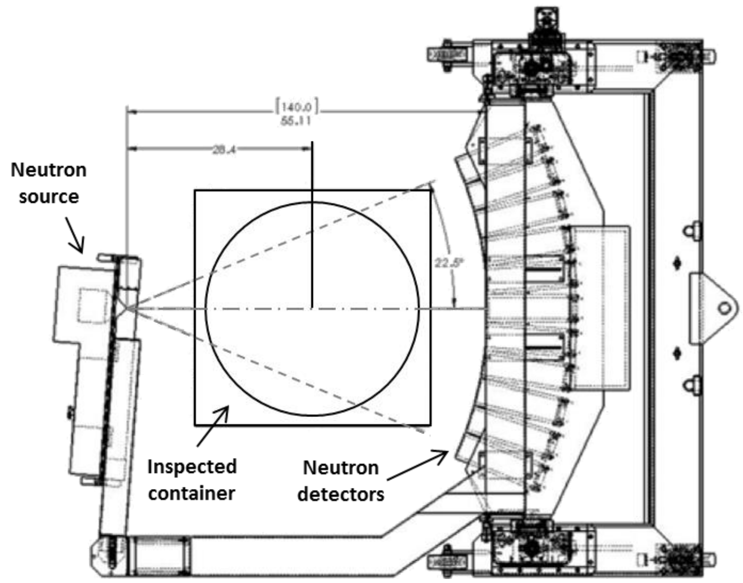

Figure 1: One embodiment of the transmission-type fast-neutron imager for inspecting objects in containers approximately 1 m on a side. (Photo Credit: Oak Ridge National Laboratory)

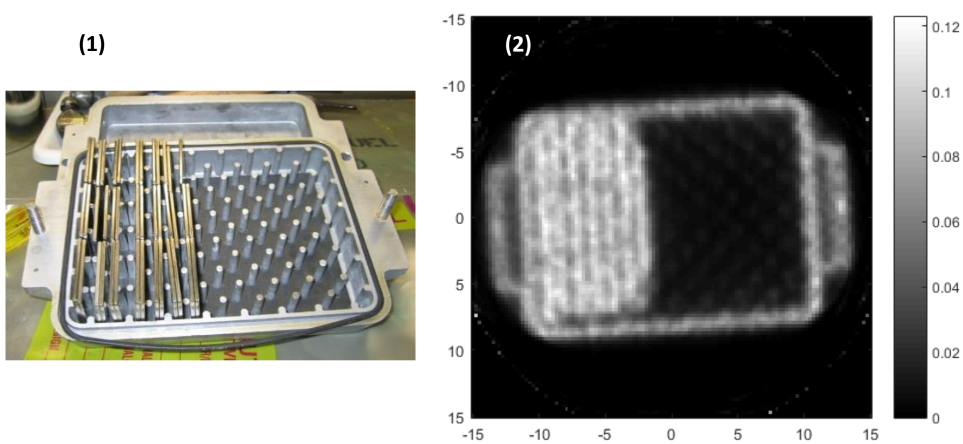

Figure 2: An example fast neutron tomographic image of a "clam shell" half full of PuAl plates reconstructed from 30 projections through the object. Comparison of the (1) photograph and (2) reconstructed image illustrate that small features can be resolved with relatively large detectors. (Photo Credits: (1) Idaho National Laboratory, (2) Oak Ridge National Laboratory)

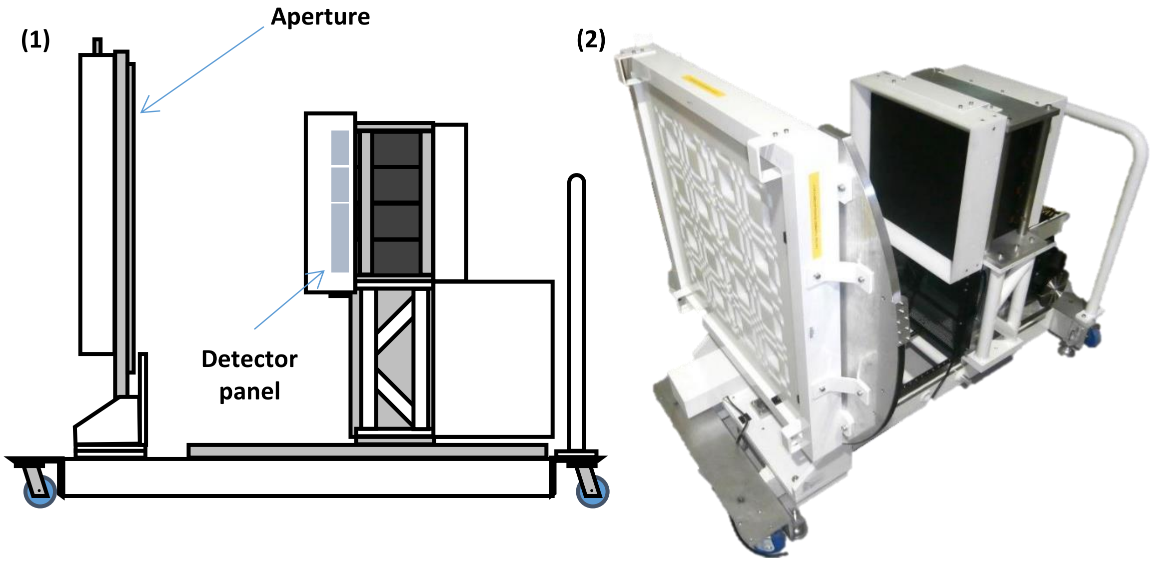

Figure 3: One embodiment of the emission-type fast-neutron imager for imaging the neutron emanations of SNM objects. This imager can fit through a standard doorway. (Photo and Image Credits: (1) Oak Ridge National Laboratory, (2) Oak Ridge National Laboratory)

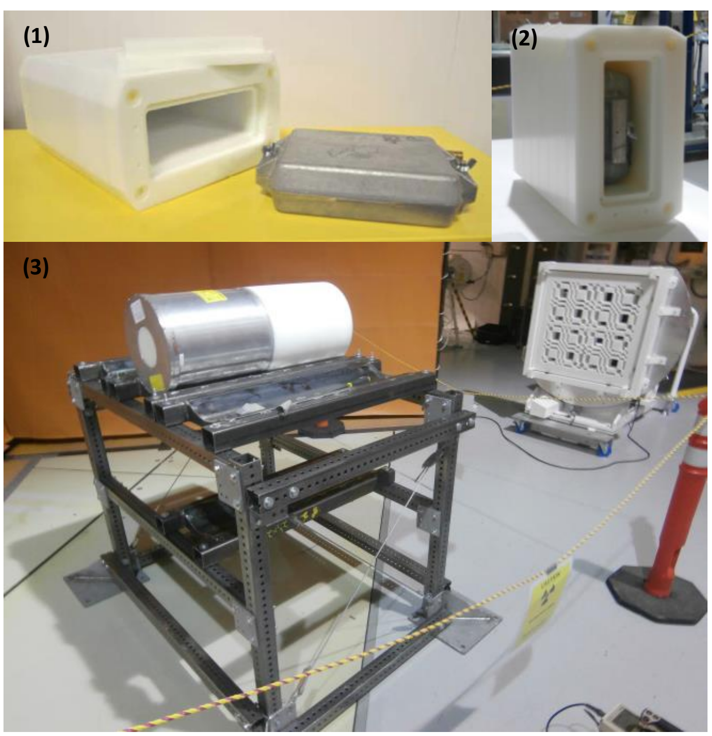

Figure 4: Configuration of emission imaging of a "clam shell" with PuAl plates in it shielded by polyethylene. In this instance, the source-to-aperture distance is approximately 3 m. (Photo Credits: Idaho National Laboratory)

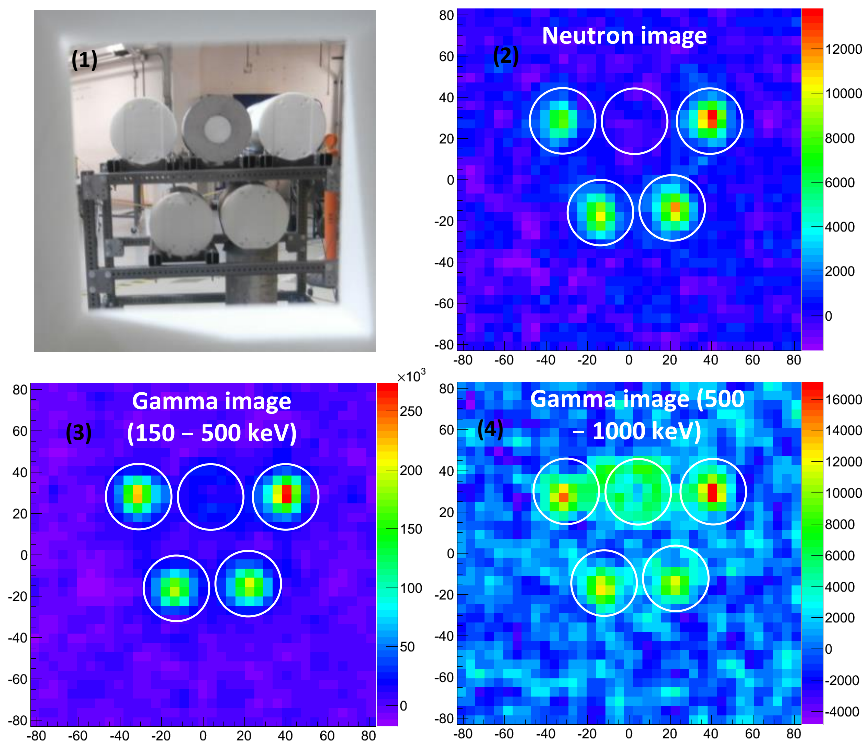

Figure 5: A configuration of nuclear material consisting of four neutron sources (clam shells containing PuAl plates) and a single depleted uranium annulus gamma-ray source and their corresponding fast neutron and gamma-ray images. (Photo and Image Credits: Idaho National Laboratory: (1) Idaho National Laboratory, (2–4) Oak Ridge National Laboratory)

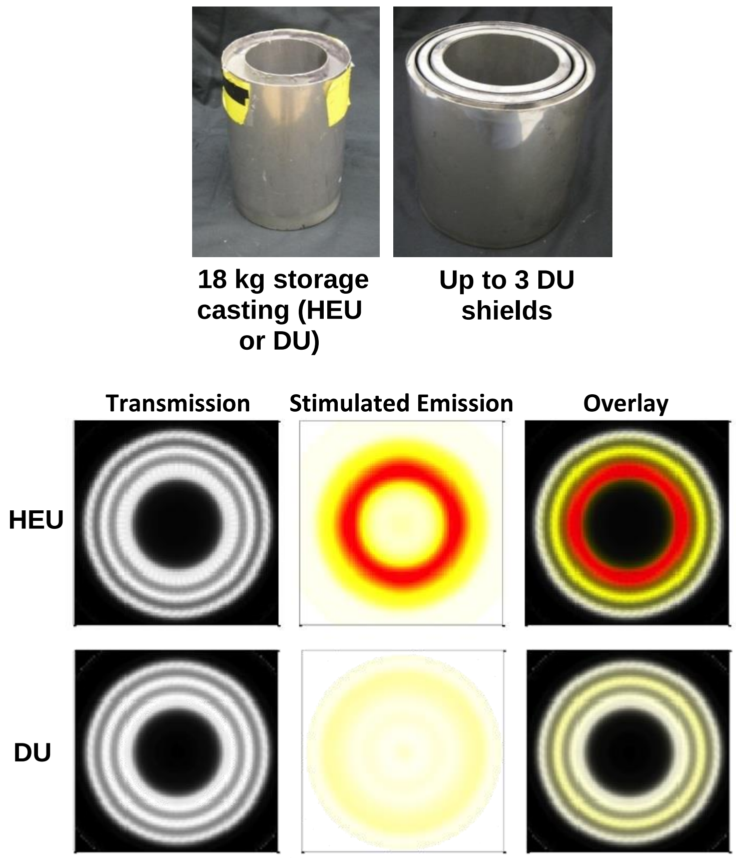

Figure 6: Top: photographs show a storage casting and depleted uranium (DU) shields. Bottom: stimulated emission imaging measurements using the associated-particle technique of a storage casting shielded by DU shields are performed for an HEU casting and a DU casting at the Y-12 Nuclear Detection and Sensor Test Center. Contrast between the HEU and DU items is apparent. (Photo and Image Credits: Oak Ridge National Laboratory)

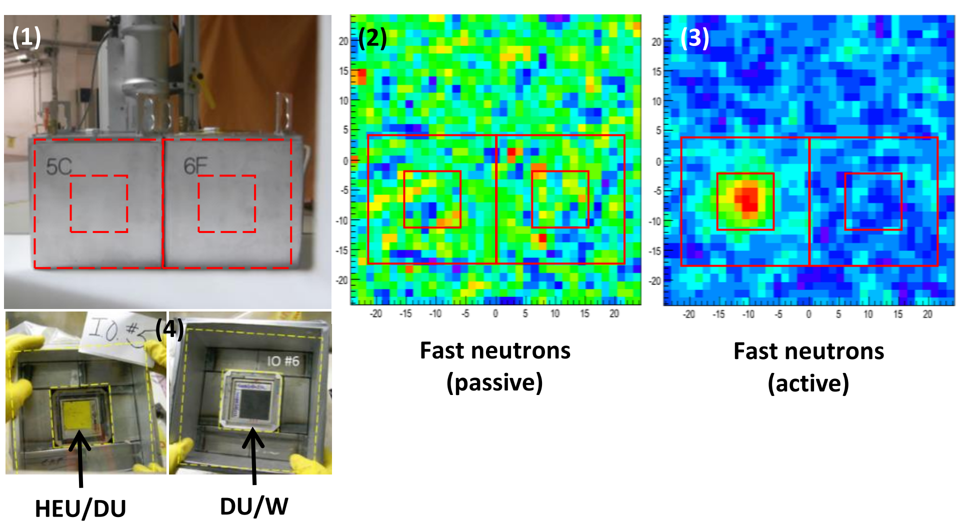

Figure 7: Stimulated emission imaging measurements of two "inspection objects," one with HEU and one with DU using the delayed multiplication technique. Contrast between the HEU and DU items is apparent. (Photo and Image Credits: (1) Idaho National Laboratory, (2–3) Oak Ridge National Laboratory, (4) Idaho National Laboratory)