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Title: Review of Active Interrogation Techniques and Considerations for Their Use behind an Information Barrier

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REVIEW OF ACTIVE INTERROGATION TECHNIQUES AND CONSIDERATIONS FOR THEIR USE BEHIND AN INFORMATION BARRIER

September 29, 2010

EXECUTIVE SUMMARY

Active interrogation techniques have been used to detect and measure properties of special nuclear material (SNM). The interrogation can be done using photons or neutrons, and the result of the interrogation can be seen by observing the gamma rays or neutrons emitted by the SNM. The effects observed are due to neutrons from induced fissions of the SNM, the neutrons and gamma rays produced by the fission fragments, or the characteristic gamma rays emitted by the excited SNM nuclei. Several different techniques are discussed, along with their strengths and weaknesses. We recommend further investigation of two techniques: (1) The Plutonium Scrap Metal Coincidence Counter, which has been used for passive measurements of plutonium and can be adapted into an Active Well Coincidence Counter for active measurements of uranium; and (2) The Nuclear Resonance Fluorescence method, which appears to offer several potential advantages, including the ability to distinguish different isotopes, as well as and a fairly penetrating signal.

1 INTRODUCTION

An attribute measurement system (AMS) with an information barrier (IB) is intended to measure several characteristics of a sensitive, SNM item (e.g., mass and isotopic composition) and to display an unclassified version of these characteristics—an attribute. These attributes can be used to confirm a declaration (made by the host party) concerning the SNM without revealing any sensitive information to the monitoring party. Until now, AMSs have been used to make passive measurements of SNM (mainly plutonium), but active interrogation measurements could be made using similar methods. Adding active interrogation would allow these measurement systems to be extended to measuring uranium items. The discussion presented here will concentrate on active measurements on uranium.

Important attributes for measuring uranium are enrichment and mass. Unlike plutonium, uranium (both ^{235}U and ^{238}U) has a very low spontaneous fission rate. This low rate makes it difficult to determine uranium properties using passive neutron techniques. Passive gamma-ray techniques have been developed for determining uranium enrichment. These techniques rely on the analysis of gamma-ray measurements using ratios of gamma-ray intensities from ^{235}U and ^{238}U. An assumption must be made that the selected measurement area is completely representative of the total uranium mass. The strongest gamma rays from ^{235}U, with energies of 144, 186, and 205 keV, are easily attenuated by the container and its packing. If these low-energy gamma rays cannot be observed, no passive measurement of the enrichment is possible.

Active interrogation techniques have been developed for the measurement of uranium. These techniques use active neutron and photon systems, either inducing fission and measuring the corresponding coincidence or measuring the gamma rays emitted. The neutron source is either a random source (a radioactive source or a neutron generator) or a spontaneous fission source such as ^{252}Cf. The photon source is typically a bremsstrahlung source.

Although some work has been done to determine uranium mass or enrichment, most of the effort has been aimed at uranium detection for nonproliferation purposes using various techniques (see the attached bibliography).

This report is arranged in several sections. Section 2, "Active Interrogation Techniques," includes two photon active interrogation techniques and several neutron interrogation techniques. The discussion of each of these active techniques includes subsections of advantages and disadvantages. Section 3 discusses the implications of information barriers on active techniques. Section 4 is a recommendation on the path forward for NA-243; Section 5 provides a bibliography.

A list of references is associated with each active technique. Each active technique title includes the reference numbers identifying selected items in the bibliography that are associated with it.

2 ACTIVE INTERROGATION TECHNIQUES

2.1 Photon Interrogation Techniques

2.1.1 Photofission [71–75]

Photon fission has been used to detect the presence of highly enriched uranium (HEU) in cargo by irradiating the container with high-energy gamma rays (with end-point energies ranging from 6 to 10 MeV) from a bremsstrahlung source and observing the fission signatures with suitable detectors. During the interrogation, the detectors are saturated from the bremsstrahlung source and cannot observe the prompt signals from fission. After the detectors recover, on the order of milliseconds, delayed fission signals can be observed.

The technique is based on the fact that heavy nuclei have a highly deformed shape. With the absorption of some energy, such as from a photon or low-energy neutron, a nucleus fissions, releasing two fission fragments that are rich in neutrons and in a highly excited state. The excess energy is shed by emitting, on average, two prompt neutrons and eight prompt gamma rays (prompt decay). The neutron-rich fission fragments fly apart with kinetic energies of about 200 MeV and decay by beta decay. This decay leaves the daughter nucleus in a very highly excited state, where it can decay by neutron emission (delayed neutron emission) or gamma-ray emission (delayed gamma-ray emission).

The technique can detect hundreds of grams of HEU. However, the matrix material and the spatial distribution of the special nuclear material (SNM) have a major influence on the evaluation of the mass.

2.1.1.1 Advantages

The advantages are that

- the technique uses an electron accelerator, which can be switched off and
- The high-energy gamma rays can penetrate many layers of material.

2.1.1.2 Disadvantages

The disadvantages are that

- The technique has been used to detect HEU; diagnostic information has not been implemented. A research effort would be needed to develop the software tools to extract diagnostic information.

- Heavy shielding would be required to reduce the escaping radiation to a safe level.

2.1.2 Nuclear Resonance Fluorescence (NRF) [92–94]

Nuclear resonance fluorescence (NRF) uses a photon source for the active interrogation. Figure 1 shows a typical NRF experimental arrangement. An electron beam from an accelerator bombards a converter, typically tungsten, generating a bremsstrahlung gamma-ray source. The gamma rays leave the converter primarily in the forward direction. Some of the gamma rays bombard the sample material, generating excitations. The physical process behind NRF is that the nucleus absorbs electromagnetic radiation in discrete energy levels, and these levels de-excite by re-emitting gamma-ray radiation of discrete energies characteristic of the nucleus. The emitted photons have energies of several MeV, which can penetrate many layers of material. This technique provides isotopic information that can be used to detect SNM.

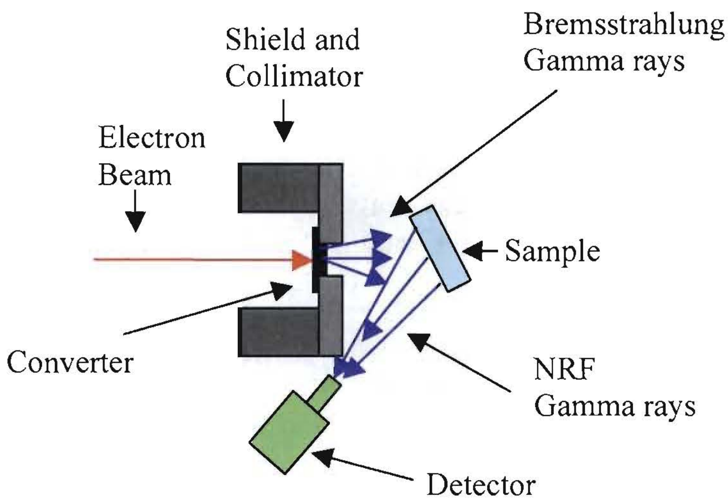

Figure 1. A typical NRF experimental arrangement.

NRF excitations in ^{235}U have been identified within the energy range of 1.0 to 2.5 MeV using a continuous bremsstrahlung source. The NRF gamma peaks of statistical significance in ^{235}U occur at 1733, 1815, and 1862 keV. The NRF gamma peaks of statistical significance in ^{238}U are at 2176, 2255, and 2468 keV. The ratios of these gamma-ray lines can be used to determine the uranium enrichment.

Typical interrogation sources used for NRF are a continuous wave (CW) bremsstrahlung source, a pulsed bremsstrahlung source, or a narrow bandwidth source using Compton backscattering to generate a narrow-energy photon beam. The CW bremsstrahlung source provides the highest total count rate when normalizing the measurements to the same physical geometry because this source excites many gamma lines at once. The narrow bandwidth source had the highest count rate on a given resonance peak and provides a higher signal-to-noise ratio than the bremsstrahlung sources. The pulsed bremsstrahlung sources are limited by pileup in the detector to about 0.1 of a count per beam pulse.

The NRF technique is best suited for measuring the enrichment; however, with the same bremsstrahlung source, an estimate of the mass can be obtained. This estimate can be accomplished by taking a transmission measurement through the item or by observing the Compton-scattered gamma rays off of the item to provide information on the density of the material. If we create a "crude" image, a shape can be inferred and thus the volume. Alternatively, the volume could be assumed based on the container or declarations about the item. Given the density and the volume, a mass can be calculated.

2.1.2.1 Advantages

The advantages are that

- the emitted gamma radiation from the sample is of relatively high energy and can penetrate many layers of material;
- When a high-purity germanium detector (HPGe) is used, the NRF technique can detect almost every major element in the sample; with appropriate attenuation corrections, enrichment information can be obtained;
- the NRF technique uses an accelerator that can be turned off, unlike a radioactive source, which cannot; and
- the same accelerator can be used to determine the mass.

2.1.2.2 Disadvantages

The disadvantages are that

- The NRF technique requires an intense 3-MeV source that may require shielding or removal of personnel from the area during operation. Because the emitted radiation is of relatively high energy, this radiation may escape the system, and an adversary could measure it with a remote detector.
- Heavy shielding may also be required to shield the detector from the source.

2.2 Neutron Interrogation Techniques

2.2.1 Active Well Coincidence Counters (AWCCs) [4, 65–67]

The basic principle behind the AWCC is fast-neutron interrogation using a random neutron source [such as americium-lithium (AmLi)] and counting the induced fission reaction neutrons from the uranium using coincidence techniques. A neutron generator can also be used as the interrogating source. Figure 2 shows a typical AWCC. The doubles and triples (fission neutron coincidence) count rates are used to solve for the induced fission rate and multiplication. The doubles and triples count rate are two and three fission neutrons detected in the ^{3}He tubes simultaneously after the fission neutrons have been moderated in the polyethylene. The ratio of the triples count rate to the doubles count rate gives the multiplication. The interaction of the random source neutrons with the uranium (called "coupling") makes active multiplicity counting more complex than passive multiplicity counting for plutonium assay.

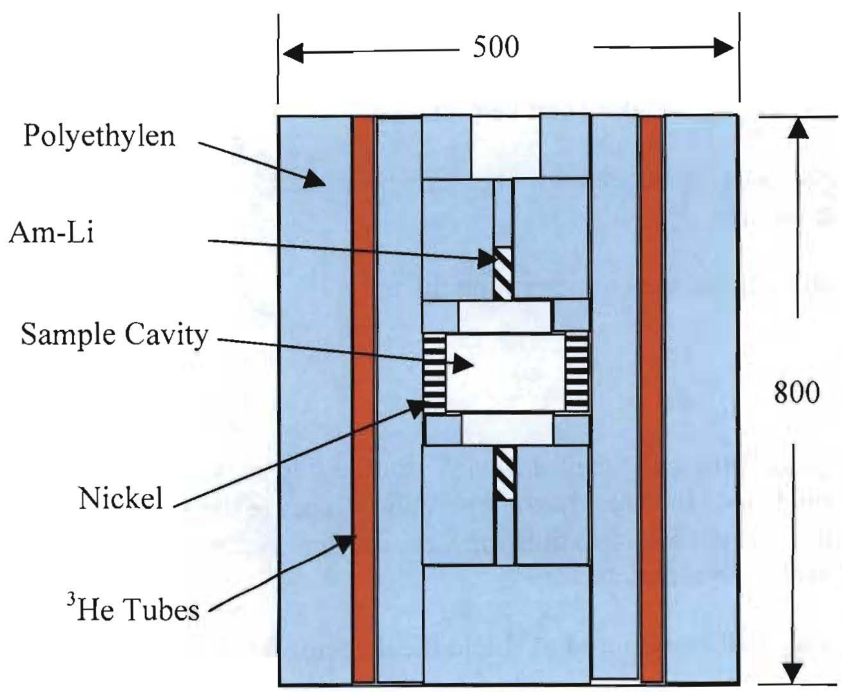

Figure 2. A typical AWCC.

The determination of the uranium mass is dependent on the induced fission rate and the coupling, which must be determined. The coupling depends on the item's geometry, ^{235}U density, chemical and isotopic composition, and location in the assay chamber. The coupling is determined from calibration curves of coupling vs multiplication using physical standards of composition similar to what is to be measured or Monte Carlo calculations. These calibration curves are nonlinear because of the multiplication and absorption in the uranium; they are sensitive to the geometry and density of the item. If we know the coupling, the induced fission rate, and the total output of the AmLi sources, the uranium mass can be determined. The AWCC achieves 1% counting precision for items containing 4 kg or more of ^{235}U. Using multiplicity counting makes the technique relatively insensitive to the random, singles neutrons from the interrogating source, while retaining efficiency for counting the fission neutrons. The AWCC uses many ^{3}He tubes embedded in polyethylene for the detection of thermal neutrons to achieve the high efficiency required for coincidence counting.

The AWCC can be operated in a thermal-neutron mode by placing a cadmium liner in the well to assay small or low-enriched uranium (LEU) samples, or it can be operated in a fast-neutron mode by removing the cadmium liner, for assaying large quantities of ^{235}U. An HPGe detector can be used to determine the enrichment by observing the 186-keV peak from HEU and the 1001-keV peak from depleted uranium. With the appropriate attenuation corrections, the ratio of the peak areas gives the enrichment.

2.2.1.1 Advantages

The advantages are that

- the AmLi source's neutron energies are low enough that ^{238}U does not fission and the ^{235}U mass measurement is not overestimated, which simplifies data analysis;
- the AWCC can operate in either a thermal-neutron mode for small samples or a fast-neutron mode for large quantities of ^{235}U. The AWCC has a minimum detectable mass for ^{235}U of a few grams; and
- Active well counters have been commercially available for many years.

2.2.1.2 Disadvantages

The disadvantages are that

- a longer measurement time, 1000 seconds or more, is required to obtain good precision on the triples coincidence;
- the AmLi source strength is limited to 10^4 to 10^5 neutrons/second. Using a larger source increases the accidental rate;
- a typical commercial cavity for an AWCC is 9 in. in diameter, which limits the size of samples; and
- a radioactive source is used, which needs to be placed in a shielded configuration when not in use. However, replacement of this source with a neutron generator would eliminate this disadvantage.

2.2.2 Californium Shuffler (Shuffler) [4, 67]

An alternative to the AWCC, the shuffler, uses ^{252}Cf sources to induce fissions. The energy of the neutrons from the californium is higher, 2.2 MeV, as compared with the 0.4-MeV AmLi source used in the AWCC. The external ^{252}Cf neutron-source emission rates are generally 10^9 neutrons/second. These rates are higher than in the AWCC. With this high rate, the system cannot detect prompt fissions. Instead, the shuffler counts the delayed neutrons that are emitted seconds to minutes after fissions. The californium source must be removed quickly to a shielded location to allow measurement of the delayed neutrons because they represent only 1% of the fission neutrons. By repeatedly irradiating the sample and counting delayed neutrons, a desired precision can be obtained.

Figure 3 shows the operation of a typical shuffler. In the figure, the gray block is the assay chamber and the upper block is the shielded storage for the californium source. The red circles are the ^3He detectors.

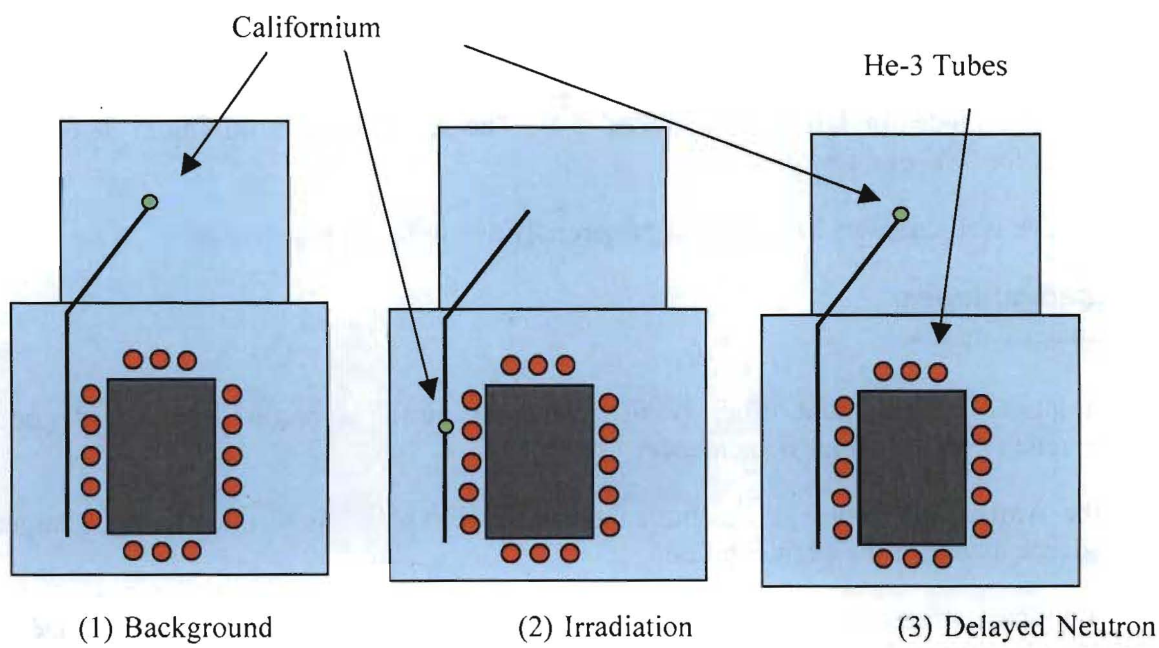

Figure 3. Operation of a californium shuffler.

The background rate for the shuffler is fairly low, about 25 counts per second, and the background rate for the AWCC can be many thousands of counts per second. Therefore, delayed neutrons can be measured with the shuffler and not by the AWCC.

The shuffler is large enough to hold 55-gallon drums; if these drums have small quantities of SNM (less than 10 g) and the best relative precision is needed, the shuffler is the best instrument to use.

A relative precision of 1% is typical with 55-gallon drums.

Shufflers are not as common in the field as AWCCs because of the larger size, the greater expense, and the fact that intense californium sources are more difficult to handle.

2.2.2.1 Advantages

The advantages are that the shuffler

- generates a high-precision measurement for bulk uranium, where gamma-ray measurements cannot be used and the item cannot be placed in an AWCC;
- has a lower background than the AWCC, allowing better precision; and
- can be used in the passive mode for bulk items.

2.2.2.2 Disadvantages

The disadvantages are that

- the shuffler uses an intense californium source, which has radiation safety implications;
- the system is very large and expensive; and
- the shuffler requires careful calibration to convert the delayed neutron count rate to an accurate mass of ^{235}U.

2.2.3 Differential Die-Away (DDA) [40, 42-48, 52-54, 56-59]

In the differential die-away technique, a deuterium-tritium (D-T) neutron generator produces repetitive pulses of neutrons that are directed into an item for inspection. The neutrons are thermalized in the item matrix and absorbed on the surface of any SNM present in the cavity, generating fission neutrons. The fission neutrons generate an epithermal spectrum due to slowing down in the medium. If we use shielded and bare detectors, the epithermal signal from fission can be differentiated from the thermal interrogating signal. Figure 4 shows a typical DDA system. Typically, ^{3}He detectors embedded in a moderator are positioned around the item, forming a chamber. To monitor the interrogating thermal-neutron flux, a low-efficiency, bare ^{3}He proportional counter is placed within the chamber. The ratio of the prompt-fission neutron counts to the interrogating flux monitor counts is proportional to the amount of fissile material present.

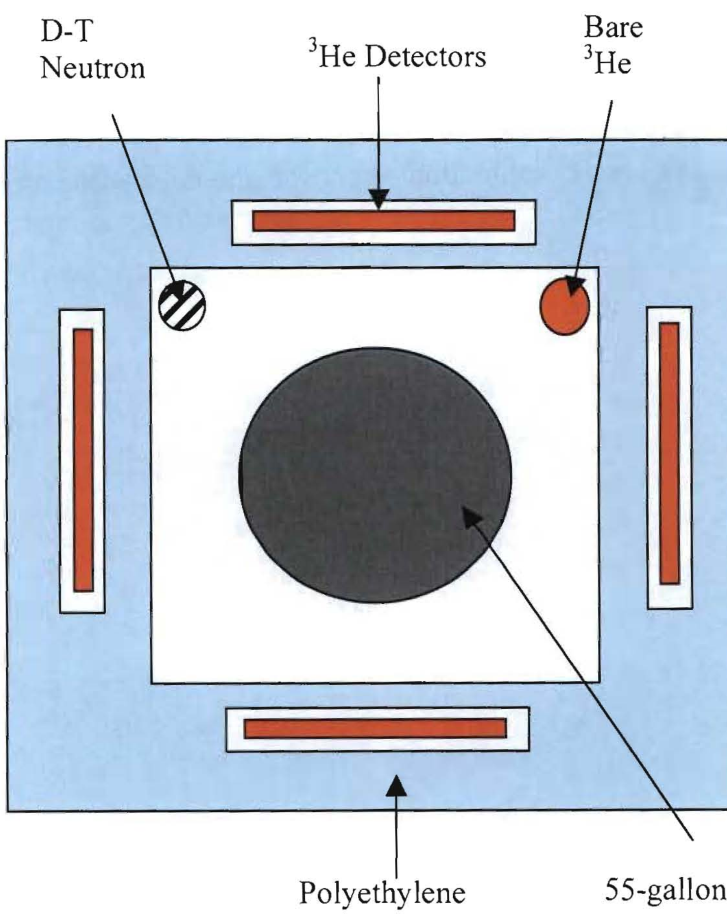

Figure 4. A top view of a typical DDA setup.

DDA systems have been used to monitor fissile material in waste drums and are capable of detecting milligrams of fissile material in dispersed form.

Figure 5 shows a typical time history response of the shielded detectors of a package monitor with (upper curves) and without (lower curve) fissile material in the chamber.

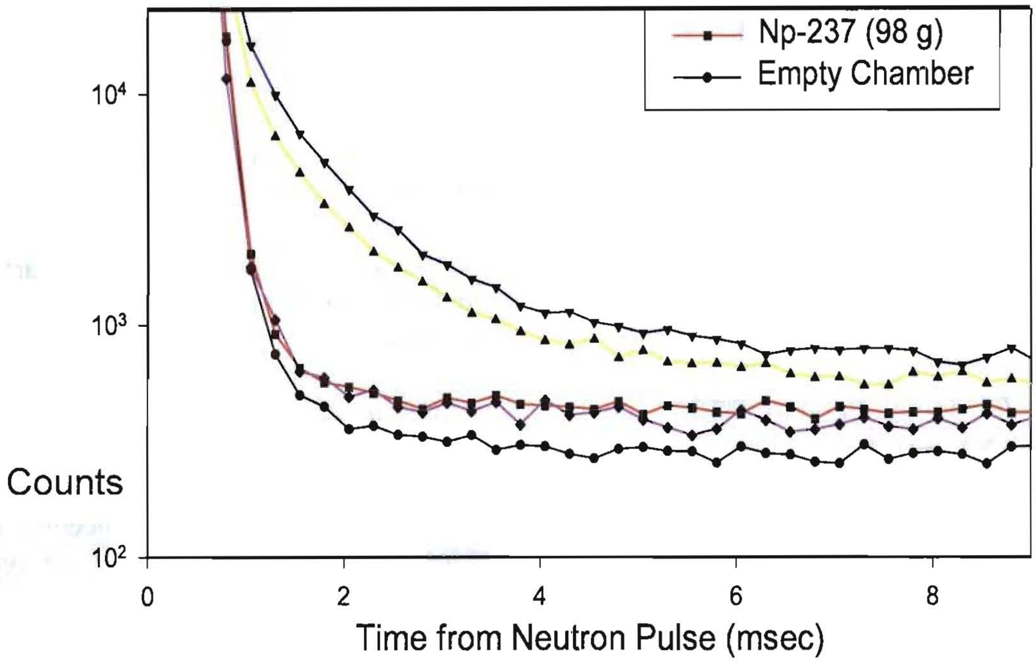

Figure 5. Time history of shielded detector response with (upper curves) and without (lower curve) SNM.

2.2.3.1 Advantages

The advantages are that

- this system can detect milligrams of fissile material in dispersed form; and
- DDA uses a D-T generator, which can be turned off.

2.2.3.2 Disadvantages

The disadvantages are that

- the DDA technique is not suited for lumps of metal samples because the thermal neutrons are unable to penetrate the full volume of the sample; and
- the system requires a large quantity of moderator; for systems large enough to assay 55-gallon drums, the moderator may weigh several thousand pounds.

2.2.4 Delayed Neutron Reinterrogation Technique [68]

In this technique, an external pulsed generator, for example (photons above 5 MeV or 14- MeV neutrons), induces fissions into the uranium sample. Approximately 270 different fission fragments emit delayed neutrons. The yield per fission of each delayed neutron precursor is dependent on the fissioning isotope and the particle inducing fission.

The concept is to create an intrinsic steady-state source of delayed neutrons artificially by using the pulsed source to perform repetitive interrogations and generate a uniform distribution of fission products throughout the fissile material. This delayed-neutron source strength is dependent on the intensity and ability of the active source to generate fissions in the fissile material. The delayed neutrons leak from the system, get captured, or induce more fissions.

Typical data analysis for this technique uses neutron noise analysis. This analysis is a variance-to-mean technique using various moments of the neutron counting distribution to assess information about the subcritical neutron chain reaction system.

Delayed neutron reinterrogation has been used to determine uranium enrichment of subcritical systems ranging from 3.8 to 22 kg.

This technique has been demonstrated as a proof of principle, and more research is needed if it is to be used as a standard approach for safeguards measurements. Figure 6 shows a typical experimental arrangement for delayed neutron reinterrogation.

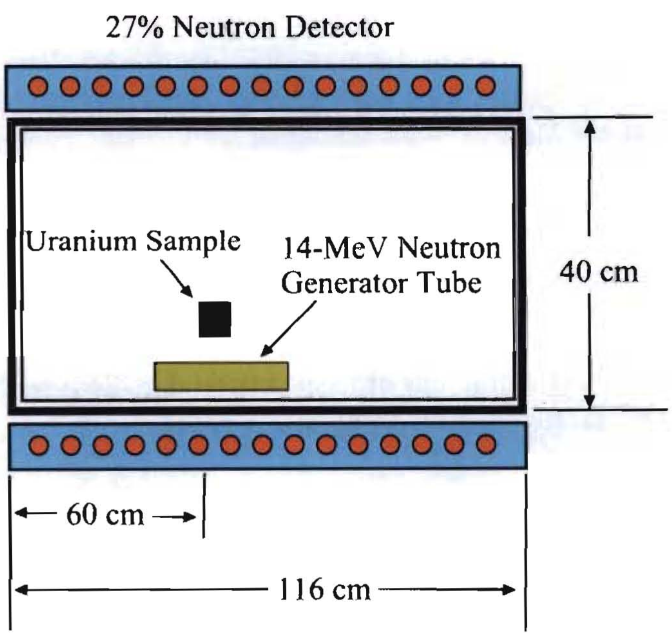

Figure 6. Typical setup for delayed neutron reinterrogation measurements.

Figure 7 shows the delayed-neutron-driven response for two different uranium enrichment samples. The upper (blue) curve is data from 91% enriched HEU, and the lower (black) curve is data from depleted uranium.

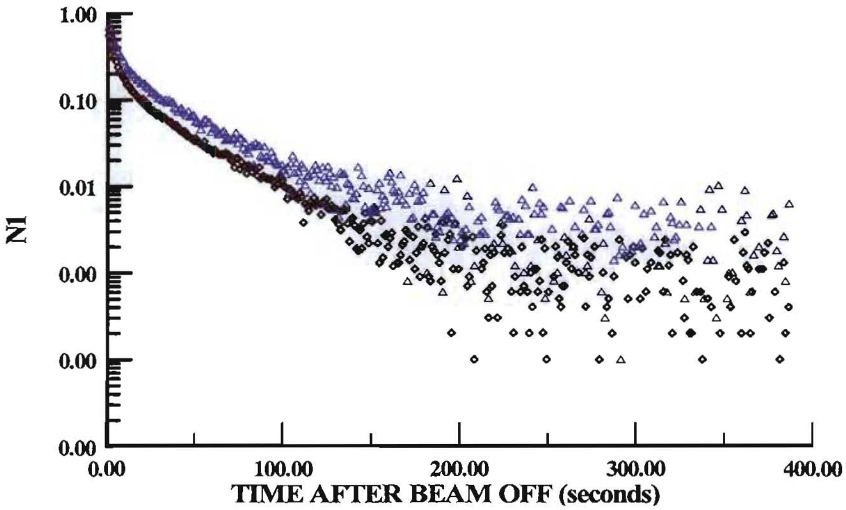

Figure 7. Delayed-neutron-driven response for 91% enriched uranium (upper curve) and 0.2% depleted uranium (lower curve).

2.2.4.1 Advantages

The advantages are that

- this technique uses a generator that can be switched off for the interrogation source, and
- measurement standards are not needed to calibrate the system.

2.2.4.2 Disadvantages

The disadvantages are that

- this technique is still in the research phase and would need considerable effort to use it for treaty verification.

2.2.5 Associated Particle Technique [69]

A D-T generator generates not only neutrons, but also alpha particles. For every 14-MeV neutron generated, a corresponding alpha particle is generated and travels in a direction opposite to the neutron for momentum conservation. The D-T generator has a built-in pixilated alpha detector. Detection of the alpha particle allows the direction and time of the associated neutron to be "tagged." By placing fast-neutron detectors behind and to the side of the object being interrogated and incorporating appropriate electronics, time correlations (coincidences) between events in the alpha detector with events in the different neutron detectors can be obtained. Correlations can be made between the alpha detector and a pair of neutron detectors to determine if fissionable material is present. The coincidence counting rate is an indication of the mass. Gamma-ray detectors can also be used to detect the fission gamma rays given off from the fissioning of the ^{235}U. Figure 8 shows a typical experimental arrangement.

The technique is limited to kilogram quantities of HEU. The packing limits the image but does not limit the detection of HEU.

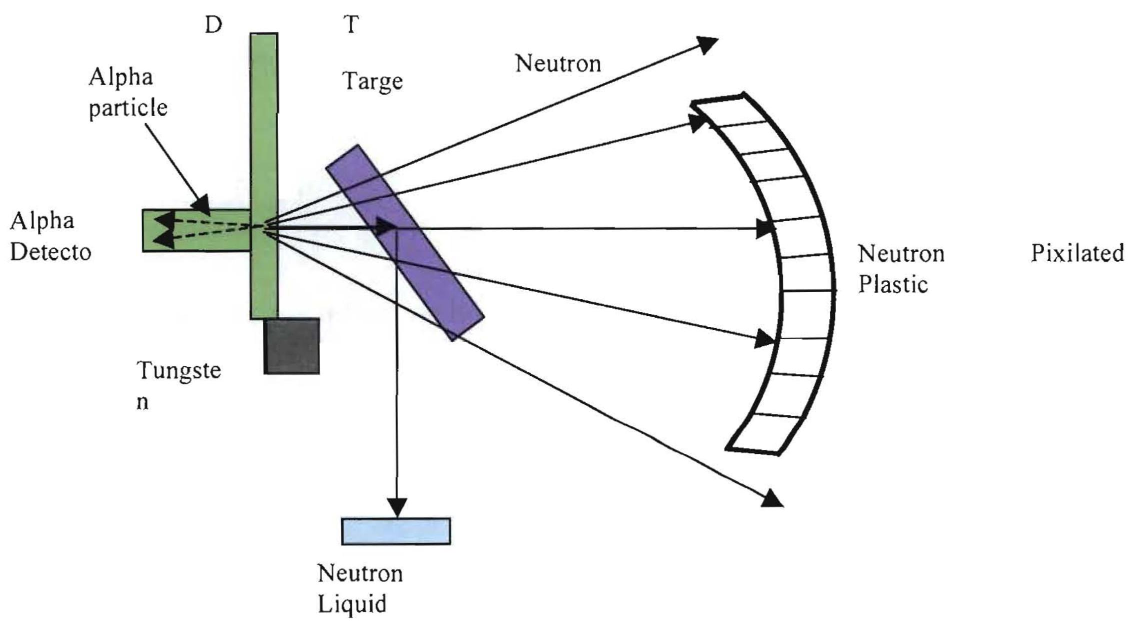

Figure 8. A typical associated particle experimental setup.

Advantages:
The advantages are that

- the system is modular, fairly lightweight, and can be moved around easily;
- the system uses fast-neutron detectors and has good timing; and
- the D-T generator can be turned off, unlike a radioactive source, which cannot.

Disadvantages:
The disadvantages are that

- the efficiency of the system is low;
- the system uses a D-T generator that requires periodic maintenance; and
- the data analysis is not yet automated and requires guidance and interpretation by experts.

3 SUMMARY OF IB CONSIDERATIONS FOR ACTIVE INTERROGATION SYSTEMS [100-113]

An active AMS contains many of the same components as a passive AMS. The radiation detection, data acquisition, and data processing systems of an active interrogation AMS are similar to passive AMSs built in the past e.g. the [fissile material transparency technology demonstration (FMTTD), next-generation AMS (NG-AMS), and Russian neutron/gamma AMS (AVNG)]. For these components, established IB techniques can be used, including

- opaque enclosures to prevent visual observations of the systems,
- Faraday cages to minimize radio frequency (RF) signal leakage from the electronics,
- a data barrier to ensure that only the agreed-upon attributes are displayed to the outside operator,
- filtering of the electrical power input to prevent information passing through the power lines, and
- use of optical fibers to bring the permitted information to the outside while blocking a path for RF signal radiation.

The sensitive information inside the IB can be further protected by including a system to detect a breach of the enclosure and deleting all the sensitive information should this occur. This protection can be provided either by shutting off the power to the information-containing devices, which are designed to lose all stored information with the loss of power, or by having software delete the information when it is notified of an enclosure breach.

The size of the enclosures required to contain an active AMS will vary, depending on the technique used and the size of the components. For large radiation sources, a larger enclosure may be needed.

Both passive and active AMSs measure some form of radiation that can be detected and analyzed to reveal sensitive information. This radiation can penetrate the IB enclosures. In passive plutonium-measurement AMSs, the radiation contains detailed gamma-ray spectra and neutron counting and multiplicity information. For the active system, the information will depend on the interrogation technique used. In the passive systems, this problem has been addressed by administrative means: strict controls have been placed on what the monitors can bring to the AMS and their allowed proximity to it. For active systems, the radiation may be much more energetic and intense. A similar solution would require that controls extend to larger distances, possibly hundreds of feet. In large facilities with large controlled areas, larger distances should be achievable.

Active interrogation AMSs can be classed as using radioactive sources (e.g., ^{252}Cf or AmLi) or accelerator sources for the interrogation particles. The radioactive sources are "always on"; although their radiation may create safety problems, it is relatively constant and not a source of information leakage.

In principle, the accelerator-based systems could provide an information leakage path. The accelerator beam can be viewed as a potential information carrier; however, unless it is modulated, no information is being transmitted. If the computer, or other electronics, has control of the accelerator, this modulation could be seen as a possible mechanism to send information outside of the enclosure. The beam intensity could be varied, or, in the case of a pulsed source, the period could be varied. If we assume that the AMS is designed and built by the host, the host could ensure that no such mechanism existed; if supplied by the monitor, this would be a concern. For some of the active interrogation techniques, it might be possible to have the accelerator external to the IB enclosure and therefore have it clearly not influenced by any component that had access to sensitive information. As with a passive AMS, care must be taken not to create an inadvertent information leakage path. This path could be created by collecting data until a predefined uncertainty has been achieved or setting the accelerator intensity to produce a given transmission rate through the item. The data collection conditions should be independent of the item being assayed.

Another way that there could be information in the beam is that the beam is modified by its passage through the item being assayed and that this information can be detected some distance from the AMS. One method is that the beam might "cast a shadow" of the SNM, creating a projected image of the item downstream of the AMS. Radiation caused by the accelerator beam interacting with the item might also be detectable. For instance, in the NRF system, the fluorescence gamma-ray lines (either emitted by the item or absorbed by it) might be detectable.

The accelerator-based systems have the advantage that they can be turned off. This advantage could be used as a safety mechanism if any information leakage were suspected. Additionally, when these systems are not being used, there is no radiation safety concern and the potential information path has been shut off.

Systems that produce an image of the item and use this to calculate an attribute could have several potential problems. If the image is to be compared with an expected one, the host may not be willing to release this "template." Even information such as why the host will not release the image, how it might affect an attribute, or even where not to look may be sensitive. If the image is completely internal to the AMS and no comparison is being made (e.g., the information is used to calculate a volume of SNM present), there should generally not be an issue, although again, if some particular shape might affect an attribute calculation, the host might not want to discuss it or use that attribute. General image analysis software can be complex, and because it will have to run autonomously inside the AMS IB, it must be robust enough that both parties are confident of its operation under all circumstances.

Because of the higher radiation intensity involved in active interrogation systems, the use of radiation-hardened components may be necessary. During the accelerator operation, radiation safety considerations may mean that no people will be allowed to be in its vicinity. Thus, the "guards–and-guns" administrative component of the protection system may be less effective—no one will be present to observe what is happening. This high level of radiation will probably not be a significant factor from an IB perspective, but it should be considered for authentication of the system by the monitors. During the period of system operation, people may not be allowed to maintain visual contact with the system and may have to rely on tamper-indicating devices or cameras for continuity of knowledge.

For some of the active interrogation techniques, the sample is irradiated and measurements are made after the radiation is removed (e.g., the californium shuffler, the delayed neutron reinterrogation, and the differential die-away). During the radiation phase, many fissions are being produced in the SNM, and although the technique does not use the prompt fission radiation and products, they may still carry some information.

Most of the far-field radiation issues could be addressed by adding plenty of shielding around the system. The shielding could reduce the radiation by absorbing it, scatter the radiation to degrade any image information, contain high-Z material to create "false" images, or emit/absorb gamma-ray lines or regions to obscure spectral information.

4 PATH FORWARD

We recommend two approaches. In the first approach, Los Alamos National Laboratory has a multiplicity counter behind an IB that was used for passive measurements on plutonium. This counter could be converted into an AWCC fairly easily. This conversion would include making modifications to the existing software to enable active measurement analysis to be performed to determine the mass of ^{235}U. Software code modifications for measuring the enrichment would also need to be made for the enrichment determinations of the uranium.

For the second approach, we recommend investment into the NRF technique. We do not know of any NRF system currently operating behind an IB. NRF offers the potential ability to measure both mass and enrichment behind an IB.

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