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Author(s): W.H. Geist, M.T. Swinhoe, D.S. Bracken, C.R. Freeman, and M.R. Newell

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Calibrating and Training of Neutron Based NDA Techniques with less SNM Standards

W. H. Geist, M. T. Swinhoe, D. S. Bracken C. R. Freeman, and M. R. Newell
Los Alamos National Laboratory

ABSTRACT

Accessing special nuclear material (SNM) standards for the calibration of and training on nondestructive assay (NDA) instruments has become increasingly difficult in light of enhanced safeguards and security regulations. Limited or nonexistent access to SNM has affected neutron based NDA techniques more than gamma ray techniques because the effects of multiplication require a range of masses to accurately measure the detector response. Neutron based NDA techniques can also be greatly affected by the matrix and impurity characteristics of the item. The safeguards community has been developing techniques for calibrating instrumentation and training personnel with dwindling numbers of SNM standards. Monte Carlo methods have become increasingly important for design and calibration of instrumentation. Monte Carlo techniques have the ability to accurately predict the detector response for passive techniques. The Monte Carlo results are usually benchmarked to neutron source measurements such as californium. For active techniques, the modeling becomes more difficult because of the interaction of the interrogation source with the detector and nuclear material; and the results cannot be simply benchmarked with neutron sources. A Monte Carlo calculated calibration curve for a training course in Indonesia of material test reactor (MTR) fuel elements assayed with an active well coincidence counter (AWCC) will be presented as an example. Performing training activities with reduced amounts of nuclear material makes it difficult to demonstrate how the multiplication and matrix properties of the item affects the detector response and limits the knowledge that can be obtained with hands-on training. A neutron pulse simulator (NPS) has been developed that can produce a pulse stream representative of a real pulse stream output from a detector measuring SNM. The NPS has been used by the International Atomic Energy Agency (IAEA) for detector testing and training applications at the Agency due to the lack of appropriate SNM standards. This paper will address the effect of reduced access to SNM for calibration and training of neutron NDA applications along with the advantages and disadvantages of some solutions that do not use standards, such as the Monte Carlo techniques and the NPS.

INTRODUCTION

Nondestructive assay instrumentation has been used for years for material control and accounting of special nuclear material. In the United States these instruments are used to satisfy requirements in DOE orders for the accounting of nuclear materials and internationally NDA instruments are used by the International Atomic Energy Agency to confirm nuclear material inventories declared by the host country. NDA instrumentation are used in all aspects of the fuel cycle and at both bulk and item facilities.

All NDA instrumentation requires the use of SNM standards at some point during the development of the technology. The steps where standards are typically used include development and testing, proof of principle, calibration, and quality control. In the development and testing phase, standards are measured to collect a data set with known properties that is used to develop analysis algorithms. Depending on the type of instrument and the intended use, a few or many standards may be required. In the proof of principle phase, standards are measured to ensure that the system is assaying the items to the required specifications. The best practice is to use standards that closely resemble the items that will be measured. The number and type of standards required for calibration depends on the assay technique. Some NDA methods do not require any standards for calibration while others may require a set of standards that very closely resemble the characteristics of the items to be assayed. Standards are also used for training safeguards practitioners to properly use the NDA equipment.

In recent years concerns about terrorism, dirty bombs, and environmental contamination has resulted in tighter controls on the use of nuclear material. Issues such as site wide roll up of nuclear material safeguards category and material at risk (MAR) necessitate the use of nuclear facilities while using safeguards category I or II levels of special nuclear material. The operational cost in a nuclear facility is often prohibitively expensive for many nuclear nonproliferation projects and training courses. Use of safeguards category III or lower levels of SNM is possible at non-nuclear facilities but MAR issues require that most of the materials are in ANSI certified containers to comply with safety and environmental regulations. Proposed and recent changes to the rules that govern the use of SNM has made it more difficult and costly to use significant amounts of nuclear material. Over the past 10 years, nuclear nonproliferation programs access to safeguards category I and II levels of SNM has gone from easy and relatively inexpensive to very difficult and prohibitively expensive [1].

NDA techniques that require the use of category level IV or lower level of SNM have not been impacted greatly. This includes both neutron and gamma applications such as waste measurements, TGS, SGS, differential die-away, and uranium measurements for measurement of mass, activity, or enrichment. Of greatest impact is NDA techniques that assay large masses of SNM. In general neutron based NDA techniques will require more and larger standards than gamma ray based NDA techniques. The reason neutron techniques require larger standards is the sensitivity to the properties of the entire item such as the mass and multiplication. Neutron techniques are normally used to assay large mass items, while in general gamma ray techniques are usually not used to measure the mass of the item because of the self shielding properties of gamma rays. The wide-ranging importance of representative standards for testing and calibration versus the mass of the standard for different NDA techniques is shown in Figure 1. Figure 1 is a cartoon representation of the use of standards for most common NDA applications and there are cases where certain techniques will fall outside the range indicated on the graph.

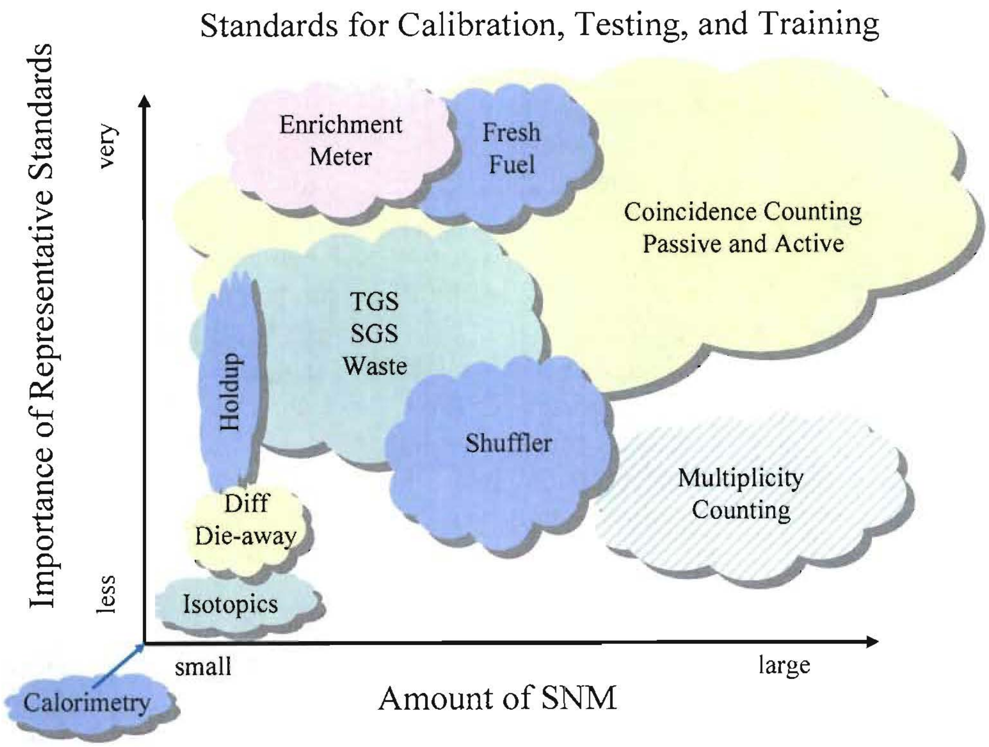

Figure 1: Pictorial representation of the importance of representative standards versus the amount of special nuclear material required for the standard.

Since neutron based techniques in general require larger SNM items for calibration and testing than gamma ray based techniques, this paper will focus on the impact of neutron based NDA to nuclear nonproliferation programs resulting from less access to large quantities of SNM. To mitigate these effects calculational and equipment based tools have been developed. This paper will describe these tools and discuss the advantages and disadvantages to using these tools in place of SNM for equipment testing, calibration, and training.

MONTE CARLO

Monte Carlo calculations are becoming a very powerful tool that enables the design and calibration of an instrument in some instances without ever using standards. For safeguards applications the most common Monte Carlo code used is the Monte Carlo N-Particle eXtended (MCNPX) [2] code. Many of the physical properties of fission and neutron transport are incorporated into MCNPX which allows for good agreement with measured data. The MCNPX code has the ability to model the coincidence response of a detector which is one of the most important measurement observables used to determine the assay mass. Past experience has shown that Monte Carlo modeling of spontaneous fission such as plutonium and californium have resulted in excellent agreement with declared values to within the statistical and systematic errors associated with the reference sources.

Modeling of active neutron interrogation techniques has proven more difficult. Several properties of the sources which are not always well known even for reference material affect the measured response. Properties such as the interrogation source energy distribution and exact geometry of the assay material can have an impact on the final result.

An example of the usefulness and drawbacks of the Monte Carlo modeling can be shown through some recent modeling and calculations completed to support a training course. One part of the training course was to perform measurements on MTR fuel elements. The MTR fuel elements are measured with an AWCC using an active interrogation technique. The AWCC is placed on its side with the end plugs removed and an AmLi neutron source is used to induce fission in the ^{235}U within the MTR fuel assemble. The measured doubles rate is then related to a ^{235}U mass from an empirical calibration curve. Unfortunately, no calibration curve existed for AWCC measurements on this type of MTR fuel elements and a suitable set of calibration items was not available for calibration. After the Monte Carlo calculational calibration was complete, the facility notified us that they would be able to supply a set of fuel elements for calibration. This resulted in an ideal situation to compare a Monte Carlo generated calibration with an empirically measured calibration curve [3].

MCNPX was used to generate a calibration curve for the MTR fuel. The Monte Carlo code requires that the geometry of the model be defined. Shown in Figure 2 is the geometry of the system. The geometry of both the NDA instrument and the nuclear material must be well known to get good agreement between the measured and calculated results.

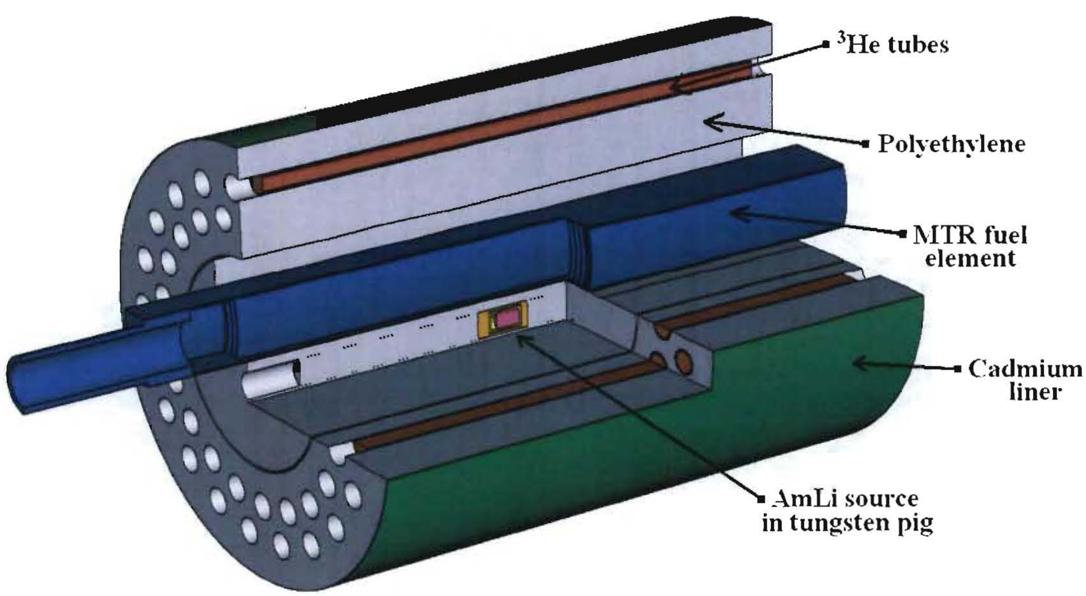

Figure 2: MCNPX generated geometry for an AWCC configured for MTR fuel measurements.

A Monte Carlo derived calibration was made by calculating the doubles rate for several different fuel loadings of the MTR fuel element. The MCNP calculations did a good job of predicting the shape of the calibration curve but the absolute value was off by at most

7% as seen in Figure 3. The disagreement between the calculated and measured assay results is most likely because of uncertainty in the AmLi source strength and spectrum and small differences between the modeled and true geometries. The example of the MTR fuel plates is a case where the geometry and physical properties of the fuel are extremely well known. The accuracy of the Monte Carlo results is directly proportional to how well the characteristics of the nuclear material are known. One would expect that the more uncertainty in the characteristics of the nuclear material the worse the Monte Carlo results will be.

Monte Carlo calculations have the ability to reduce the quantity of SNM standards needed but not to eliminate the use of standards. Standards are also very useful to confirm and benchmark any Monte Carlo calculations. Some general comments about Monte Carlo calculations and standards are given below.

- ⇒ For plutonium and other sources with significant source strength, Monte Carlo calculations do an excellent job in predicting the detector response often to a couple of percent or better.
- ⇒ For uranium items which require induced fission from an external source, Monte Carlo techniques do a reasonable job in predicting the shape of the detector response but often require a standard for absolute calibrations.
- ⇒ Detailed knowledge of the source and detector geometry are required to get good results. This is even more important for active interrogation techniques because the interrogation source interacts with the material surrounding the SNM before inducing fissions.
- ⇒ Source shape and composition can greatly affect the calculated results. Alpha, n neutrons from impure plutonium items are difficult to model and uncertain source geometry and material characteristics of the SNM will effect the multiplication. In these cases working reference standards perhaps characterized by calorimetry would likely give much better results than a Monte Carlo based calibration [4,5,6].

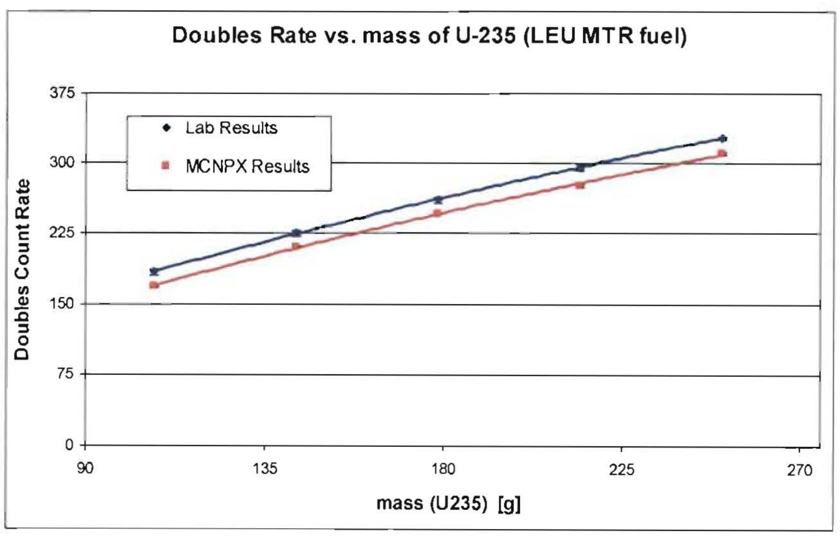

Figure 3: Comparison of Monte Carlo calculated calibration curve with experimentally measured data for MTR fuel measurements with an AWCC.

NEUTRON PULSE SIMULATOR

The neutron pulse simulator (NPS) [7,8] is an electronic module that is capable of producing both random and correlated pulse streams. The NPS can be used to produce a pulse stream that accurately simulates a detected neutron pulse stream from radioactive material. A picture of the NPS is shown in Figure 4. The module is used to test data acquisition systems and for procedural training on the operation of neutron coincidence and multiplicity counters.

Figure 4: Picture of the neutron pulse simulator.

A windows based user interface is used to operate the NPS. The user has multiple options for specifying correlated pulses. The user may select "*Correlated*" and directly enter the singles, doubles and triples rates. This mode requires the die-away time, predelay and gate width be specified. The NPS will then produce correlated pulses that will yield the expected rates measured by an instrument with specified parameters. By selecting the "*Sample*" tab of the user interface as shown in Figure 5 the user can specify the correlated pulses produced based on plutonium item parameters and detector system parameters. In this mode, the NPS will calculate and produce the singles, doubles and triples rates equivalent to rates produced from the actual instrument/Pu source combination. The rates are calculated from the point model equations [9] and only produce realistic pulse streams for a range of the input parameters. The "*student*" tab option as shown in Figure 5 was designed specifically for the IAEA for training purposes. In this mode, the user specifies the source type, the measurement type, and the specific instrument used. The NPS will produce the rates required to simulate the specified instrument/source combination. The singles, doubles, and triples rates produced under the "student" tab are determined from actual measurement data of real items. When the

NPS is used for training, the output of the NPS is connected directly into a shift register. In this case, the NPS unit simulates the NDA counting system measuring SNM sources.

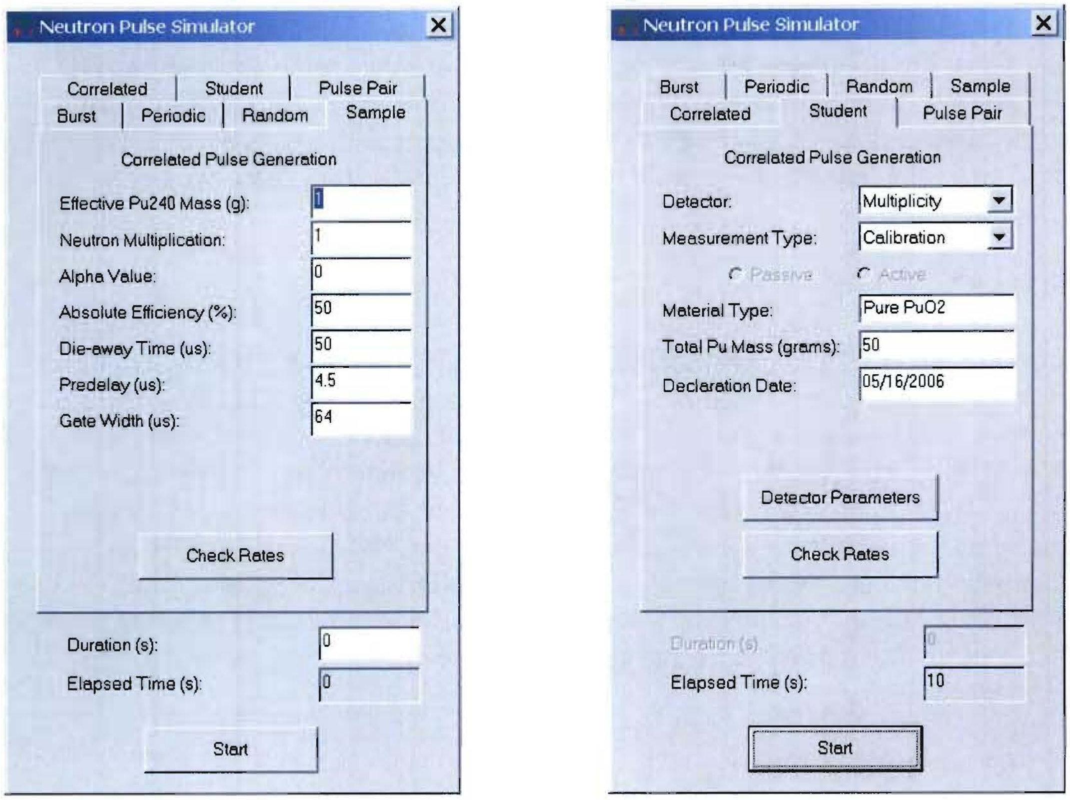

Figure 5: Two screen shots from the software used to control the NPS. Shown is the sample and student tabs, both of which can be used to generate pulse streams representative of real nuclear material for training purpose.

The NPS is used by the IAEA to train all new inspectors who are required to attend the Introductory Course on Agency Safeguards (ICAS). The inspectors use the NPS when learning neutron based NDA techniques and the associated data acquisition and analysis software, International Neutron Coincidence Counting (INCC). The NPS allows the students to take simulated data and use the INCC software without requiring the use of SNM standards. There are many advantages and disadvantages to using the NPS instead of SNM standards. Some general comments about using the NPS in a training environment instead of NDA equipment with SNM sources are listed below:

⇒ The ability to take realistic data without the need for SNM sources. The NPS eliminates the need to work in a radiological area and reduces operational costs.

⇒ The NPS only tests the back end of a NDA system. The data acquisition and analysis software can be tested but not the actual detector and associated electronics. In a training scenario, this is an excellent tool for students to learn how to operate the software associated with a detector system.

⇒ For training on fundamental physics principles and overall measurement procedures, the NPS is not an effective tool. The NPS does not allow a student to learn from their mistakes such as improper loading of the item, incorrect operation of the neutron counter, and basic ability to learn to problem solve when the instrument is not operating correctly.

⇒ The NPS does not allow for any experimentation. Perhaps one of the most valuable learning tools used to answer student's questions is by performing impromptu experiments. Only through the use of sources can one have the flexibility to experimentally measure how different variables affect the NDA results. In our experience in teaching both domestic and international training course, this flexibility to measure different items and different configurations is one of the best ways for students to fully understand the basic measurement principles.

SUMMARY

Nuclear materials are becoming increasingly difficult to access for testing, calibration, and training of NDA technologies. This has the potential to result in a new generation of safeguards professionals without any hands on SNM assay experience. Technologies such as Monte Carlo and the NPS have reduced the burden of access to nuclear materials but use of some standards is required for development and calibration of NDA technologies. To effectively train IAEA inspectors and NDA professionals on fundamental nuclear physics principles and use of NDA technologies requires the use of uranium and plutonium standards. The NPS is an effective training tool for teaching limited measurement procedures and operation of neutron NDA data acquisition and analysis software.

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