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The Importance of Nondestructive Assay (NDA) Measurements to Nuclear Safeguards, Material Control and Accountability, Safety, and Security

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EXECUTIVE SUMMARY

Nondestructive Assay (NDA) measurements are performed to determine properties of nuclear material bearing items without opening the item or altering the physical or chemical state of the nuclear material. Applications of NDA measurements range from simple *qualitative* detection or identification of nuclear materials to the accurate *quantitative* determination of the amount present. The results of NDA measurements are used for various purposes associated with nuclear facility operations to determine whether a facility is operating in a safe, secure, and compliant manner. The improper performance or application of NDA measurements within a facility has the potential of misleading both facility personnel and outside inspectors or auditors into inaccurate conclusions regarding aspects of the operation of the nuclear facility or the usage of nuclear material. Since NDA techniques provide a core capability in determining defensible accountability values across the domestic U.S. nuclear complex, providing independent measured values for international inspectors, providing input into criticality safety compliance, and are a key part of enabling process flow and production in all facilities; any major weakness in the application of NDA techniques has the potential to suspend facility operations. Personnel who are involved in performing, analyzing, managing or using the results of NDA measurements must be properly trained and supported in their activities to reasonably expect that NDA measurement results with the requisite accuracy are achieved and to have confidence that facilities are compliant with regulations and procedures. Consistent and comprehensive NDA training is required to give such personnel a broader understanding of how their work affects the operations of their facility and will help ensure that the application of NDA measurements across the industry is uniform.

INTRODUCTION

Acceptance by the public of the use of special nuclear materials (SNM) by industry and government is contingent in part on the ability of the nuclear establishment to ensure that the use of these materials will not bring harm. To ensure that SNM is being used within a nuclear facility in a safe, secure, and compliant manner, it is necessary to continuously control and account for all SNM that is present. High-quality measurements must be performed to confirm or quantify the various characteristics of the SNM. Without accurately knowing the amount and type of SNM that is being used in a process or that is held at a particular location, determinations as to whether the SNM is being utilized in an appropriate, safe, and secure manner cannot be optimally made. The most frequently implemented measurement techniques used to reliably determine the characteristics of SNM are Nondestructive Assay (NDA) techniques. NDA measurements involve the detection and analysis of radiation induced or emitted spontaneously from the nuclear material bearing item and can often be used to determine the isotopic composition and/or the mass of the SNM contained. Because NDA measurements are performed without opening the container or altering the physical or chemical state of the contained nuclear material, they do not generate radioactive waste by-products, are faster and safer, and usually less expensive than Destructive Analysis (DA) techniques. On the negative side, they are typically not as accurate as DA techniques unless one includes sampling errors in the uncertainty estimation. NDA measurements are often adequate and may offer the only viable alternative.

The applications of NDA measurements range from simple qualitative detection and identification of nuclear material to the accurate quantitative determination of the composition or amount of nuclear material present. NDA is applied to facility products, waste, and most everything in between. The results of NDA measurements are used for a number of purposes associated with nuclear facility operations including nuclear material control, nuclear material accountability, determination of nuclear material hazard category, criticality safety, health and safety, decontamination, decommissioning, as well as waste characterization and management. The improper performance or application of NDA measurements has the potential of leading personnel or outside auditors into incorrect conclusions regarding various important aspects of the operations of the nuclear facility or the usage of nuclear material and can have a wide range of negative impacts not only on the facility in which they occurred, but also on associated nuclear facilities as well.

Because NDA techniques provide a core capability in determining and verifying defensible accountability values across the nuclear complex and are a key part of enabling process flow and production in all facilities, any major weakness in the application of NDA techniques can suspend operations in production facilities. Personnel who are involved in performing, analyzing, or managing NDA measurements must be properly trained and supported in their activities in order to obtain the required measurement result accuracy and to build confidence that facilities are compliant with regulations and procedures. The training and support that NDA professionals receive is often facility specific and activity dependent. Consistent and comprehensive NDA training across the domestic nuclear complex will give personnel a broader understanding of how their work affects the operations of their facility and will help ensure that the application of measurements across the complex is uniform. In this paper, a brief discussion on how NDA measurements enable a facility to utilize SNM in a safe, secure, and a compliant manner will be given in order to illustrate the importance of effective and standardized NDA training of personnel. The current status of NDA training will be discussed and possible paths forward for improving the training of personnel involved in NDA measurements will be given.

IMPORTANCE OF NDA MEASUREMENTS

Nuclear Safeguards

It is difficult to overestimate the importance that physical measurements performed with NDA instruments play throughout the nuclear fuel cycle. They underpin decision making in many areas including nuclear safeguards. NDA measurements are generally faster, less intrusive, and can often be applied to the nuclear material in situ rather than requiring specialized equipment in a dedicated room. NDA measurements are always chosen when the urgency of getting a result exceeds the requirements regarding measurement uncertainty. Typical turnaround times of 15 minutes to 1 hour for NDA measurements contrast with turnaround times of ½ day to 2 weeks for most DA labs dedicated to a site or facility. If the DA lab is off site, it can be months between sampling and getting a measurement result. NDA measurements generally have less restrictive requirements for calibration standards and are chosen for difficult to measure items that are not amenable to other measurement techniques (either due to lack of suitable calibration materials, difficulty in sampling heterogeneous items, or difficult-to-dissolve and difficult-to-preprocess items). NDA does not consume the standard every time it is used which is often the case with DA.

Domestic MC&A

NDA measurements are preferred for measurements of low equity materials for economic reasons provided data quality objectives are met. One can generally make stable check sources and then re-use them essentially forever under well-known measurement control activities[1]. NDA measurements are also applied to high equity or product materials thereby obtaining bulk results promptly and without secondary waste, when the item is sufficiently homogeneous, or in cases where DA methods are subject to known types of bias that are difficult to quantify. Finally NDA measurements are used to locate material, like in process hold-up measurements[2,3,4], when the operator is not fully aware of where the nuclear material is, how it might be distributed, or when specific items might not be where one expects them to be. The applications range from reducing inventory differences, to locating deposits before decontamination and dismantlement activities, to criticality safety surveys, to segregating waste between expensive and more-expensive disposal options. The impact of poor quality or erroneous NDA measurement results can range from economic (loss of expensive nuclear material into a waste stream) to health and safety (a lethal criticality accident) effects.

International NDA Usage

The IAEA (International Atomic Energy Agency) is charged with independently verifying an operator's declared values on a subset of the operator's declared inventory. The IAEA has 3 broad categories of measurements: 1) Gross defect refers to an item or batch that has been falsified to the maximum extent possible; 2) Partial defect refers to an item or batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present; 3) Bias defect refers to an item or batch that has been slightly falsified so that only a small fraction of the declared amount of material is missing. NDA measurements have been used for all 3 tasks in a variety of facility types; including reactors, enrichment, and reprocessing facilities. In many cases, NDA measurements have the advantage over DA measurements of utilizing portable, or at least transportable, equipment that is comparatively simple to setup and operate. It is much easier to establish measurement "independence" when using instrumentation and check sources that have been brought into the facility rather than using the operator's measurement equipment or facilities.. The impact of poor quality or erroneous NDA measurement results on an IAEA inspection effort can vary widely, from negligible or self-canceling errors to drawing the wrong conclusion about whether a State is in compliance with its agreements to use nuclear material safely and securely without supplying any to a weapons program.

Criticality Safety

NDA measurements are essential to maintain an adequate criticality safety envelope. There have been instances in the past that if a simple NDA measurement had been taken or performed properly a criticality accident or incident could have been prevented [6]. Few material and item types (i.e. feed stock and intermediate product) in facility operations have mass accountability values that are assigned based on anything other than NDA measurement results. These mass accountability values are then used throughout the nuclear facility to ensure criticality safety limits are not violated. The professionals that set and enforce criticality safety limits are required to obtain certification (i.e. certified criticality safety engineer) via a structured training program generally following a college education yet the professionals providing nearly all of the data necessary to enforce those limits have minimal training requirements following perhaps a high school education.

The number of experienced safeguards professionals in the U.S. has declined in recent years for several reasons yet the importance and use of nondestructive assay (NDA) measurement results is increasing. Additionally, the complexity and importance of in-situ (also referred to as "holdup" measurements, or measurements of nuclear material "held up in process") measurements has increased rapidly due to changing priorities, site and DOE complex restructuring and increased decommission and demolition (D&D) activities. Uncertainty has been exacerbated by the retirements of personnel with either the process history knowledge or the relevant measurement experience that could be brought to bear constructively to the issues.

With the recent emphasis on in-situ NDA measurements by the safeguards community, the Defense Nuclear Facility Safety Board (DNFSB) recommendation 2007-1 on in-situ NDA measurements [7], and increasing D&D activities across the DOE complex, it is becoming increasingly important to address gaps and/or weaknesses in the training requirements of individuals that perform NDA measurements. Emphasis should also be given to the training needs of those who use the measurement **results**, particularly with respect to understanding the proper interpretation of reported measurement errors. This is especially true when a measurement result and its uncertainty assignment is used for a different purpose than was originally intended when the measurement was performed. Reinterpreting the result in this manner can result in overly optimistic or overly pessimistic confidence bounds. In short, it is imperative that the personnel performing the NDA assay are properly trained to provide reliable results (quantity and uncertainty) that are later relied upon for criticality safety. It is also important that the analyst and the user of the results understand what is being reported as well as the assumptions, corrections, or other variables that are involved which could affect the measurement result and even more important, the uncertainty and confidence in that measurement result.

Standard methods are lacking in measurement techniques, interpretation of measurement data, and training and qualification programs for NDA personnel. The efforts to create and maintain international standards by ASTM , ISO, or ANSI are woefully underfunded. There is no standard approach recognized for how process material holdup measurements are performed or managed at different sites. Significant variations in material types and deposit configurations and other variables often complicate standardization of holdup measurement methods. Consistent training requirements could minimize much of the above mentioned variability in implementation.

Nuclear Security

The distribution of nuclear material within a facility will necessarily be in a state of flux, and will require a robust and accurate accounting system that provides the physical protection personnel up-to-date knowledge regarding the nuclear material within the facility. Whether they are responding to a fire, security, or false alarm, security professionals can perform their function more effectively and efficiently if they know with confidence what is behind that solid door, or within the location before they enter. Like any accounting system that is used to track valuable or important materials, the nuclear material accounting system is only as good as the measured values it contains, including the uncertainties in those measured values. NDA measurements are a critical component in providing or confirming the values that exist within the accounting system. In addition to being a crucial contributor of data that is used by the accounting system, NDA techniques can be used to track the movement and location of nuclear material within the facility. Hence, NDA measurement techniques provide crucial information to the physical protection community regarding the location and relative importance of the nuclear assets they are protecting. Consequently it is productive for members of the physical protection community to understand what NDA measurements can and can not do, including an understanding of measurement uncertainty in some cases, to optimize use of community assets. Both screening and accurate mass measurements can be used by this community.

Screening measurements are qualitative measurements that can be used to determine whether people are moving nuclear material between rooms or facilities. The instruments can be hand held or large semi-permanent fixtures. They are typically one of many tools operated by personnel who are not specialists in their use. They can be utilized at portals out-of-doors, in rooms or hallways, or at doorways to rooms. Knowledge about the fundamental physics associated with these measurement techniques, including knowledge of the limits of detection, the inverse square law, as well as shielding, noise, and the importance of calibration and maintenance offers the chance for the physical protection services to better take advantage of these qualitative measurements.

While accurate mass measurements are not used directly by the physical protection personnel, they are used in the nuclear materials accounting system. They are often performed in specially shielded counting rooms by specialists. In some cases, these specialists have college degrees in addition to specific specialized training requirements. Although the physical protection personnel do not perform these measurements or operate the related instruments, they use the results in the form of accounting records that identify nuclear material locations and movements. If anomalies occur or security is compromised, physical protection assets rely on the accounting system and subsequently the underlying measurements to evaluate the security status of the facility and engage in the appropriate security actions to ensure that the nuclear material is protected.

In general, reliable commercial off-the-shelf NDA measurement equipment costs less than human resources, even when including maintenance and training. But the performance of the equipment must be quite high in terms of both mean time between failures and false alarm rates in order to prevent personnel from losing confidence in the NDA measurement equipment, which thereby causes them to not utilize potentially important information regarding the facility. If NDA plays this vital part in nuclear security, the need exists for suitably qualified and experienced NDA specialists within the nuclear security physical protection community to ensure high quality measurement practices are utilized.

Waste Management

The applicability and performance of NDA methods to the measurement of radioactive scrap and waste, in terms of precision, bias, and reliability, is understood reasonably well by working practitioners for a wide variety of waste forms and measurement conditions based on decades of operational experience, but support for the NDA professional in this domain is ad hoc. Promulgation of best practice is an important aspect to gaining public trust and a means by which the nuclear industry can demonstrate transparency and a commitment to continuous improvement. Certainly the public has demonstrated that it is not confident in the industries' ability to manage, measure, and dispose of its radioactive waste properly. This lack of confidence is not improved when a facility or auditor requires retrieval of a waste item from a repository because of a question about the measured value of the nuclear material it contains. When such retrieval involves transportation on public highways, the situation is not improved. Consensus standards committees such as ANSI N15 Methods of Nuclear Material Control and ASTM C26.10 Nondestructive Assay are a forum to foster industry wide NDA development and information sharing. But they are not well funded and too many practitioners are unaware of their function and the resulting standards.

The responsible management of radioactive waste is a complicated social, political, and economic issue because the benefits associated with radioactive waste generation are largely realized now (or have been realized already) while the legacy can be long lasting and is passed onto future generations. There are complex technical challenges as well. Regulation and policy, only partially harmonized, is based in part on the technology developments of the NDA community in demonstrating waste monitoring performance to ensure compliance with packaging, transport, and disposal guidelines and laws. NDA experts are involved in all stages of the commercial nuclear fuel cycle from prospecting for ore to safe reuse of active materials to final disposal of irradiated fuel wastes. This might be summarized as NDA expert involvement beginning-to-end with the understanding that it also includes early involvement in facility design to ensure that target performance can be met by design; as well as consultation and participation in decommissioning, decontamination, and dismantling activities. NDA experts play a key role in verifying that safeguards and non-proliferation responsibilities are met with physical measurements anchoring nuclear material protection, control, and accountancy which feeds domestic safeguards. Industrial applications of radionuclide's, accelerators, and especially neutron sources create wastes that must be evaluated and confirmed by measurement. A number of processes result in Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), the oil and gas industries being an example. Various legacy sites such as old mines and old radium facilities also remain that require clean-up and remediation with attendance to the secondary radioactive wastes produced as by-products.

There are many different classifications for radioactive waste. Often the best practical means to deal with a given waste stream requires intimate knowledge of how the waste was generated, details of the facility, familiarity with institutional norms and constraints, and a thorough understanding of end user requirements. Experimental waste characterization frequently makes use of a variety of NDA techniques including passive gamma and passive neutron emission together with heat emission along with other process history or pre-processing knowledge. Active measurements are also common with neutron interrogation being more frequently used than other active methods. The technical literature which discusses the various techniques associated with waste characterization is often daunting for individuals who are new to the field as the literature usually assumes the reader has considerable physics and application specific knowledge. The problems associated with waste measurements are often difficult and the nuances can only be discovered by doing actual measurements. This is why professional recognition and a career path which allows personally fulfilling advancement over the considerable apprenticeship period needed to master the field is paramount. Opportunities to improve the state of the practice and state of the art abound and span the gamut from radiation modeling, instrument design, systems integration and data fusion, statistical analysis, process monitoring and control, and more. The field is far from dormant. Concentrated ongoing efforts and funding are needed to maintain and enhance the profession.

Risk Impact

The improper implementation, execution, or interpretation of NDA measurements can lead to a wide range of consequences that have the potential to severely impact the safety and security of a facility, a nation, or the world. One of the most potentially severe consequences of the improper usage of NDA measurements can occur in the field of criticality safety. As NDA measurements of in-process holdup are commonly used to determine or confirm the amount of nuclear material that is located within the piping or process machinery of a facility, they provide essential data to criticality safety engineers to calculate whether a facility is operating within an appropriate criticality safety envelope. Improper NDA measurement results can directly lead to a facility to operate outside of its defined safety envelope; thereby substantially elevating the risk of significant harm to employees at the facility if quantities of nuclear material are underestimated or causing unnecessary expense if quantities are overestimated.

Improperly performing or reporting NDA measurement results can also lead to a variety of security issues for a facility including the failure to detect significant inventory differences which could indicate the possible diversion of material. Other possible risks include the possibility of not properly detecting the movement of SNM within a facility, and not detecting possible diversion of material that is shipped between facilities.

NDA TRAINING

Because all NDA measurements involve both the direct or indirect detection and quantification of the invisible emissions from radioactive nuclei, a certain level of knowledge of the physics concepts associated with the measurement is needed in order to ensure that the measurement results can be interpreted accurately. NDA can be used to measure a wide variety of material and item types without any sample preparation. In fact no sampling is normally required since in most cases the entire item is measured. Unlike other measurement techniques in which most of the variables associated with measurement such as external environment and sample preparation are tightly controlled, the NDA measurements can be performed in a wide range of locations and with very little control over the various parameters that can affect a measurement. For a large number of NDA measurement scenarios, especially dedicated counting rooms, great effort has been undertaken to control the environment associated with measurements as well as the types of materials that are measured thereby allowing for more accurate measurements to be made by following a procedure. However, to ensure that an accurate measurement is made, it is up to the personnel involved in the measurement to be aware of how various factors such as the packaging of the item and the ambient background in the room can affect the accuracy and precision of the measurement. As one cannot physically sense how gamma-rays or neutrons are being affected by their environment, a certain amount of education and experience is needed in order for a person to develop the skills necessary to become a effective NDA practitioner, including the ability to independently solve measurement problems successfully[5]. While periodic week-long training courses might suffice for instrument operators, those who review the results for quality or repair the instrumentation often require college educations and years of specialized on-going training.

To be effective in developing an NDA practitioner's expertise, NDA training needs to develop or expand the student's knowledge of and experience with the fundamental physics associated with specific NDA measurement techniques. As with most training or education programs, the presentation of these concepts should be done in a manner which involves as many of the student's senses as possible. Having the students perform "hands-on" experiments which demonstrate the various principles with actual nuclear material helps to ensure that the students retain a familiarity with the concepts. By addressing the fundamental concepts such as the sources of radiation, the interaction of radiation with matter, and the physics of detecting radiation, students will then develop an understanding of what the capabilities and limitations are for the various NDA techniques. This includes not only a discussion of what can and cannot be measured by a given technique, but what is the expected accuracy and precision that can be achieved by the technique, and what factors can have an effect on the accuracy and precision of a measurement. The training should also include discussions and exercises which illustrate the best practices in performing these measurements. By illustrating why a specific technique or procedure works the best in performing a measurement, the student is more likely to retain that knowledge when the person performs the measurements in the field.

One of the key areas that must be emphasized in NDA training is how to interpret or understand the results from the measurements. In order to be able to interpret the results appropriately, the uncertainty that is associated with the result of a NDA measurement must be properly calculated and expressed. This requires an understanding of the sources of systematic and statistical uncertainty associated with a measurement. Because NDA measurements are performed within a facility for a number of different purposes that contribute to the safe and secure operations of a facility, the personnel involved in performing these measurements should understand how to ensure that the NDA measurements that are performed satisfy the requirements that were placed on those measurements.

Although the training of NDA practitioners and professionals is critical for ensuring that the measurements performed within a facility are done appropriately, the availability of training programs in recent years for these practitioners and professionals within the U.S. has become sparse. While NDA training opportunities still exist within the U.S. at places such as Los Alamos National Laboratory (LANL) and Oak Ridge National Laboratory (ORNL), a coordinated NDA training program has not existed in the U.S. since 2007. Prior to 2007, the Department of Energy's National Training Center (NTC) would maintain and provide resources for a number of NDA training courses as part of its MC&A training program. These training courses, which were developed and organized primarily by LANL, covered a wide range of NDA measurement techniques and topics, and provided courses which covered both the fundamental concepts associated with NDA measurements for personnel new to NDA measurements, as well as advanced courses for experienced personnel. While the individual courses that could make up a NDA training program are still being offered, the ad hoc approach does not allow an NDA practitioner to progress from learning fundamental concepts to learning advanced concepts in a logical manner.

To ensure that NDA measurements continue to be properly implemented and utilized within U.S. nuclear facilities as the current experts retire, a comprehensive NDA training program is recommended to ensure that personnel that are new to NDA measurements are appropriately trained, and that more experienced NDA personnel are provided opportunities to maintain and expand their NDA knowledge and skills. Such training programs already exist for personnel who are involved in related areas such as criticality engineers, and health physicists. One of the main reasons why training programs exists for personnel in these areas, but not for NDA professionals, is the fact that these programs are required to help certify an individual as a criticality engineer or a health physicist, where as training for NDA professionals have been left to each individual institution or facility to implement. Hence, one possibility for improving NDA training in the future is the development of a NDA professional certification program. Such a program would help standardize the training of NDA professionals throughout the complex. Another benefit of such a program would be the acknowledgment of the NDA professional as holding an essential position within a facility. A second possibility for improving NDA training is to expand the current ASTM consensus standard on NDA training to include specific principles and topics that should be included in basic and advanced training programs. Specifying these concepts and topics that should be covered in a NDA training program will help standardize this training across the complex.

SUMMARY

High quality NDA measurements of nuclear material with knowledge and understanding about the associated uncertainties are necessary for routine safe, secure, and compliant operation of facilities that process nuclear material, and also for forensic or after-the-fact analysis of certain problems. Appropriate training is essential to obtaining reliable, high quality NDA measurements. Poor quality or erroneous measurement results can have a large impact on a facility - sufficiently large (and the probability of occurrence are sufficiently large as witnessed by the fact that some have already happened) that the industry can not afford to *not* mitigate the potential problem. Reluctance to spend relatively small amounts of money to prevent problems is off-set by consequence expenditure. Public confidence in NDA professionals as well as in the accounting and measurement systems is an important factor in the public acceptance of nuclear power.

We ask, if the industry and government require certification and training for personnel like criticality safety engineers who use these measurement results, shouldn't there be requirements for the measurement data they base the analysis on?

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