

RADIOLOGICAL HEALTH PROTECTION ISSUES ASSOCIATED WITH USE OF ACTIVE DETECTION TECHNOLOGY SYSTEMS FOR DETECTION OF RADIOACTIVE THREAT MATERIALS



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[For detailed information on the availability of this and other NCRP commentaries see page 50.]

Preface

The National Council on Radiation Protection and Measurements (NCRP) is preparing a series of publications related to the use of active detection technology (ADT) systems for the detection at standoff distances of special nuclear material (SNM) and other radioactive materials that could represent a terrorism threat to public health. The ADT systems currently under consideration by the Defense Threat Reduction Agency (DTRA) will utilize beams of photons such as high-intensity bremsstrahlung radiation, and particle beams of protons, neutrons or muons to elicit radiation signatures that can provide a long-range capability for detecting in cargo containers the presence of SNM of concern for acts of terrorism.

The initial NCRP publication on this subject is Commentary No. 21, *Radiation Protection in the Application of Active Detection Technologies* (2011), which evaluates the health protection aspects of designing and deploying ionizing radiation screening systems in a manner consistent with meeting the objectives of the fundamental principles of radiation protection [namely, justification, optimization (as low as reasonably achievable), and limitation of exposure]. The primary emphasis of Commentary No. 21 is on applying these principles in the design and deployment of any security screening system that utilizes ionizing radiation, including ADT systems.

This Commentary evaluates health protection and safety issues specifically for the use of ADT security systems. It addresses important factors in the design and testing of ADT systems that must be given attention prior to their deployment in maritime or land-based operational settings. This Commentary also addresses the following issues related to the possible future use of ADT security screening systems:

- potential exposures to radiation from ADT systems to the health of operating personnel, bystanders, and others in the inspected areas;
- design and operational factors that must be considered in assessing the safe and efficient operation of ADT systems;
- radiation protection design considerations, engineering controls (e.g., shielding, barriers, system performance indicators, and safety interlocks), and operational practices and procedures (e.g., operator training, recording of ADT operating parameters, and quality control test results) that must be considered in ADT system design and deployment.

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1. Introduction

The Defense Threat Reduction Agency (DTRA) is sponsoring research into a range of technologies intended to aid in the early detection and interdiction of special nuclear material (SNM) and other radioactive materials that could represent a significant threat to homeland security. The DTRA program has the goal of developing long-range, standoff active detection technology (ADT) systems that use radiation to stimulate detectable signatures from radioactive threat materials at ranges of 100 to 1,000 m. These systems include high-intensity bremsstrahlung radiation, monoenergetic gamma-ray sources, and particulate radiations including protons, neutrons and muons. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission events, x rays from muon interactions with high atomic number (Z) materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM and other potential radiological weapons materials. The stimulated signatures would facilitate long-range detection of the threat materials using detectors that are spatially and temporally linked to the ADT radiation sources.

These ADT radiation sources could pose a health risk to operating personnel, bystanders, and individuals in the inspected areas. As the National Council on Radiation Protection and Measurements (NCRP) used in Commentary No. 21 (NCRP, 2011), the term “bystanders” refers to workers involved with the shipping or handling of suspicious containers or members of the public who are in the area but ignorant of any SNM and unaware that they might be at risk of radiation exposure. Those who are clearly identified as knowingly transporting SNM are “terrorists” as referred to in U.S. Code 18, Chapter 113B (USC, 2010) and not addressed in this Commentary.

With a reasonable set of assumptions, estimated doses¹ from use of ADT systems can approach a dose limit of 5 mSv. Designing and operating an ADT system that can meet that limit without any margin of safety will be quite challenging. These radiation doses involve direct radiation exposures of individuals and secondary exposures associated with the production of activated materials. Assessing potential radiation doses from ADT systems will assist DTRA in making decisions and developing policies on the types and deployment of candidate ADT systems with the objective of optimizing both the effectiveness of these technologies and the protection of human health based on fundamental radiation protection principles and practices. The analysis presented in this Commentary is predicated upon infrequent and not repeated exposures. As described later in this Commentary, repeated exposures can present potential doses exceeding the dose limit.

U.S. citizens have become accustomed to screening at airports, entering federal buildings, and at some other venues, such as major sports events. A major difference between that screening and the detection addressed by Commentary No. 21 (NCRP, 2011) and this Commentary is that the personal screening is announced in advance, it is performed voluntarily (the individual can decide not to enter), and the screening equipment is in plain view of the persons being screened. In the present case, the vessels and items being screened and the individuals associated with them are not volunteers, they may not be aware of the process, and the screening equipment may be hidden.

¹The term “dose” as used in this Commentary refers to effective dose from ionizing radiation. Dose terminology and associated dose limits are described in Section 4.3.

While concerns about radiation exposures are important, there may be times when issues of health effects and privacy need to be carefully balanced with national security concerns. This facet increases the importance of obtaining enough sufficiently accurate information to justify the ADT screening.

DTRA commissioned two commentaries from NCRP. Commentary No. 21 addresses broad radiation protection issues raised by the use of ADT systems while this Commentary goes into greater technological detail to define the factors to be considered in the design and deployment of the ADT systems.

This Commentary:

- examines the potential radiation doses from ADT systems to operating personnel, bystanders, and other individuals in the inspected areas; and design and operational factors that must be considered in assessing the safety and efficiency of ADT systems.
- provides recommendations on the research, development and fielding of ADT systems under consideration by DTRA to optimize the effective and safe use of these systems; address the full range of safety and health concerns associated with the deployment of ionizing radiation systems that currently exist, are under development, or may be developed in the future for the detection and interdiction of weapons of mass destruction SNM devices that could be used in acts of terrorism.
- endorses the recommendations and analyses of Commentary No. 21 (NCRP, 2011) of the issues of importance in the development and deployment of security systems involving ionizing radiation.
- provides recommendations related to radiation protection design considerations, engineering controls, and operational practices and procedures for the various ADT systems that are being evaluated by DTRA and its contractors. The technologies under consideration for ADT systems will employ radiation sources for detection of SNM and other radiological materials of possible use in weapons of mass destruction. It is planned for these active detection systems to be deployable at standoff ranges or in shielded configurations. Both NCRP Commentary No. 21 and this Commentary will form the framework for the development of subsequent NCRP reports on specific leading candidate ADT systems under consideration by DTRA.

This Commentary is meant to apply to the use of ADT systems in the United States and at foreign sites. Use in non-U.S. locations will require negotiation by an appropriate U.S. agency with foreign governments.

This Commentary addresses several types of ADT systems being considered by DTRA at the time of writing this Commentary. However, only Photonuclear Inspection and Threat Assessment System (PITAS) has progressed to the demonstration phase. Therefore, many of the tasks assigned to NCRP by DTRA must await further development of ADT systems. For this reason this Commentary presents generic recommendations.

Although only PITAS is emphasized, this Commentary is recommended for use by DTRA in developing ADT systems and operational policies, by operating personnel, and by the U.S. Congress. It also provides information to members of the public who may be interested in potential radiation exposures from ADT systems.

2. Active Detection Technology System Description

The radiation sources and detectors that can be used for determining the presence and amounts of SNM in a vessel, building, or other structure are the fundamental components of ADT systems. The use of radiation sources as an integral part of ADT systems introduces health protection issues that are not present with passive detection systems. To identify the radiological health protection issues it is necessary to understand the basic design and operation of the components of ADT systems. This section presents a description of the basic components of ADT systems and their operation. The features and operation of such systems that potentially impact human health are discussed in Section 5.

2.1 Active Detection Technology Systems

The fundamental goal of SNM interdiction systems employing radiation detectors is to assess the presence or absence of a predetermined minimum amount of SNM at a specific location with a known level of confidence. An additional goal may be detection of materials that can be used to shield SNM. Passive detection systems rely on the natural (unstimulated) emission of characteristic radiations from SNM. However, the natural emissions from a source of SNM may have insufficient intensity to be detected at the desired level (mass) of SNM or may be deliberately or inadvertently shielded to prevent detection by passive detection systems. In such cases certain radiation sources can be used to irradiate SNM to enhance the emission of characteristic radiations from SNM, and the emitted radiations are subsequently detected. Systems that employ radiation sources to stimulate emissions of radiation from SNM are referred to as ADT systems.

The components of an ADT system include: radiation source (typically a high-energy particle accelerator), intensity and direction control systems for the source, and detectors to detect the radiation types and energies that will characterize SNM or associated shielding. Additionally, there are components that provide utilities and protection of the ADT system. The locations, numbers, and relative orientation of ADT system components will vary according to the system design and the associated deployment requirements.

ADT systems use radiation to stimulate detectable signatures from fissile threat materials. The possible radiation types include high-intensity bremsstrahlung radiation and particulate radiations including protons, neutrons and muons. The types of interrogating radiation are discussed in more specific detail in Section 2.3. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission events, x rays from muon interactions with high-Z materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM and other potential radiological weapons materials. The stimulated signatures would facilitate long-range detection of the threat materials using detectors that are spatially and temporally linked to the ADT system sources.

ADT systems may employ multiple sources of radiation and each source introduces its own set of human health protection issues. If multiple sources are used to interrogate the same suspected location of SNM, the potential severity and likelihood of potential health protection issues may increase. Use of multiple sources may also add to the complexity of analysis and evaluation of health effects.

The SNM to be located may be outdoors or inside a transport vessel, building, or other structure. The location and geometrical configuration of SNM is not expected to be known. The types, amounts and configuration of materials functioning as shielding of SNM are also expected to be unknown. These properties of SNM and its shielding are the primary sources of uncertainties of detection and characterization of SNM.

Interferences caused by induced emissions of radiations (from SNM or other materials) other than the desired type and energy of radiation may be nuisance interference for ADT system operators. However, such radiations can lead to additional health protection issues. Increases in the source intensity to improve the signal-to-noise ratio of an ADT system may lead to higher radiation doses from the system and additional health protection issues.

This Commentary analyzes several of the most plausible ADT systems, focusing on particle accelerators as the primary radiation source. Radiation fields produced by photons, protons, neutrons and muons are considered to be the most plausible types of radiation for ADTs. Proton accelerators and electron accelerators are likely the best sources of radiation with sufficient energy and fluence rates to accomplish the goals of ADT systems. The short ionization ranges of other ions at a specific energy limit their effectiveness for use in ADT systems.

2.2 Special Nuclear Material Characterization

As noted previously, SNM is the material to be detected and characterized. The primary types of SNM being sought with ADT systems are highly-enriched uranium and ^{239}Pu , which are radioactive materials that could be used in a nuclear explosive device. ADT systems are designed to detect the presence of a predetermined amount of SNM in a specific geometrical configuration with assumed types and amounts of shielding. The minimum amount (mass) of SNM that is to be detected by an ADT system is the parameter that has the greatest impact on system design and the associated potential for health protection issues.

Because there are numerous combinations of source amounts, geometries and shielding, ADT systems will likely be designed and operated to minimize false rejections. One of the consequences of this strategy is higher radiation dose rates at the SNM location (and in other locations) and an associated increase in the number and potential severity of health protection issues.

2.3 Radiation Source Characteristics

Radiation sources that can be used with ADT systems are categorized according to the type of radiation emitted by the source. A basic requirement of the radiation source for an ADT system is that the radiation can cause SNM to emit a characteristic radiation subsequent to the interaction of that radiation with SNM. Another requirement of the interrogating source is that the radiation can be directed toward suspected SNM (*i.e.*, the radiation source is a directional beam). In the event that an ADT system includes an isotropic source of neutrons that is placed on a transport vessel or in a building, the source configuration would increase the area of potential exposures significantly from that of a collimated beam of radiation and would introduce additional health protection issues. The discussion of radiation sources considered for ADT systems in this section is limited to radiation beams generated by charged particle (electron and proton) accelerators.

Each radiation source considered for ADT systems can produce the desired effect in SNM through fundamental physical interactions and energy deposition in SNM. The same properties of these sources gives each source the potential to deliver a very high radiation dose to persons who might be irradiated during use of the ADT system. The radiation doses to persons from each source depend on the radiation type, energy, and fluence rate (radiation intensity) at the person's location. Factors affecting radiation doses from ADT systems are described in Section 5.

Each of the radiation sources considered for use with ADT systems has advantages and disadvantages (limitations) regarding the overall sensitivity and efficacy of the ADT system in which they are used. Likewise, the potential radiation doses to system operators and other persons in the vicinity of the operating ADT system vary considerably with type of radiation source. Assessment of potential radiation doses to personnel and bystanders is an essential part of selection of the radiation source for ADT systems and is discussed in Section 5.

There are a number of good general references on the physics and operational characteristics of particle accelerators (*e.g.*, Bryant and Johnsen, 1993; Cossairt, 2008; Edwards and Syphers, 1993; Lee, 2004; Livingood, 1961; Wangler, 1998; Wilson, 2001). A discussion of the types of radiation beams produced with these accelerators is given in the following text.

2.3.1 Photons

Photons in ADT applications are generated through the physical process of bremsstrahlung production from high-energy electrons originating from an electron accelerator. Photon (bremsstrahlung) beams generated with electron accelerators originate from the fundamental interactions of high-energy electrons with high-*Z* materials (targets). When electrons interact with matter, the fraction of the electrons' energy that generates photons increases with the energy of the electrons and with the atomic number of the material with which they interact.

Although photon production is the dominant means by which high-energy electrons lose energy in matter, some energy is manifested in neutron production (chiefly through the giant resonance process), and the generation of other energetic particles as various production thresholds are exceeded. Other radiations may be produced by interactions of high-energy electron beams, but those radiations are produced much less frequently than photons and neutrons. The remaining fraction of the electron energy is deposited in the material as heat.

In general, photon beams produced with electron accelerators have a wide range of energies, but "filtering" with in-beam absorbers narrows the range of energies, thereby resulting in optimum photon beam energies. Attenuation lengths or mass attenuation lengths such as those provided by the Particle Data Group (Amsler *et al.*, 2008) or the National Institute of Standards and Technology (NIST, 2011) are often used to further characterize beam attenuation in material media and thus the fluence rate at each point of interest.

The basic components of an electron accelerator are listed below. Each component has its associated health hazards and, for some components, radiation hazards.

- *Electron gun* is the initial source of electrons; a large portion of the current generated by the gun may be lost at the gun exit or in the first portion of the accelerator.
- *Klystron tubes (klystrons)* are linear-beam vacuum tubes used to generate and amplify ultra-high frequency electron beams. They employ radiofrequency (RF) power to accelerate electrons in accelerator cavities; electron collectors within klystron tubes require heavy shielding. Klystrons may generate x rays in locations in addition to the collector, requiring additional local shielding. There are other types of RF devices in common use that have characteristics similar to klystron tubes.
- *Bending and focusing magnets* are used to steer, focus and control the shape and size of the electron beam at its point of origin. Improper adjustment of the magnet settings may cause beam losses by incorrectly steering the beam into undesirable directions under various abnormal scenarios. Local shielding or collimators may be required.
- *Cooling system* usually consists of a closed circuit of deionized water that is typically required to dissipate heat from devices such as beam dumps, magnets, and collimators.

- *Vacuum system* consists of vacuum pumps connected to sections of beam pipe. High vacuum minimizes beam losses on residual air and generation of gas bremsstrahlung.

The use of electron accelerators to generate a photon beam is the most mature of the ADT systems in development. With current technology, relatively compact electron accelerators can be built with energies of several tens of million electron volts with average currents of the order of 100 μA and different pulse lengths and repetition rates. The electron beam is aimed at a target generating photons that have a range of energies, with the maximum photon energy equal to that of the electron beam. In addition to filtering the beam with thin in-beam absorbers within the source system, air encountered throughout the beam path will attenuate lower-energy photons in the beam, so the average photon energy in the direct beam will increase with distance from the source. However, the photons that are removed from the beam through attenuation interactions (*e.g.*, scattering) produce a secondary radiation field that increases in area with distance from the source.

As noted above, the photon beam from an electron accelerator is the most mature of the ADT systems in development. A transportable prototype ADT system, PITAS, has been developed and tested at Idaho National Engineering Laboratory. Nominal operating parameters of PITAS are discussed in Section 5.

2.3.2 Protons

Proton beams are potential radiation sources for use in ADT systems. A proton accelerator is a viable candidate for use with an ADT system because protons can be produced readily at low energies and have the sufficiently long ranges compared to other nuclear ions. The range data are readily available in scientific literature including the general tabulations of the Particle Data Group (Amsler *et al.*, 2008) and the more specific results in the form of the Stopping and Range of Ions in Matter Code (Ziegler *et al.*, 1996). Because protons are hadrons (elementary particles that are subject to the strong nuclear interactions, as are neutrons and mesons), when penetrating a material they are attenuated approximately exponentially. As discussed in several of the references (Cossairt, 2009; Edwards *et al.*, 2008; Fasso *et al.*, 1990; ICRU, 1978; NCRP, 2003a; Patterson and Thomas, 1973), below 150 MeV the mean free path of protons increases with proton energy. For protons having energies greater than ~ 150 MeV the mean free path becomes an approximate constant, not strongly dependent upon proton energy and is greater in materials with higher atomic mass number A .

A shower of electromagnetic radiation can occur when very high-energy photons interact with matter. This process is called an *electronic cascade*. Similarly, a shower of hadrons (*i.e.*, protons, neutrons and mesons) can occur when energetic protons interact with matter. This process is called a *hadronic cascade*. An energetic proton-beam incident on some materials can induce fission due to the interactions of secondary neutrons or neutrons from a hadronic cascade.

Accelerated protons can be used to generate the radiations needed to perform the interrogations intrinsic to ADT systems. While accelerated protons produce fewer photons than accelerated electrons, protons are likely the most effective accelerated particle for producing neutrons, both prompt and delayed, and muons for ADT systems.

The maximum proton kinetic energies achievable with electrostatic systems range from ~ 1 MeV for Cockcroft-Walton accelerators to ~ 20 MeV for Van de Graaf accelerators. High power RF systems are needed to achieve higher energies. The technology of such systems is well-known for conventional room temperature applications. Superconducting RF acceleration systems now in use offer certain advantages over room temperature RF systems: reduced electrical power consumption, a better ability to provide continuous wave, rather than pulsed

operation, and perhaps smaller physical dimensions. The chief advantage of continuous wave operation is that of increased time that the beam can be produced.

Plausible ADT systems utilizing proton acceleration to produce interrogative neutrons and muons would likely require achievement of kinetic energies in approximately the 0.5 to 10 GeV domain.

2.3.3 Neutrons

The use of a proton-beam or a deuterium-tritium generator is the most plausible method of producing energetic neutrons compared with that possible with electrons or photons. However, the deuterium-tritium generator is limited to producing only 14 MeV neutrons, thereby limiting its versatility as a source of neutrons in ADT systems. Neutrons produced by a proton beam, before any moderation, could have energies of the same order of magnitude as the primary protons. While accelerator-produced neutrons would be secondary particles of almost certainly lower fluence rates than that of the primary protons, the neutron hazard should be quantified as should the emissions of any fission processes that might result. The neutron hazard, dependent upon both the choice of technology and the configurations of the actual ADT systems could involve both fast and moderated (thermalized) neutrons. If thermal neutrons are involved, the possibility of exothermic thermal-neutron capture reactions may be a factor on the necessary hazard assessment. Using neutrons for imaging purposes only is not likely to result in significantly enhanced radiation levels due to secondary particles produced as part of this process, but the design needs to be evaluated for verification of this result.

A proton accelerator used in an ADT system to produce neutrons would consist of an ion source to produce either protons (H^+) or negative hydrogen (H^-) ions. Following production of the ions, the initial stage of a modern proton accelerator to be utilized for this purpose would likely be a radiofrequency quadrupole. While conventional focusing of charged particle beams is typically performed with electrostatic or magnetic quadrupole lenses (Cossairt, 2008), radio-frequency quadrupoles afford the ability to simultaneously accelerate and focus a low energy proton beam (Wangler, 1998). After the first stage of acceleration, the proton beam would be injected into a linac, cyclotron or synchrotron for acceleration to the final desired energy. Once the final energy is reached, the beam would be delivered to and focused on to a target to produce the desired neutrons. The neutron beam would likely be collimated in some manner toward suspected SNM that is the object of the active interrogation to avoid excessive beam spray at large angles relative to the intended direction. In addition, a suitable beam absorber capable of safely handling the proton-beam intensity would be needed.

Neutron radiation fields delivered by proton accelerators employed in an ADT system require collimation as they are produced copiously over a wide range of production angles (*i.e.*, the angle between the trajectory of the produced neutron and the incident proton beam). Such collimation would define a specific solid angle of emission that, neglecting absorption and scattering by intervening air, would generate a cone of irradiation with the neutron fluence rate decreasing according to the inverse square law with distance. Absorption and scattering by the intervening air would serve to increase the solid angle of emission and modify the neutron energy spectrum.

In view of the approximate yields of producing neutrons by means of energetic protons interacting in targets (Cossairt, 2009; IAEA, 1988; NCRP, 2003a; Patterson and Thomas, 1973), the achievement of neutron fluence rates up to $\sim 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ would likely require proton-beam currents at least of the order 10^{15} s^{-1} (a beam current of $\sim 160 \text{ }\mu\text{A}$), under optimum conditions for producing and collecting the emitted neutrons. This beam current is large enough to be of considerable significance with respect to radiation protection.

2.3.4 Muons

Electron beams with energies well-above the muon production threshold of 211 MeV are capable of producing pairs of positive- and negative-charged muons. However, by far the most productive way of generating muons is to use protons to produce muons by means of pion (pi meson) decay, and at higher energies and to a lesser degree, kaon (K meson) production. This method involves the delivery of a proton beam having a kinetic energy well-above the pion production threshold of ~140 MeV. Thus the use of either protons or electrons to produce muons requires an accelerator of considerable energy and size.

A proton accelerator is the most logical device for producing a beam of muons in an ADT system. To do this, the most effective method is to create the proton beam and deliver it to a production target typically of low-*Z* such as carbon (graphite) or beryllium oxide. Proton interactions with the target material produce secondary charged pions. If the proton kinetic energy is greater than the kaon production threshold of ~500 MeV, charged kaons could also be produced. Because all of these particles are charged, in contrast with neutron production, electromagnetic fields can be used to focus these charged particles to optimize the profile of the resultant muon beam. The muon beam could then be delivered through air to SNM that is the object of the active interrogation process. The general characteristics of a muon-based ADT system utilizing a high-energy proton accelerator as the source of the muons would be very similar to that of a proton accelerator used to produce neutrons except that the proton accelerator for muon production would require the highest possible proton energy in order to produce a sufficient intensity of secondary pions and kaons.

The pions produced by the protons in a muon production mode are then allowed to traverse a region of vacuum (preferred) or air where they are allowed to decay into muons. (Because the corresponding threshold for kaon production is ~500 MeV and the pion production threshold is only ~140 MeV, pionic muon production is always favored over the kaonic process.) Because pions participate in the strong (*i.e.*, nuclear) interaction, a backstop of an optimized thickness would serve to absorb the pions that do not interact while readily allowing penetration by the muons. Muons in this technology have relatively long ionization ranges as their participation in strong interaction processes is, at plausible energies for ADTs, an effect of only minor significance.

For sufficient production of muons, in view of the threshold phenomena involved, the originating proton beam must have a kinetic energy well-above 500 MeV to produce sufficient pions to make a potentially usable fluence of muons. If kaon production of muons is to be included, then proton-beam energies approximating 1 GeV are required. Production yields of muons due to proton interactions have been provided elsewhere (*e.g.*, Fasso *et al.*, 1990). To provide a sufficient fluence rate of muons, a high intensity proton beam is required, likely exceeding the intensity required for neutron generation in a neutron-based ADT system.

For a given ADT installation, the fluence rate of a given muon beam is determined from the relativistic kinematics of the production process along with the arrangement of shielding, pion absorbers, and any magnetic fields present. The long ionization range of muons is likely to be employed by future ADT systems, perhaps principally to produce muonic atoms in high-*Z* materials. Some values of ionization range as a function of energy are given by NCRP (2003a), Particle Data Group (Amsler *et al.*, 2008), and Sullivan (1992). For the energy domain of likely interest for use in the technology of ADT systems, Barkas and Berger (1964) give a detailed set of results for both muon stopping powers and ranges.

A plausible additional application of muons in ADT systems is the emission of muonic x rays by muons in atomic quantum states. Such x rays would give a unique energy signature of high-*Z* materials in this particular active interrogation scheme. To do this would require the energy of the interrogating muons to be adjusted so that they are stopped, presumably by ionization, in the material of interest.

The physical size and general characteristics of the proton accelerator used to produce the muons is similar to that anticipated for neutron production. The main difference is the requirement to include the region needed to focus the pions and kaons, and allow for their decay to the resulting muons. The dimensions of such a decay region are not small in view of the fact that the length traversed by these particles must take into account the finite mean-lives of the moving parent pions and kaons as measured in the laboratory frame of rest. While the muons produced in this manner have a greater intensity in the direction of the incident pion and kaon beams, it is plausible that focusing of the muons using magnetic devices beyond the decay region would be needed to further optimize a muon beam. Furthermore, in addition to the beam absorber needed to handle the primary proton beam, the pions and kaons would need to be disposed of in either the same beam absorber as that used for the protons or in a separate device.

3. Optimization of Active Detection Technology Systems

The success of any ADT system depends on a careful balance between the source output and its associated detection system. The strongest source emission achievable will yield use-less results if the emission is not matched to an appropriate detector located an acceptable distance from the SNM. Likewise, the most capable detection system available will simply register events resulting from natural background radiation if a suitable source emission is not employed.

The solution to the balance issue can be approached in one of two manners: *forward approach* (based on source capabilities) or the *reverse approach* (based on detector capabilities). Each of these approaches is predicated upon the output of a certain ADT system (forward) or the capabilities of a specific detector (reverse). Regardless of the technique chosen, the process will likely require an iterative approach to adequately balance the source emission strength, detector capabilities, and the desired standoff distances.

3.1 Forward Approach Based on the Source Requirements

In the forward approach, one uses a viable source emission strength along with a knowledge of the source-to-SNM and SNM-to-detector standoff distances to evaluate the ability of a radiation detector to distinguish the resultant radiation signature. The adequacy of the detector can be evaluated by calculating the particle flux at the detector using the relation:

$$\phi_D = K S(\Omega) \left(\frac{d\Omega}{dA} \right) F(\Omega) \Delta\Omega_{\text{SNM} \rightarrow D}, \quad (3.1)$$

where:

K	=	accounts for the attenuation of all particles in air (source-to-SNM and SNM-to-detector) and in shielding
$S(\Omega)$	=	angular source distribution from the interrogating beam
$d\Omega/dA$	=	corrects for differences between the solid angle and spherical coordinates
$F(\Omega)$	=	angular source distribution resulting from the interrogation of SNM
$\Delta\Omega_{\text{SNM} \rightarrow D}$	=	fractional solid angle subtended by the detector at the centerline of SNM-to-detector standoff distance (Evans, 1982)

It should be noted that there will be significant variances in the K term for use in a mobile platform due to the movement of the source and SNM.

For a point-source interrogation beam creating an isotropic signal (photofission, etc.) within SNM, Equation 3.1 becomes:

$$\phi_D = K \left(\frac{S_0}{4\pi} \right) \left(\frac{A_D}{R_1^2} \right) \left(\frac{F_0}{4\pi} \right) \left(\frac{A_D}{R_2^2} \right), \quad (3.2)$$

where:

S_0	=	number of particles per second emitted by the ADT system
R_1	=	centerline distance from the ADT system to SNM

$$\begin{aligned} A_D &= \text{effective detector area} \\ R_2 &= \text{centerline distance from SNM to the detector} \end{aligned}$$

Note that if a monostatic (same location) source and detector is employed Equation 3.2 can be reduced to:

$$\phi_D = K \left(\frac{S_0 F_0}{16\pi^2} \right) \left(\frac{A_D}{R_2^4} \right). \quad (3.3)$$

If the particle flux calculated in this manner is acceptable, no additional consideration needs to be taken into account. However, if the flux is inadequate, one or more of the following actions must be taken:

- reduce the standoff distances;
- increase the source emission strength within the confines of the dose limits; or
- increase the size of the detector.

If the detector is not colocated with the ADT system, the standoff distances may be altered independently to achieve an acceptable detector flux.

3.2 Reverse Approach Based on the Detector Requirements

If the reverse approach is employed, one begins with an acceptable particle flux for a given detector and standoff distances, then solves Equation 3.1 or 3.2 for the necessary source emission characteristic (S_0). If the ADT system is capable of producing the required S_0 , no further analyses need be performed. However, if the required S_0 is greater than the maximum output of the ADT system, the standoff distances must be decreased. As was the case with the forward approach, the standoff distances can be adjusted independently if a monostatic system is not utilized.

3.3 Radiation Detection

3.3.1 Detector Types

The selection of the detector will be controlled by the choice of the interrogating radiation type and energy because these parameters will determine the prompt emissions escaping from SNM. In general, prompt photon emissions will always be induced in SNM regardless of the incident radiation and type. However, proton and neutron beams can also produce fission in fissionable or fissile material, resulting in neutron emissions.

3.3.1.1 Ideal Detectors. Regardless of the type of interrogating radiation that is used, the ideal detector for this application will possess the best overall combination of the following important characteristics:

- intrinsic efficiency (sensitivity);
- obtainable geometries;
- response time;
- signal-to-noise ratio;
- availability;
- versatility; and
- cost.

A high intrinsic efficiency will allow for greater standoff distances between SNM and detector and a fast response time will ensure that emission from SNM can be quickly processed.