

RADIATION PROTECTION IN THE APPLICATION OF ACTIVE DETECTION TECHNOLOGIES



RADIATION PROTECTION IN THE APPLICATION OF ACTIVE DETECTION TECHNOLOGIES

January 6, 2011

**National Council on Radiation Protection and Measurements
7910 Woodmont Avenue, Suite 400 / Bethesda, Maryland 20814-3095**

LEGAL NOTICE

This Commentary was prepared by the National Council on Radiation Protection and Measurements (NCRP). The Council strives to provide accurate, complete and useful information in its documents. However, neither NCRP, the members of NCRP, other persons contributing to or assisting in the preparation of this Commentary, nor any person acting on the behalf of any of these parties: (a) makes any warranty or representation, express or implied, with respect to the accuracy, completeness or usefulness of the information contained in this Commentary, or that the use of any information, method or process disclosed in this Commentary may not infringe on privately owned rights; or (b) assumes any liability with respect to the use of, or for damages resulting from the use of any information, method or process disclosed in this Commentary, *under the Civil Rights Act of 1964, Section 701 et seq. as amended 42 U.S.C. Section 2000e et seq. (Title VII) or any other statutory or common law theory governing liability.*

Library of Congress Cataloging-in-Publication Data

Radiation protection in the application of active detection technologies.

p. ; cm. -- (NCRP commentary ; no. 21)

"January 6, 2011."

Includes bibliographical references.

ISBN 978-0-9823843-4-3

1. Radiation--Safety measures. 2. Radiation--Toxicology. 3. Radiation--Measurement. 4. Radioactive fallout--Health aspects. I. National Council on Radiation Protection and Measurements. II. Series: NCRP commentary ; no. 21.

[DNLN: 1. Radiation Protection--methods--Guideline. 2. Nuclear Weapons--Guideline. 3. Radiation Dosage--Guideline. 4. Radiation Monitoring--methods--Guideline. 5. Radioactive Fallout--adverse effects--Guideline.

6. Terrorism--Guideline. WN 650]

RA569.R2658 2011

363.17'99--dc22

2011005829

Copyright © National Council on Radiation
Protection and Measurements 2011

All rights reserved. This publication is protected by copyright. No part of this publication may be reproduced in any form or by any means, including photocopying, or utilized by any information storage and retrieval system without written permission from the copyright owner, except for brief quotation in critical articles or reviews.

[For detailed information on the availability of this and other NCRP commentaries see page 44.]

Preface

The United States faces continued threats of attack from terrorist organizations and their supporters. These threats include the possible use of biological, chemical, radiological and nuclear sources capable of causing harm and death to many individuals. Radioactive material used to contaminate or irradiate has the potential to cause great disruption and panic, threatening health and safety. Conventional explosives coupled to radioactive materials can appreciably increase dispersal, further increasing concerns about health, safety, and disruption of normal routines. Stolen or improvised nuclear explosive devices have the potential for widespread and long-lasting damage to human health and the built and natural environment. The use of fissile materials in nuclear devices could cause severe injury or death and widespread disruption of the sense of well-being and the essential components of life such as food, water, utilities, transportation modes, and other basic services. This Commentary addresses unique aspects of the detection of special nuclear material (SNM), whether assembled in a nuclear weapon or components of a nuclear weapon.

The U.S. government has a compelling need to locate, deactivate, and impound or destroy SNM before it can be used for terrorism. Appropriate agencies require technologies, devices and techniques that will allow them to detect SNM before it is brought into the United States and/or deployed. Detection systems must be sensitive enough to detect SNM even when small in quantity or heavily shielded. Some detection systems must be mobile to access specific sites. To this end, the Defense Threat Reduction Agency (DTRA) of the U.S. Department of Defense is sponsoring research to develop active detection technology (ADT) systems that can meet the above criteria. While passive detection systems are usually capable of detecting radioactive material with naturally-high activity, the radiation emitted from SNM is often low enough (energy and/or intensity) to preclude detection. The purpose of ADT systems is to stimulate SNM to emit detectable, radiation signatures. ADT is a broad term for systems that generate radiation in order to stimulate a physical response from SNM, allowing identification of SNM from a distance.

To obtain radiation protection guidance on appropriate use of ADT systems, DTRA contracted with the National Council on Radiation Protection and Measurements (NCRP). NCRP was asked to review the ADTs and their anticipated uses, to analyze their potential for exposure to humans, and to recommend dose limits for operating personnel and bystanders. NCRP was further asked for guidance on how to best achieve its recommendations.

To facilitate accomplishment of the above charge, NCRP convened two scientific committees. Scientific Committee (SC) 1-18 was tasked with addressing the application of fundamental objectives of radiation protection to ADT systems and developing recommendations for radiation protection goals for such systems. SC 1-19 was asked to consider the technical aspects of ADTs and to provide specific radiation protection requirements for ADT systems. Each scientific committee was charged with putting their findings into the form of a commentary. This Commentary was prepared by SC 1-18. Serving on the Committee were:

Kenneth L. Miller, *Chairman*
Penn State Hershey Medical Center (retired)
Hershey, Pennsylvania

Debbie B. Gilley, *Vice Chairman*
Florida Department of Health, Bureau of Radiation Control
Tallahassee, Florida

Members

J. Donald Cossairt
Fermi National Accelerator Laboratory
Batavia, Illinois

Joseph M. Kaminski
U.S. Food and Drug Administration
Silver Spring, Maryland

Thomas A. Cotton
Complex Systems Group, LLC
Washington, D.C.

Sayed H. Rokni
SLAC National Accelerator Laboratory
Menlo Park, California

David M. Hassenzahl
Chatham University
Pittsburgh, Pennsylvania

Scott O. Schwahn
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Consultant

Norman Fost
University of Wisconsin–Madison
Madison, Wisconsin

Glen Reeves
TASC
Lorton, Virginia

Advisor

S. James Adelstein
Harvard Medical School
Boston, Massachusetts

NCRP Secretariat

Terry C. Pellmar, *Staff Consultant*
Cindy L. O'Brien, *Managing Editor*
David A. Schauer, *Executive Director*

The Council wishes to express its appreciation to the Committee members for the time and effort devoted to the preparation of this Commentary. NCRP also thanks DTRA for its financial support of this project.

Thomas S. Tenforde
President

Contents

Preface	iii
1. Introduction	1
1.1 DTRA Development Efforts	2
1.2 Need for Active Detection Technology Systems	3
1.3 Existing Technologies	4
1.3.1 X-Ray Devices for Screening Humans	4
1.3.2 Pulsed Fast-Neutron Analysis Systems for Security Surveillance	6
1.3.3 Accelerator-Produced High-Energy X Rays for Scanning Cargo	6
1.3.4 Gamma Radiation for Contraband Detection	7
2. Radiation Technologies for Active Detection Technology Systems	9
2.1 Detection Technologies	9
2.2 Radiation Interrogation Sources	9
2.2.1 Photons	9
2.2.2 Protons	10
2.2.3 Muons	10
2.2.4 Neutrons	11
2.3 Hazard Considerations	11
3. Radiation Protection Goals and Objectives and Their Application to Active Detection Technologies	12
3.1 Radiation Effects	12
3.2 Goals and Objectives of Radiation Protection	12
3.2.1 Justification	12
3.2.2 Optimization	13
3.2.3 Dose Limits	13
3.2.3.1 Occupational Exposure	13
3.2.3.2 Exposure to Members of the Public	13
3.2.3.3 Sensitive Groups	14
3.3 Radiation Protection Objectives Applied to Active Detection Technologies	14
4. Radiation Protection Requirements and Methods for Active Detection Technologies	18
4.1 Output Determinations	18
4.2 Interlock Systems	19
4.3 Emergency Response	19
4.4 Determination of Doses to Individuals and Notification	20
4.5 Records and Documentation	20
4.6 Environmental Considerations	21
5. Guidance for Active Detection Technology Use	23
5.1 Ethical Principles	23
5.1.1 Justification of Use	23

5.1.1.1	Benefit-Risk Ratio	23
5.1.1.2	Guidelines for Benefit-Risk Analysis	24
5.1.2	Optimization of Radiation Protection	24
5.1.3	Disclosure of Risk	25
5.1.4	Reparation	25
5.2	Communication	26
5.2.1	Stakeholder Involvement	27
5.2.2	Locus of Responsibility for Communication	27
5.2.3	Communication Standards	28
5.2.3.1	Effective Risk Communication Practices	28
5.2.3.2	Use of Analogies for Specific Practices	28
5.2.4	Communication with Foreign Countries	29
5.3	Other Considerations in Active Detection Technology Development	29
6.	Summary and Conclusions	30
6.1	Active Detection Technologies	30
6.2	Benefit-Risk Analysis	30
6.3	Optimization of Radiation Protection: Automatic Termination Mechanisms ..	31
6.4	Dose Limits	31
6.5	Ethics and Communication	32
Appendix A.	Health Effects of Radiation	33
A.1	Deterministic Effects	33
A.2	Stochastic Effects	33
A.2.1	Genetic (heritable) Risk	33
A.2.2	Cancer Risks Attributable to Low Doses of Ionizing Radiation	34
A.2.3	Acute Low-Dose Exposures	34
A.2.4	Protracted Low-Dose Exposures	34
A.2.5	Extrapolation of Risks to Lower Doses	34
Appendix B.	Risk Associated with Doses Higher Than the Limit	36
Appendix C.	Safety Design Features	38
C.1	Radiation Control System	38
C.1.1	Shielding	38
C.1.2	Active Radiation Control System	39
C.1.3	Radiation Control System: Passive Versus Active Systems	39
C.2	Access Control System: Access Controls, Interlocks, and Emergency Switches	39
References		40
NCRP Commentaries		44

1. Introduction

With the threat of terrorism, concerns about the use of special nuclear material (SNM) in terrorist acts are high. In this Commentary, SNM refers to all items containing SNM, whether by itself or assembled in a nuclear weapon or a component of a nuclear weapon. SNM is defined by the U.S. Nuclear Regulatory Commission (NRC, 2011) as plutonium, ^{233}U , or uranium enriched in the isotopes ^{233}U or ^{235}U . Billions of dollars have been appropriated in the United States for the development and deployment of new technologies to monitor SNM within the United States and overseas (Medalia, 2009). The U.S. Congress has enacted laws requiring that containers be scanned by imaging and radiation detection equipment before loading onto vessels in foreign ports (USC, 2007), with the intention of preventing terrorists from smuggling SNM into the country.

Detection of SNM can impede a terrorist nuclear attack in two ways: deterrence and defense. A successful detection capability, in combination with the inherent difficulties of constructing an effective nuclear weapon, could convince adversaries that any attempt to launch an attack with such a weapon will fail or that such an attack would be too complex to execute. These consequences could dissuade them from action. If, however, deterrence fails, detection systems would be needed, allowing the discovery and interdiction of SNM to prevent its use. The detection technologies could be used to search vehicles, structures, containers, and possibly individuals for SNM at border crossings, transit routes, and other locations of concern.

The U.S. government is actively pursuing efforts to develop, acquire and support the deployment of enhanced detection systems for SNM. While the Domestic Nuclear Detection Office in the U.S. Department of Homeland Security is the lead agency in this area, both the U.S. Department of Energy (DOE) and the Defense Threat Reduction Agency (DTRA) in the U.S. Department of Defense (DOD) support programs to develop and field an active detection technology (ADT) system. This Commentary focuses on the efforts of DTRA to deploy a detection system that addresses their mission. It is intended as guidance to inform the development process with respect to radiation protection issues. The comments and recommendations in this Commentary are broadly applicable to all ADTs used to detect SNM. Subsequent reports are planned that will cover more technical details regarding implementation of the guidelines in this Commentary.

This Commentary reviews the new remote detection technologies that are being developed, focusing on the requirements for radiation protection and provides guidelines to ensure that doses are within recommended limits for operating personnel and bystanders in the inspected areas.¹ Section 1 puts the requirement for the new ADT systems into context and provides an overview of other security screening and contraband detection systems that have previously been reviewed by the National Council on Radiation Protection and Measurements (NCRP). Section 2 describes the basic characteristics of the possible ADTs. Section 3 reviews radiation effects and considers dose limits related to the use of ADT systems. Section 4 discusses

¹For consistency throughout this Commentary, the term “operating personnel” is used to indicate those who are involved with the operation of ADT systems and “bystanders” are workers involved with the shipping or handling of suspicious containers or members of the public who are in the area but unaware of any SNM and that they might be at risk of radiation exposure. Those who are clearly identified as knowingly transporting SNM are “terrorists” as referred to in Chapter 113B: 2332b and 2339 of Title 18, United States Code (USC, 2010) and not addressed in this Commentary.

radiation protection requirements as they relate to ADTs. Section 5 focuses on the ethical considerations and communication requirements associated with use of ADT systems. Section 6 presents a summary of the key points and recommendations in this Commentary.

The dose limits recommended in this Commentary are consistent with limits previously recommended by NCRP (2003a; 2004; 2007) and the International Commission on Radiological Protection (ICRP, 2007) for occupational exposure and exposure to members of the public from sources such as security screening applications, contraband detection, and use of ADT systems.

1.1 DTRA Development Efforts

DTRA oversees the development of new detection technologies in support of the DOD mission of detecting, identifying and eliminating threats from radiological and nuclear weapons of mass destruction (DTRA, 2008). In this context, detection devices would not be used for routine screening, but rather for targeted interrogations based on credible information. For national defense, DOD might need to search for radiological or nuclear materials in hostile environments with equipment that can withstand a range of harsh conditions. With international cooperation, the detection technologies may be used in international waters or on foreign soil. These requirements distinguish DOD technologies from those that might be deployed for homeland defense at border crossings (Medalia, 2009). This Commentary concentrates on the DTRA effort to detect SNM with ADTs.

The DTRA program has the goal of “standoff detection”² of SNM. ADT systems are one of the promising candidate technologies capable of accomplishing this goal. These systems use radiation to stimulate detectable signatures from SNM. The possible radiation types used include high-intensity bremsstrahlung radiation, monoenergetic gamma-ray sources, and particulate radiations including neutrons, protons and muons. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission, x rays from muon interactions with high atomic number (*Z*) materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM. The stimulated signatures would facilitate long-range detection of SNM using detectors that are spatially and temporally linked to the active detection sources.

DTRA issued a Broad Agency Announcement that called for development of new standoff detection technologies (DTRA, 2008). This Broad Agency Announcement set forth the requirement that there be a minimum of 100 m standoff between the interrogating device (and operators) and the targeted object. In addition, it required a minimum distance of 50 m from targeted object to the detector, which is not required to be colocated with the interrogating device. The expectation was that the equipment would be operable outdoors from sea level to 1,500 m elevation under a broad range of humidity and temperatures. Other possible environmental conditions include the inherent motion of the platform, such as a ship at sea, and sea spray.

While the technologies to meet these demanding specifications are being developed, DTRA asked NCRP to provide guidance on the effective design, development and deployment of the proposed ADTs with a focus on the radiation protection aspects of these systems. While some risk is associated with radiation generating devices such as ADTs, the intention is to design and use the ADT systems in a way that would ensure radiation doses are as low as reasonably achievable (the ALARA principle) and do not exceed dose limits for operating personnel and bystanders.

²Standoff detection involves sensing the presence of SNM when the interrogating and monitoring devices are physically separated from the targeted object.

1.2 Need for Active Detection Technology Systems

ADT systems use a beam of radiation to interrogate an object or location suspected of containing SNM. If SNM is present, such interrogation will stimulate the release of signature radiation that, ideally, will allow identification of type, quantity and location of the material. At a minimum, an ADT system will include an interrogation source, one or more receptors to detect stimulated radiation, and software to interpret the detected signal. Likewise, there are associated radiation risks to operating personnel, to individuals who might be exposed to the interrogation beam, and to individuals who might be exposed to the stimulated response.

Inspection of cargo containers represents one application of ADTs. Lubenau and Strom (2002) estimated the number of cargo containers imported into the United States to be at least 50,000 d⁻¹ (Figure 1.1). While it is impossible to manually inspect each container and its individual contents, rapid, accurate scanning devices can accomplish such a task. ADT systems might fill this need.

Another potential application of ADT systems is detection at long distances (Figure 1.2). Distant detection is advantageous when looking for SNM along smuggling routes, in distant vehicles or aboard ships at sea, in facilities, in an inaccessible territory, or in a city (Medalia, 2009). These operations might require scanning of large areas to locate SNM or rapid data acquisition if the material is moving quickly across a detection field.

Nuclear weapons, which can be small (~1 m in length), require fissile material, typically ²³⁵U or ²³⁹Pu. However, the energies of the gamma rays emitted by both radionuclides are low, making detection and identification difficult, especially if the radionuclide is shielded by a high-*Z* material such as lead. In addition, to achieve detection the detectors must be relatively close to the radionuclide, usually within a few meters to no more than a few tens of meters. DTRA considers the development of effective detection systems high priority since technologies with long standoff distances are not yet available. Systems have been developed that take advantage of the fluorescence that occurs when high-energy photons interact with the electrons of uranium or plutonium. Electrons under these conditions are either elevated to a



Fig. 1.1. Seaport terminal example showing cargo conveyance ship, cranes, and lay-down yard (Kouzes, 2005). At least 50,000 cargo containers have been estimated to come into the United States daily.

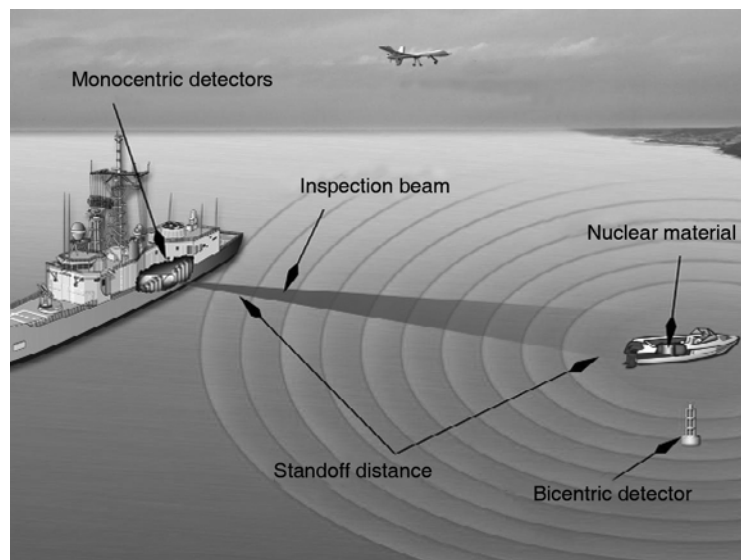


Fig. 1.2. Detection of SNM at distances of up to hundreds of meters presents unusual problems.

higher energy state or ejected from the atom. Either case generates photons with energies that are highly characteristic of the element emitting them. Existing computerized detection systems can readily differentiate the specific energies of the secondary photons being emitted from the element during the fluorescence process. The use of higher energy photons can also be employed to take advantage of the preferred scattering angles for photons interacting with a specific element. Detectors at angles from the source-to-object path can measure the scattering at the specific angles. Still higher energy photons can lead to gamma-neutron interactions with uranium or plutonium, which result in the emission of photons from the excited nucleus that have higher energy than those emitted with normal ^{235}U or ^{239}Pu radioactive decay. Passive and active neutron detection systems have also been used in safeguard applications for decades. ADT systems in development and under consideration (Section 2) will take advantage of these concepts.

1.3 Existing Technologies

NCRP, in the past, looked at emerging technologies for homeland security applications and developed guidelines for their usage (NCRP, 2003a; 2003b; 2007). Selected systems are described here to provide a general overview of each technology.

1.3.1 X-Ray Devices for Screening Humans

NCRP Commentary No. 16 (NCRP, 2003b) addressed radiation devices for human screening, their use, and their exposure potential. Primarily, the two types of screening systems evaluated were the x-ray backscatter devices (Figure 1.3) and x-ray transmission devices (Figure 1.4). These devices produce x-ray energies similar to those used in clinical diagnostic imaging (*i.e.*, using tube voltages of 50 to 125 kVp). Backscatter devices work well for detecting objects near the surface of the body but are unable to image objects inside the body, such as items swallowed or inserted into a body cavity. Individuals imaged by these devices receive $\leq 0.1 \mu\text{Sv}$ (effective dose) per scan. Consequently, it would require an improbable number of scans (2,500) in a year to a single individual for that individual to receive an annual effective dose that exceeds the administrative control recommended by NCRP for general-use systems (0.25 mSv) to a

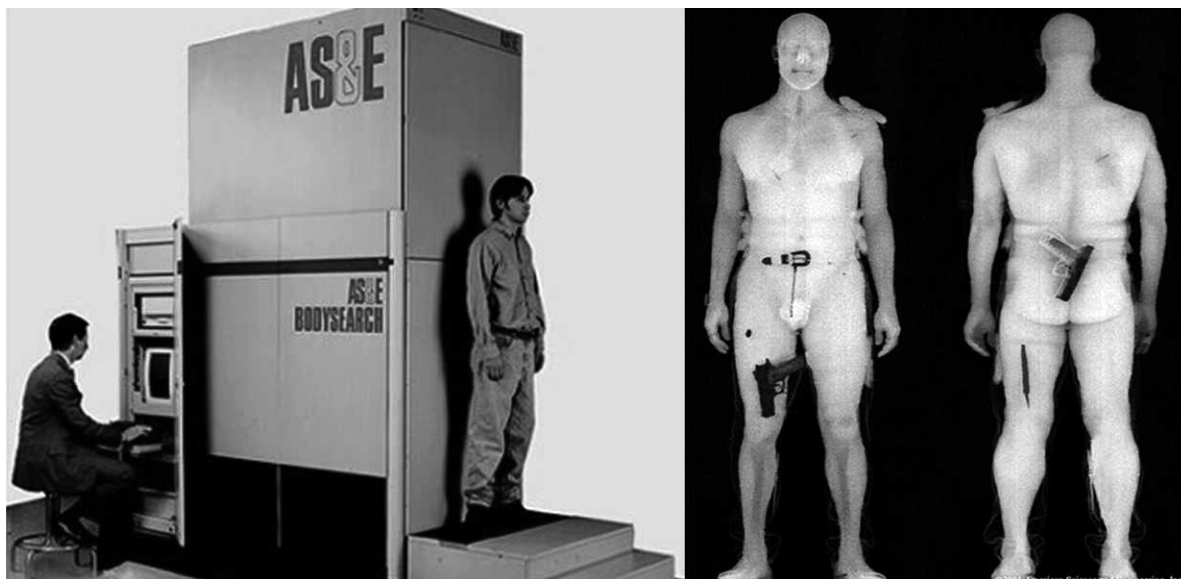


Fig. 1.3. American Science and Engineering's BodySearch® backscatter system and sample images (photographs courtesy of American Science and Engineering, Inc., Billerica, Massachusetts).



Fig. 1.4. The Compass® transmission system and sample image (photographs courtesy of X-Ray Equipment Company, Miami, Florida).

member of the public from a single source or set of sources under one control (NCRP, 2003b). Many of these scanners were installed in airports in the wake of the December 25, 2009 terrorist attempt to set-off a chemical explosive on a Detroit-bound airplane (Capehart, 2010).

Transmission scanning devices (Figure 1.4) result in higher effective doses per scan to the individual than backscatter devices (>0.1 and ≤ 10 μSv per scan). For these devices, the number of individuals or the number of scans per individual should be limited (*i.e.*, they are limited-use systems) (NCRP, 2003b). At 10 μSv per scan, an effective dose of 0.25 mSv (the administrative control) would be reached after 25 scans.

1.3.2 Pulsed Fast-Neutron Analysis Systems for Security Surveillance

Pulsed fast-neutron analysis (PFNA) systems for the detection of weapons or other contraband materials held in large containers such as truck trailers were evaluated by DOD and its contractors several years ago. The system that was designed involved nanosecond pulses of 8.5 MeV neutrons for scanning cargo contents. Detection of prompt gamma emissions that result when fast neutrons are absorbed by the contents of the containers [the (n, γ) reaction] provides data for construction of a three-dimensional image of the elemental composition of the contents of the container. The PFNA beam was designed to have a sufficiently high fluence ($\sim 6.5 \times 10^5$ neutrons cm^{-2}) for imaging and determining the chemical signature of the cargo content, even with partial shielding of the cargo content.

NCRP Commentary No. 17 (NCRP, 2003a) evaluated the radiological aspects of a full-scale PFNA system operating at a border crossing into the United States. The considerations included measurement technology suitable for evaluating dose to inadvertently-exposed individuals and other materials that may be present in a scanned cargo container; the potential upper limit of effective dose received by inadvertently-exposed individuals in a scanned container; and the activation products that would be created in scanned materials over a wide range of atomic numbers, including pharmaceutical products and medical devices. NCRP (2003a) also reviewed the radiation safety plan for routine operation of a PFNA scanning system that was prepared as part of the required environmental assessment. NCRP (2003a) recommended that the PFNA system be designed and operated in a manner that ensures the effective dose to an inadvertently-exposed individual will be <1 mSv. That limit could be raised to 5 mSv, if necessary, to achieve national security objectives (NCRP, 2003a). The levels of activation products, including those in food, pharmaceutical products, and medical devices were determined to be very low and the resultant effective dose received by any individual would be far below the limit for members of the public.

A prototype PFNA system for operational testing was deployed at a border crossing in El Paso, Texas. The system was found to be generally reliable, and measurements of potential effective doses to inadvertently-exposed individuals were made with the use of anthropomorphic physical phantoms contained within typical cargo contents and configurations. It was later decided, however, that the cost of producing a large number of PFNA security surveillance systems would be unacceptably high and the program was discontinued.

1.3.3 Accelerator-Produced High-Energy X Rays for Scanning Cargo

NCRP Commentary No. 20 (NCRP, 2007) evaluated the use of high-energy x rays produced by accelerators and used in cargo scanning. The images produced by the Cargo Advanced Automated Radiography System (CAARS) are similar to the images produced by the security screening systems used with humans [*i.e.*, either backscatter images (Figure 1.5) or transmission images]. NCRP Commentary No. 20 recommended that:

- effective dose to an individual inadvertently exposed to radiation within a conveyance that is being inspected in the CAARS exclusion zone not exceed 5 mSv;

- accelerator energy, beam current, filter configuration, and minimum scan speed be controlled and CAARS be interlocked so that irradiation is terminated, if necessary, to prevent the effective dose to the occupant of a conveyance from exceeding 5 mSv;
- CAARS staff receive adequate training on the health hazards of radiation and on the effect of shielding, distance and time in reducing radiation levels;
- CAARS facility staff wear appropriate dosimeters to verify that the effective dose to staff outside the exclusion zone is consistent with the design specification of not exceeding 0.5 μ Sv in an hour;
- effective dose at the perimeter of a CAARS facility (*i.e.*, the area unrestricted to members of the public) not exceed an administrative control of 0.25 mSv y^{-1} ; and
- a quality assurance/control system be established that includes periodic testing and documentation to ensure that systems continue to perform within design specifications throughout their useful operating lifetime.

1.3.4 Gamma Radiation for Contraband Detection

High-energy gamma radiation sources can also be used to obtain nonintrusive imaging of the contents of closed moving vehicles (Figure 1.6), cargo containers or cargo on pallets. The vehicle or cargo is exposed to gamma rays from a radioactive source, usually ^{60}Co or ^{137}Cs . On the opposite side of the inspected object, sodium iodide detectors measure the transmitted radiation and software generates a density map or image that can be viewed by the operator. The distance between source and detectors is limited; in most configurations it is <30 m. These devices have been used successfully at borders for cargo truck and railroad freight-car inspections. The devices have been used to detect weapons, hazardous material (including chemical and radioactive sources), drugs, stolen vehicles and other illegal cargo, stowaways, illegal immigrants, and other undeclared cargo. The devices are only sensitive to density differences and cannot specifically identify SNM.

The growing use and applications of gamma-ray screening systems requires consideration of the same radiation protection objectives and practices discussed in Sections 3 and 4. Unintentional exposures of the operator, members of the public, or the environment in the direct beam would be the greatest concern from use of these devices. The manufacturer recommends additional barriers external to the device be established to reduce the likelihood of exposure. However, the radiation output of these devices is generally low. For example, the units made by Science Applications International Corporation (SAIC, 2008) generate a nominal dose equivalent per scan of 0.04 μ Sv for the ^{137}Cs source configuration, and 0.1 μ Sv for the ^{60}Co source at the centerline of a targeted object.



Fig. 1.5. Backscatter image of inadvertently-exposed individuals in a cargo conveyance (courtesy of American Science and Engineering, Inc., Billerica, Massachusetts).



Fig. 1.6. A gamma-ray scanner system for use with transportation vehicles (SAIC, 2009).

2. Radiation Technologies for Active Detection Technology Systems

2.1 Detection Technologies

There are two general types of remote detection technologies available to monitor for illicit SNM: passive and active. Passive technologies use detectors that are sensitive to the emissions from the source. Passive detection of explosives, for instance, uses sensitive detectors (*e.g.*, ion mobility spectroscopy, chemoluminescence, or other means) to recognize one or more component chemicals. Passive technologies do not require direct interaction with the source. For detection of contraband SNM, the capabilities of passive technologies can be severely limited by shielding, type of radiation emission, and distance. Because SNM generates only weak radioactive emissions, passive nuclear detectors can pick up these emissions from no more than a few meters away and only in the absence of substantial shielding.

ADTs have the potential to overcome many of the difficulties associated with passive detection. ADTs generate radiation of sufficient energy to stimulate a characteristic energy emission from SNM, which may allow identification of SNM from a distance. Shielding designed to reduce the normally low-energy radiation from the radioactive decay of SNM may be penetrated by the radiation used in the ADT to reveal the presence of hidden material.

In the design of ADTs, the detectors can either be colocated with the interrogation source or they can be on separate platforms. The latter option might permit detection from distributed sensors, from ships or trucks, or unmanned aerial or underwater vehicles. At the present time, the specific technology or technologies to be used for ADT systems remains undetermined. This Commentary considers several of the most plausible ADT systems, focusing on the source of radiation. This Commentary considers only accelerator-based radiation sources. Proton accelerators and electron accelerators are likely the best sources of such secondary radiations (*i.e.*, photons, muons, neutrons) with sufficient energy and flux density to accomplish the goals of ADT systems.

2.2 Radiation Interrogation Sources

This section provides an overall summary of the various types of ionizing radiation that can be generated by ADT systems and used for interrogation of SNM.

2.2.1 Photons

High-speed electrons lose some of their kinetic energy in material through the production of bremsstrahlung (photons). The energy of the photon produced can range anywhere from near zero to the maximum energy of the electrons. For the thick targets that are likely to be used in an ADT system, the number of bremsstrahlung photons as a function of photon energy E per unit energy decreases with energy proportional to E^{-2} (IAEA, 1979). For high kinetic-energy electrons (tens of million electron volts), the resulting photon energy is predominantly on the order of 50 % or less of the kinetic energy of the electron. The atomic number of the target material with which the electrons interact impacts the intensity of the photons produced. Thus, the choice of the energy to which the electron is accelerated and the atomic number of the target material determine the energy spectrum and the intensity of the generated