

PULSED FAST NEUTRON ANALYSIS SYSTEM USED IN SECURITY SURVEILLANCE



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Issued December 22, 2003

Revised August 11, 2004

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Library of Congress Cataloging-in-Publication Data

Pulsed fast neutron analysis system used in security surveillance.

p ; cm. — (NCRP commentary ; no. 17)

“Issued December 2003”

Includes bibliographical references.

ISBN 0-929600-79-7

1. Nuclear activation analysis—Health aspects. 2. Nuclear activation analysis—Safety measures. 3. Electronic security systems—Safety measures. 4. Radiation—Safety measures. 5. Radiation dosimetry. I. National Council on Radiation Protection and Measurements. II. Series [DNLM: 1. Fast Neutrons—adverse effects. 2. Dose-Response Relationship, Radiation. 3. Neutron Activation Analysis—methods. 4. Radiation Monitoring—standards. WN 110 P982 2003]

QP519.9.N8P84 2003

363.18'9—dc22

2003061527

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Protection and Measurements 2003

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of this and other NCRP commentaries see page 56.]

Preface

This Commentary has been prepared at the request of Sensor Concepts and Applications, Inc. (SCA) of Phoenix, Maryland. SCA, working with the U.S. Department of Defense (DoD) and federal agencies with the responsibility for control of commerce between the United States, Mexico, and Canada, asked the National Council on Radiation Protection and Measurements (NCRP) for advice regarding a pulsed fast neutron analysis (PFNA) system. The PFNA system is being evaluated as a security surveillance device, and a six-month test of the system will be undertaken to evaluate its effectiveness. This Commentary is a compilation of responses to three separate requests from SCA concerning the PFNA system.

The first response was completed in September 2002, entitled *Radiation Protection Advice for Pulsed Fast Neutron Analysis System Used in Security Surveillance*. It covers: (1) the appropriate dose limit for persons inadvertently irradiated by the PFNA system, (2) the proper methods to determine the dose received, and (3) an opinion on whether the use of the PFNA system could result in levels of activation products in pharmaceuticals and medical devices that might be of concern to public health.

The second response was completed in February 2003, entitled *Radiation Protection Advice for the Pulsed Fast Neutron System Used in Security Surveillance: Part II. The ALARA Principle and Related Issues*. It covers: (1) a description of the relevant concepts of radiation protection that should be applied to the PFNA system; (2) a critique, in the form of advice on the necessary content of the draft System Safety Specifications and the draft Radiation Safety Plan for the PFNA system; and (3) the application of the “as low as reasonably achievable” (ALARA) principle to the PFNA system.

The third response was completed in July 2003, entitled *Radiation Protection Advice for the Pulsed Fast Neutron System Used in Security Surveillance: Part III. Methods for the Determination of Effective Dose to Inadvertently Exposed Individuals*. It covers the specific methods and instruments recommended for the measurement of and the determination of the radiation dose (*i.e.*, the effective dose) that an individual would receive by inadvertent exposure to radiation from the PFNA system.

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The Council wishes to express its appreciation to the Committee members for the time and effort devoted to the preparation of this Commentary, and to SCA for the financial support provided for its preparation.

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1. Summary

The National Council on Radiation Protection and Measurements (NCRP) was asked on three occasions by Sensor Concepts and Applications, Inc. (SCA), who is working with the U.S. Department of Defense (DoD), to provide radiation protection advice on a pulsed fast neutron analysis (PFNA) system. The PFNA system is being evaluated by the responsible agencies of the United States government as a security device for analyzing the contents of large cargo containers such as truck trailers. The specific application is a six-month test of the PFNA system at a port of entry to evaluate its effectiveness.

In the first request, NCRP was asked to address the following matters:

- what is the appropriate dose limit for persons inadvertently irradiated by the PFNA system;
- what are the proper methods to determine the dose received; and
- provide an opinion on whether the use of the PFNA system could result in levels of activation products in pharmaceuticals and medical devices that might be of concern to public health.

In the second request, NCRP was asked to provide:

- a description of the relevant concepts of radiation protection that should be applied to the PFNA system;
- a critique of the draft System Safety Specifications and the draft Radiation Safety Plan for the PFNA system; and
- the application of the “as low as reasonably achievable” (ALARA) principle to the PFNA system.

In the third request, NCRP was asked to describe in more detail the specific methods and instruments recommended for the measurement of and the determination of the radiation dose (*i.e.*, the effective dose) that an individual would receive by inadvertent exposure to radiation from the PFNA system.

1.1 The Appropriate Dose Limit for Persons Inadvertently Irradiated by the Pulsed Fast Neutron Analysis System

This Commentary recommends that the PFNA system be designed and operated in a manner that ensures that an inadvertently exposed person will receive an effective dose (E) of less than 1 mSv. The Commentary further recommends that this limit can be raised to 5 mSv, if necessary, to achieve national security objectives. A limit of 5 mSv is allowed for infrequent annual exposures in NCRP’s current guidance for exposure to members of the public (NCRP, 1993).¹ In all cases, the PFNA system should be designed and operated in accordance with the ALARA principle.

¹Throughout this Commentary, the International System (SI) of Units, specifically the units of millisievert (mSv) and milligray (mGy), are used. The relationships between the SI units and the previous units are: 1 mSv = 100 mrem (millirem); and 1 mGy = 100 mrad (millirad).

In forming this recommendation, this Commentary considered that:

- an inadvertently exposed person would be exposed only once, or at most only a few times, to the PFNA system;
- the E limit should be consistent with previous NCRP recommendations and provide a level of protection consistent with that accorded to members of the public; and
- the limit should consider the requirement for protecting individuals of all ages.

The law enforcement authority responsible for the system should provide information about the exposure to individuals known to have been inadvertently exposed. The information should be easy to understand and presented in a language understood by the individual or through a translator, where practicable.

1.2 Effective Dose

The radiation protection quantity of interest for an exposed individual is the effective dose (E). The general method for obtaining values of E is described in Sections 2.3.1, 2.3.2, and 2.3.3 and is derived from previous recommendations (ICRP, 1991; ICRU, 1993a; NCRP, 1993; 2000a). The effective dose (E) can be evaluated for a series of likely PFNA system scenarios that describe the irradiation conditions for cargo containers, using a combination of radiation transport calculations and supporting dosimetry measurements.

Practical implementation can be accomplished by comparing the actual PFNA system characteristics against the planned PFNA system characteristics. Values of E for individuals who have been exposed can be estimated from the E values for the likely irradiation scenarios noted above.

1.3 Neutron Activation in Pharmaceuticals and Medical Devices

This Commentary concludes that activation of pharmaceuticals and medical devices by the PFNA system will not result in E values of concern for public health. Absorbed dose (D) calculated for the elements expected to produce the highest values of D , using the specified neutron fluence for the PFNA system, will result in E values that are far less than the E limit for the general public. This conclusion is based on the findings that:

- the maximum whole-body D value, due to consumption of activated pharmaceuticals, is less than 10^{-6} mGy; and
- the maximum absorbed dose rate ($\dot{D}$) due to activated medical devices is less than 10^{-9} mGy h⁻¹ at 5 cm, and such values of $\dot{D}$ occur only near the device.

1.4 Applicable Radiation Protection Concepts for Workers and Members of the Public

For occupational exposures to radiation workers, NCRP (1993) recommends that the cumulative lifetime effective dose not exceed the age of the individual in years times 10 mSv. NCRP

(1993) also recommends the use of 50 mSv as the limit on the annual effective dose, and that new facilities be designed to prevent the annual effective dose from exceeding 10 mSv.

NCRP (1993) recommends that continuous exposure of members of the public be limited to an annual effective dose of 1 mSv. This limit excludes exposures from natural background radiation and radiation exposure associated with medical diagnosis and treatment. The limit applies to the sum of exposures from all other man-made sources, not to each source individually. Generally, the exposure from a single source or set of sources under one control should be constrained to 0.25 mSv annually (NCRP, 1993). This Commentary uses the term “administrative control” for this 0.25 mSv y^{-1} value.

A review of the relevant concepts of radiation protection that should be applied to the PFNA system is given in Sections 3.3 and 3.4.

1.5 The “As Low As Reasonably Achievable” Principle and Its Application to the Pulsed Fast Neutron Analysis Facility

The ALARA principle (*i.e.*, keeping exposures as low as reasonably achievable, taking into account economic and social factors) has been introduced into radiation protection programs because of the prudent assumption that potential deleterious effects might occur at any level of exposure, while recognizing that as the doses become lower and lower, the likelihood of a deleterious effect becomes less and less.

The ALARA principle should not be misinterpreted as simply a requirement for dose reductions irrespective of the dose level; sound judgment is essential in its proper application. Nevertheless, even at very low exposure levels, if simple and low-cost means would result in still lower exposures while retaining the beneficial outcome, ALARA considerations would indicate that such means should be implemented.

There are four aspects of the operation of the PFNA facility where advice on the application of the ALARA principle was requested. They are: tritium production and release, inadvertently exposed persons, neutron activation of foodstuffs, and the radiation levels outside the facility. These four aspects are addressed below.

- Operation of the PFNA system results in production of tritium atoms. The following ALARA considerations are advised: (1) ensure that the facility is properly equipped to manage the tritium that is produced in the beam line; (2) minimize the risk that the target assembly where tritium accumulates over time will rupture during operation; and (3) decide how to manage tritium produced in the target (*i.e.*, by venting tritium to the atmosphere before significant inventories have accumulated, or by capturing the tritium so that it can be managed as a solid or liquid radioactive waste).
- Dose to inadvertently exposed persons is directly related to the neutron fluence required for detection of contraband. The only ways to reduce neutron fluence are: (1) increase the sensitivity of gamma-ray detection; or (2) accept reduced resolution of the measurements, which may compromise the ability of the PFNA system to determine the composition of the cargo.
- The production of trace amounts of radioisotopes *via* neutron activation in foodstuffs would be similar to that for pharmaceuticals and medical devices (Section 1.3). For example, ^{24}Na from the (n,γ) reaction with natural sodium in salty processed foods such as potato chips (assuming consumption by an individual of 10 g of sodium immediately after activation by PFNA inspection) results in an effective dose of approximately 1×10^{-6} mGy, or about 10,000 times less than the annual negligible individual dose

(NID) recommended by NCRP (1993). Consequently, significant effort or cost to reduce this dose is not warranted.

- Dose to individuals outside the facility is also directly related to the neutron fluence used to detect contraband. However, there are standard radiation protection measures to reduce the radiation levels reaching individuals outside the facility. These methods are: (1) increasing the shielding thickness, (2) increasing the distance between the source and those individuals, or (3) reducing the amount of time during which the individuals are exposed. Decisions to implement these measures should be based on evaluation of the overall costs and benefits, which is the usual approach to implementing the ALARA principle.

1.6 Advice on the System Safety Specifications and the Radiation Safety Plan

The System Safety Specifications need to set forth the basic requirements for radiological safety of the PFNA system. These specifications should be consistent with applicable federal and state regulations, the recommendations of the NCRP, the ALARA principle, and Customs and Border Protection (CBP) policy. Maximum acceptable dose rates at specific locations can be determined based on the applicable annual effective dose limit or the administrative control (Section 1.4), the maximum source operating time per year, and the maximum time any individual would be present in the area per year.

The Radiation Safety Plan is the detailed policy for the implementation of the System Safety Specifications for the PFNA system, and needs to be specific to each installation. The plan should incorporate both engineered and administrative procedures for ensuring that the requirements of the System Safety Specifications are met.

For a PFNA facility, a key part of the Radiation Safety Plan is a system for controlling access to areas where elevated radiation exposures may occur. Experience has shown that this is most easily accomplished by defining a set of nested areas that are characterized by differences in maximum exposure, access requirements, and training requirements. In a typical PFNA facility there would be four classifications: (1) uncontrolled access, (2) controlled access, (3) restricted access, and (4) radiation-generating device (RGD) area.

Area 1 (uncontrolled access) is the world outside the boundary of the PFNA facility. There is no control of access to this area (*i.e.*, it is available for up to full time occupancy by the general public) and no effort is made to train the public in radiation protection procedures. The only requirement for design and management of the PFNA system, relative to Area 1, is that the effective dose to an individual not exceed an administrative control of 0.25 mSv y^{-1} .

Area 2 (controlled access) also has an administrative control of 0.25 mSv (effective dose) per year, but Area 2 includes the PFNA system, and access is limited to authorized personnel (or registered visitors). In order to receive authorization to work in Area 2, a person must have general employee radiation training (GERT).

Inside Area 2 is Area 3 (restricted access), which also has an administrative control of 0.25 mSv y^{-1} when the RDG is not operating (*i.e.*, there is no neutron beam). But, access to Area 3 is limited to employees who have also received PFNA system operator training. Dose rates in Area 3 may be substantially above background levels when the RGD is operating, but will return to background levels when the accelerator is not producing neutrons. Administrative procedures and engineered systems (*e.g.*, interlocks) ensure that facility personnel exit Area 3 before the production of a neutron beam begins, and that neutron production is terminated if anyone enters the area. Individuals with access to Area 3 must have GERT and wear appropriate dosimeters.

Access to Area 4 (the RGD area) when the accelerator is not producing high voltage requires RGD operator training and an appropriate personnel dosimeter, and also has an administrative control of 0.25 mSv y^{-1} . Dose rates in Area 4 can be substantially above background (*i.e.*, occupancy can result in an annual effective dose above the administrative control of 0.25 mSv) when the RGD is generating high voltage, whether a deuteron beam is being produced or not. Access to Area 4 by PFNA facility personnel is prevented by engineered controls whenever the RGD is capable of generating high voltage. Maintenance work on the accelerator may require access to Area 4 by specially trained workers while the high voltage is being generated. This work requires a separate Radiation Safety Plan and Radiation Worker Training Program developed by the maintenance organization, and the 50 mSv y^{-1} limit for occupational exposure is applicable. When the RGD is generating a neutron beam, there is no access to the RDG area.

A summary of the characteristics that define the four types of areas is provided in Table 3.1 in Section 3.5 of this Commentary.

The Radiation Safety Plan should also address radiation monitoring, including the following: methods for personnel monitoring, active area monitoring locations, and passive area monitoring for long-term compliance with the appropriate dose limit or the administrative control. The purpose of personnel monitoring is to confirm that no individual has exceeded the relevant effective dose limit or the administrative control. Personnel who might receive more than a significant fraction of the appropriate annual effective dose limit or the administrative control should be provided with a passive personnel radiation dosimeter sensitive to fast neutrons as well as photons.

Active radiation monitors should be placed in Areas 3 and 4 in order to provide an alarm if radiation levels exceed normal operating parameters.

To meet the access control requirements for Areas 3 and 4, it is necessary that anyone in those areas be notified when the accelerator is about to start, and has immediate access to a device to prevent the accelerator from starting. Fail-safe interlocks, warning devices, and emergency switches are required. Any interlock that stops the progress of the container through the PFNA scanner should also stop neutron beam production.

Shielding walls enclosing Area 4 and the boundaries of Area 3 should be designed to maintain the dose rate at any point in Area 2 below a value required to prevent effective doses in excess of the administrative control of 0.25 mSv y^{-1} .

The Radiation Safety Plan for a RGD also needs to include the appropriate responses for radiological emergencies such as accidental exposures or accidental release of radioactive material (*e.g.*, rupture of a deuterium target containing significant tritium), and also for all other types of emergencies (*e.g.*, such as a fire or natural disaster) that may be exacerbated by the radiation generated.

1.7 Potential Effects on Nuclear Weapons in Scanned Cargo

The maximum neutron fluence rate that can be produced by the PFNA accelerator is minuscule compared to that needed to cause a significant yield of secondary neutrons or thermal energy from a clandestine nuclear weapon or cache of nuclear material located in a cargo container. Thus, neutron irradiation from the PFNA system cannot cause a clandestine nuclear weapon to detonate by direct action.

1.8 Approach to Determination of Effective Dose for Inadvertently Exposed Individuals

Dose assessment for inadvertently exposed individuals requires the use of radiation transport calculations normalized to a unit fluence of the fast neutron beam incident at a selected

reference site (e.g., incident on the container or emitted from the PFNA system components). The dose assessment will require a series of calculations for likely scenarios, employing the irradiation characteristics of the incident fast neutron beam, the characteristics of the cargo container and its contents, the radiation scattering characteristics of the shielding and equipment surrounding the container, the likely locations of an individual in the container, and the simulation of a human body with simulated organs and tissues at these locations.

Because of the large number of variables involved, it is not feasible to evaluate E after exposures have occurred. Instead, it is recommended that the specific combination of load composition and the location within the load that yields the maximum credible effective dose (designated E^*) to an inadvertently exposed individual be determined. The actual value of E received by an inadvertently exposed person would have substantial variation, but would not exceed E^* .

Section 4.6 of this Commentary provides a succinct set of conclusions, presenting the rationale for determining the values of E and E^* in the event that an individual is inadvertently exposed in the process of scanning cargo containers with the PFNA system.

1.9 Determination of Effective Dose for Inadvertently Exposed Individuals

The buildup of secondary radiations, the modification of the incident neutron energy spectrum, and the backscatter of neutrons as well as neutron attenuation all play significant roles in determining E to an individual at a specific location within a scanned container. The geometry and composition of the collimator, shielding tunnel, and the container itself all contribute to these factors, but they are relatively constant from one scan to the next. The contents of the container may vary dramatically, from hydrogenous materials such as foodstuffs and paper to higher atomic number materials such as fabricated steel parts or raw materials. These differences in the load can result in very different values of E .

Also, the distribution of the load within the cargo container can vary, from low-density materials such as potato chips that completely fill the cargo space to high-density materials such as steel bar that fills only a small fraction of the volume of a container when the maximum allowed mass is present. The atomic composition, and particularly the hydrogen content, of the load are particularly important in determining the attenuation and backscattering characteristics, and therefore E as a function of location within the load. Thus it is important to explore loadings of realistic density and representative compositions, both as homogeneously distributed cargo, and as high density slabs in various configurations when evaluating E^* .

As the PFNA system is used, potential improvements to its design may be identified. If these improvements result in changes to the shielding, collimator, source, or relative positions of these components with respect to the scanned container, they may result in significant changes to the values of E , and E^* should be reevaluated.

In order to perform the neutron and gamma-ray calculations at various locations in a truck, it is necessary to construct reasonably accurate models of a number of aspects of the radiation environment, including the neutron source term, the speed of the tow vehicle, the collimator system, the tunnel, the truck and cab, the location of the inadvertently exposed person in the cargo container, and the truck cargo. Each of these aspects is discussed in Section 4.3.1.

While it is anticipated that E^* would occur in locations nearest the neutron source with little intervening material, E^* could conceivably occur behind some amount of “buildup”

material or at greater distances from the source where neutron albedo and capture gamma rays from the tunnel walls and structures contribute most strongly.

The neutron transport code used to perform the calculations should be capable of determining the neutron and gamma-ray spectra in three dimensions as well as performing the conversions from spectral fluence to absorbed dose at a point. The quality factor (Q) relationship as a function of linear energy transfer (L) [*i.e.*, $Q(L)$] given in Equation 2.5 in Section 2.3.2 (ICRP, 1991; ICRU, 1993a; NCRP, 1993) is recommended for conversion of absorbed dose at a point to dose equivalent at the point. The quantity E should be calculated using the recommended formalism in NCRP Report No. 132 (NCRP, 2000a) and Report No. 142 (NCRP, 2002), and using a MIRD-like adult anthropometric model (*e.g.*, Cristy and Eckerman, 1987; Kramer *et al.*, 1982; Snyder *et al.* 1978) to obtain the organ dose equivalents (ICRU, 1993a) needed to compute E (see Sections 2.3.2 and 2.3.3).

A suggested approach to the calculations to search for the conditions that yield E^* is detailed in Sections 4.3.1.8 and 4.3.2. It involves performing calculations at the nine locations noted in Figure 4.1 (Section 4.3.1.6) for: (1) an empty truck; (2) a representative sampling of commonly transported homogeneous loadings (*e.g.*, steel, water, aluminum and concrete) that cover a range of atomic weights, mixtures and densities to simulate realistic packing and loading arrangements; and (3) some inhomogeneous cargo configurations with high albedo and capture gamma-ray production.

1.10 Validation Measurements and Uncertainties

Due to the inherent uncertainties in the calculation of E for the complex radiation field of neutrons and gamma rays, validation is required prior to routine use of the PFNA system for scanning cargo containers. Although E is not a measurable quantity due to its dependence on nominal values of tissue weighting and radiation weighting factors, there is a closely related quantity [*i.e.*, the $Q(L)$ -weighted lineal energy density] that can be derived from both measurements and calculations.

The $Q(L)$ -weighted lineal energy densities at depths of 1 and 10 cm in a hydrogenous physical phantom can be calculated by radiation transport codes and can be measured by a method that uses a tissue-equivalent proportional counter (TEPC) (Section 4.3.3) in such a way as to determine a reasonable estimate of the uncertainty of the calculated value of E using the MIRD-like model. The TEPC structure itself should be included in a special calculation for the hydrogenous physical phantom so that the discrepancy between the calculated and measured $Q(L)$ -weighted lineal energy densities will be as low as possible.

The limiting condition for operation of the PFNA system is that $E^* (1 + 2 r_c)$ should be less than the recommended E limit of 1 mSv (or 5 mSv in the case of compelling national security requirements). The quantity r_c is the combined relative standard uncertainty for the ratio of the calculated to experimental values, and is taken to be a valid estimate of the combined relative standard uncertainty for the ratio of the MIRD-like model calculations of E^* to the true value of E^* . The factor of two multiplying r_c provides a 95 percent confidence interval for the assurance that the E^* received by an inadvertently exposed individual will be less than the designated limit.

In addition to the TEPC measurements, incident (*i.e.*, without a phantom) spectral fluence rate measurements for both neutrons and gamma rays should be carried out for the configuration that yields E^* to verify that the major features of the observed spectra are qualitatively in agreement with the calculations.

1.11 Application of the Results

The results of the radiation transport code calculations described in Sections 4.2 and 4.3 can be expected to provide an estimate of E to an individual located at the position in the cargo container where E is the highest (*i.e.*, E^*). Since it is possible for an inadvertently exposed individual to be at the location of E^* , the calculated value of E^* should provide the basis for operation of the PFNA system. However, if it is known that there are no individuals in the cargo container or truck cab (by prescreening or manned in-container inspections), this limitation does not apply.

1.12 Quality Control of Pulsed Fast Neutron Analysis System Performance

Any change in the design of the shielding (composition or dimensions), the accelerator, the target, or the inspection tunnel from those used in the radiation transport calculations could result in invalidating the calculated values of E . In order to ensure against any unrecognized impact from such changes, a document listing those items that could affect the reliability of the calculated values should be available to designers, operators, maintenance personnel, and facility management.

Specific recommendations for quality control are given in Section 4.5 for the accelerator fluence rate, the target assembly rotation rate, and the rate of container travel, and are summarized below.

- The fluence rate is the most appropriate measure of the output of the accelerator. Therefore, a live-time display of the fluence rate should be available to the operators whenever the accelerator is in operation, and the data should be recorded.
- The rotation rate of the target assembly provides the vertical scanning rate. As a result, the rotation of the target assembly should occur at or above the specified rate, and procedures to establish and maintain the rotation rate values are essential to ensure that the calculated values of E continue to be applicable.
- The horizontal scanning rate is determined by the speed of the cargo container. As a result, the tow vehicle, the truck, and the cargo container should pass through the scanning beam at or above the specified rate and with a high degree of reliability. Vehicle travel rate should be tied to accelerator operation.

2. The Appropriate Dose Limit for Inadvertently Exposed Individuals and Levels of Activation Products in Pharmaceuticals and Medical Devices

2.1 Introduction

SCA, working with DoD, asked NCRP to provide recommendations on the appropriate dose limit for persons inadvertently irradiated by the PFNA system (Brown *et al.*, 2001) and the proper method(s) to determine the exposure. In addition, NCRP was asked to provide an opinion on whether the use of this vehicle scanning system could result in levels of activation products in pharmaceuticals and medical devices that might be of concern to public health. Section 2 of this Commentary addresses these matters.

2.2 The Appropriate Dose Limit

2.2.1 Prior NCRP Recommendations

NCRP has a long tradition of developing recommended dose limits for a variety of applications, most recently for workers and the public (NCRP, 1993), for space activities (NCRP, 2000a), and detailed recommendations have been made on limiting radiation exposure to the skin (NCRP, 1999a; 2001a).

For radiation workers, the recommendation is based on limiting the additional lifetime risk of fatal cancer to less than three percent for the maximally exposed individual. NCRP's overriding recommendation applied a nominal risk estimate of four percent per sievert (0.004 percent mSv^{-1}), utilizing the linear nonthreshold hypothesis (NCRP, 2001b), and suggested a lifetime limitation scheme (dose limit) for workers to be “age in tens of millisievert” (NCRP, 1993). For example, the limitation in risk, for fatal cancer, at age 65 would be 650 mSv times 0.004 percent mSv^{-1} , which is 2.6 percent.

For members of the public, NCRP observed that the nominal risk estimate of fatal cancer associated with exposure to radiation was five percent per sievert (0.005 percent mSv^{-1}). The larger risk estimate for members of the public reflects potential exposure at all ages, including infants, children and adults. NCRP also noted that the average annual exposure to natural background, excluding radon, results in an effective dose of about 1 mSv. Considering the increased potential period of exposure over a lifetime (assuming a 75 y lifetime) and the wider range of sensitivities to be found in the general population, NCRP recommended that the annual value of E for the general public not exceed 1 mSv (NCRP, 1993). This limit assumes that the exposure occurs every year (*i.e.*, 1 mSv y^{-1} times 75 y, or a lifetime value for E of 75 mSv).

Because a member of the public might be exposed to more than one source of radiation in a year, NCRP recommended that the effective dose from each source of exposure be constrained to 0.25 mSv y^{-1} (or less) unless it is known that the sum of the effective doses from

all sources of public exposure for the individual does not exceed 1 mSv y^{-1} . This Commentary uses the term “administrative control” for this 0.25 mSv y^{-1} value. This administrative control also assumes that the exposure occurs every year (*i.e.*, 0.25 mSv y^{-1} times 75 y, or a lifetime value for E of approximately 19 mSv). Similarly, the U.S. Environmental Protection Agency Superfund-based value of 0.15 mSv y^{-1} assumes a lifetime of exposure (*i.e.*, 0.15 mSv y^{-1} times 75 y, or a lifetime value of E of approximately 11 mSv) (CERCLA, 1980; EPA, 1997).

NCRP has not specifically addressed the embryo/fetus in its basic recommendations (NCRP, 1993), except in the specific case of a pregnant radiation worker. For the embryo/fetus potentially exposed in the occupational environment, NCRP recommended an occupational equivalent dose limit of 0.5 mSv per month to the embryo/fetus or a cumulative equivalent dose of 4.5 mSv during the entire period of gestation. The limitation on the equivalent dose per month to the embryo/fetus was developed in consideration of the two-month period (8th to 15th weeks of gestation) that is a sensitive time in fetal brain development. The intention of this recommendation is to limit the equivalent dose to any tissue undergoing organogenesis to 1 mSv over any two-month period. In addition, the International Commission on Radiological Protection (ICRP) recommended a limit of 2 mSv to the abdomen of a pregnant worker over the entire period of gestation (ICRP, 1991). The limit of 2 mSv to the abdomen results in approximately 1 mSv equivalent dose to the embryo/fetus. ICRP based its recommendation on a review of the same body of literature reviewed by NCRP and a consideration that the embryo/fetus should be considered as a member of the public. Both NCRP and ICRP guidance given above indicate that the inadvertently exposed embryo/fetus would be well protected by the effective dose limit of 1 mSv suggested below, and would be adequately protected with an effective dose limit of 5 mSv if this higher limit were needed for national security reasons.

2.2.2 Recommendations for the Pulsed Fast Neutron Analysis System

This Commentary recommends that the PFNA system be designed and operated to ensure that an inadvertently exposed person receive an effective dose of less than 1 mSv, but recommends that this limit can be raised to 5 mSv, if necessary, to achieve national security objectives. A limit of 5 mSv for infrequent annual exposures is allowed in NCRP’s current guidance for exposure to members of the public (NCRP, 1993). Assuming the linear, nonthreshold hypothesis, a single exposure with a value of E below 1 mSv means that the incremental increase in the average lifetime risk of fatal cancer from such inadvertent exposure would be less than 0.005 percent. The lifetime risk of fatal cancer from all causes for the United States population is 15 to 20 percent. Therefore, the added risk associated with a one-time effective dose of 1 mSv is small, *i.e.*, adds less than 0.005 percent (or 0.025 percent for the 5 mSv limit) to the risk of 15 to 20 percent that occurs naturally.

In establishing this recommendation on the appropriate effective dose limit for individuals inadvertently irradiated by the PFNA system, this Commentary has assumed that an individual is unlikely to be exposed more than once or at most, a few times. This is primarily because a person can be easily observed by the scanning system and, consequently, will be made fully aware that an exposure has occurred and how it occurred. This Commentary considers that inadvertently exposed individuals, even though possibly engaged in illegal activities, should be provided a level of protection consistent with that accorded to the general public. The recommendation of a limit of 1 mSv, or 5 mSv in the case of national security considerations, are intended as boundary conditions with the expectation that every effort will be made to keep radiation exposures from the PFNA system ALARA (NCRP, 1993). This Commentary further recommends that each person who has been inadvertently exposed in a PFNA scanning event be carefully informed of the exposure by the law enforcement authority

responsible for the PFNA system. At a minimum, the law enforcement authority should provide such individuals with easy to understand information about the amount of effective dose received, in a language understood by the individual or through a translator, where practicable.

2.3 Determination of Effective Dose

2.3.1 Dosimetry Approach

The use of fast neutrons for cargo inspections results in a complex distribution of photons (gamma rays) and neutrons (fast, epithermal and thermal) inside the cargo container. The radiation spectrum (*i.e.*, type, energy and direction of the radiation) that reaches an individual inside the cargo container is dependent on the materials that make up the container, the contents of the container, and the location of the individual inside the container.

In less complicated situations, when only x and gamma rays interact with the human body, the mean absorbed dose in an organ or tissue [D_T (*i.e.*, the total amount of the energy deposited in the organ or tissue divided by its mass)] is the basic quantity in radiation protection. In this more complicated system, D_T must be modified to reflect the greater biological effect of neutrons. Also, the radiation field incident on the container is significantly altered, as noted above, before it reaches an individual, which makes this irradiation case more complex than usual. The quantity D_T is modified in two ways. First, to reflect the increased biological effectiveness of neutrons compared with x and gamma rays, a modifying factor for radiation type called the radiation weighting factor (w_R) is applied and yields the quantity that represents the equivalent dose (H_T) to an organ or tissue. The w_R values apply to the type of radiation incident on the body. Second, to reflect the variations in radiation risk among different organs or tissues in the body, a different modifying factor for tissue type called the tissue weighting factor (w_T) is applied. The w_T values are the same for all radiations. The sum of the products of H_T and w_T yields the quantity effective dose (E), which is the quantity used to express the radiation dose received by an exposed individual (NCRP, 1993). The dosimetric approach and the specific formulas showing how these modifying factors are applied for this more complicated case are given later in Sections 2.3.2 and 2.3.3.

Use of existing conversion coefficients (ICRP, 1996; ICRU, 1998) that relate a radiation field quantity (such as fluence) to E is not directly applicable to the complex irradiation conditions found inside the cargo container. The dosimetric approach that is recommended will provide a reasonable approximation for the value of E .

Dose assessment for individuals located inside a cargo container being irradiated by a high-energy neutron beam requires the use of radiation transport calculations normalized to a unit fluence of the fast neutron beam incident at a selected reference site (*e.g.*, incident on the container or emitted from the PFNA system components). This will require a series of calculations for likely scenarios, employing the irradiation characteristics of the fast neutron beam, the characteristics of the cargo container and its contents, and the likely locations of an individual or individuals in the container. This approach (*i.e.*, for each selected scenario) allows one to obtain the energy imparted at each interaction site in the interior of the container and permits calculation of the dose equivalent (H) at points in the cargo container by utilizing the current quality factor relationship [$Q(L)$] (ICRP, 1991; ICRU, 1993a; NCRP, 1993).²

² $Q(L)$ is the quality factor [*i.e.*, as a function of linear energy transfer (L)] by which absorbed dose [$D(L)$] at a point is modified to obtain the dose equivalent (H) at the point, in order to express the effectiveness of an absorbed dose on a common scale for all types of ionizing radiation.

The energy imparted and the mean quality factor at all interaction sites in an organ or tissue can be used to obtain a quantity called organ dose equivalent (ICRU, 1993a), given the symbol $\bar{H}_T$ by NCRP (2002). The quantity $\bar{H}_T$ was adopted by NCRP as an acceptable approximation for H_T for situations where complex internal spectra are generated by high-linear energy-transfer radiation (NCRP, 2000a; 2002).

Therefore, if a simulated person with simulated organs and tissues is located inside the container, the resulting value of $\bar{H}_T$ for each internal organ or tissue of the individual can be calculated utilizing the $Q(L)$ relationship, and the quantity E can be estimated by substituting $\bar{H}_T$ for H_T (i.e., for $w_R D_T$). The evaluation of $\bar{H}_T$ can be performed with computerized anthropometric models in conjunction with an appropriate radiation transport code. In this way, a value of a conversion coefficient (i.e., E divided by the fluence) for the irradiation conditions encountered with the PFNA system in the specific scenario can be obtained.

The proposed dose assessment approach for PFNA systems, used in inspecting cargo containers, requires further evaluation of the methods for determining the potential E values, and the methods for monitoring the PFNA system in practice, as follows:

Methods of determining the potential E values:

- identify the neutron beam parameters, container and content characteristics, scanning rate, and surrounding environment for a number of potential inspection scenarios;
- estimate E values for individuals, using radiation transport codes and appropriate mathematical phantoms to calculate the internal radiation environments for selected scenarios (i.e., beam parameters, container and content characteristics, and location of individuals inside the containers);
- conduct a sensitivity analysis of the E values for PFNA systems (i.e., evaluate the amount of change in the values of E over the range of selected scenarios);
- validate the calculations with physical measurements (i.e., with appropriate tissue-equivalent phantoms and appropriate radiation detectors to measure the photon and various neutron components) for scenarios that represent the maximum contribution from buildup, albedo, backscatter, and capture gamma rays to the dose inside the cargo container; and
- evaluate the practicality of determining the value E that results from an inadvertent exposure using the actual beam characteristics, container and cargo characteristics, scan time, and values of E from the pre-established database for the likely scenarios.

Methods for monitoring the PFNA system in practice:

- monitor the beam characteristics (i.e., scan rate, fluence rate, beam energy, and beam current) of the PFNA system to confirm that the actual characteristics conform to the characteristics planned for the application of the PFNA system; and
- conduct periodic (e.g., monthly) quality control checks of the fluence rate incident on the cargo container for fixed neutron beam conditions.

The application of the proposed methods given above for dose assessment for PFNA systems is described in further detail in Section 4 of this Commentary.

2.3.2 Effective Dose Formulation

The information below provides the specific dosimetry formulations pertinent to the dosimetry approach outlined in Section 2.3.1 above.

The dose limits and the administrative control for delayed stochastic effects are expressed in effective dose (E), where: