Presidential Report on Radiation Protection Advice for the Pulsed Fast Neutron System Used in Security Surveillance:
Part II. The ALARA Principle and Related Issues

A Report Prepared by the National Council on Radiation Protection and Measurements

Scientific Committee 1-11

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Preface
1. Summary
    1.1 Applicable Radiation Protection Dose Limits
    1.2 The ALARA Principle and its Application to the PFNA Facility
    1.3 Advice on the System Safety Specifications and the Radiation Safety Plan
    1.4 Potential Effects on Nuclear Weapons in Scanned Cargo
2. Introduction
3. Review of PFNA Facility
4. Principles of Radiation Protection
    4.1 Effects of Concern in Radiation Protection
        4.1.1 Deterministic Effects
        4.1.2 Stochastic Effects
    4.2 The Radiation Protection System
        4.2.1 Radiation Workers
        4.2.2 Members of the Public
        4.2.3 Negligible Individual Dose
5. As Low as Reasonably Achievable (ALARA) Philosophy
    5.1 Application of ALARA to the PFNA Facility
    5.2 Radiation Levels at the Inspection Station
        5.2.1 General Dose Reduction Techniques
        5.2.2 Levels of Tritium Release
    5.3 Doses to Stowaways or Others from Inadvertent Exposure
    5.4 Activation Products in Food, Pharmaceuticals, Medical Devices and Other Cargo
    5.5 Radiation Levels Outside the Facility
6. System Safety Specifications
7. Radiation Safety Plan
    7.1 Radiological Area Classifications

7.2 Access Controls
    7.3 Radiation Detection and Monitoring
    7.4 Interlocks and Emergency Switches
    7.5 Shielding
    7.6 Emergency Response
    7.7 Training
8. Potential Effects on Nuclear Weapons in Scanned Cargo
9. Conclusions
    9.1 Characteristics of the PFNA System
    9.2 Radiation Protection Considerations
References

Preface

This Presidential Report 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 other 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 specific application is a six month test of the PFNA system to evaluate its effectiveness as a security surveillance device.

This is the second Presidential Report prepared for SCA concerning the PFNA system; the first was completed in September 2002, entitled Radiation Protection Advice for Pulsed Fast Neutron Analysis System Used in Security Surveillance. It covered: (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.

In this second Presidential Report, SCA requested NCRP: (1) to describe the relevant concepts of radiation protection that should be applied to the PFNA system; (2) to provide a critique of the draft System Safety Specifications and the draft Radiation Safety Plan for the PFNA system; and (3) to pay special attention to the application of the "as low as reasonably achievable" (ALARA) principle to the PFNA system.

This Presidential Report addresses these additional matters.

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Thomas S. Tenforde
President

1. Summary

The Pulsed Fast Neutron Analysis (PFNA) system is being evaluated by the responsible agencies of the U.S. government as a security surveillance device for analyzing the contents of large cargo containers such as truck trailers. In response to a request from the Department of Defense, the National Council on Radiation Protection and Measurements (NCRP) provides, in this Presidential Report, advice to these agencies regarding radiation protection of radiation workers, operators of the PFNA system, general employees of the facility where the PFNA system is used, the general public outside the boundaries of the PFNA facility, inadvertent exposures of persons (*e.g.,* stowaways) who may be inside of the cargo containers, and the impact of the PFNA analysis on cargo that is inspected. A critique, in the form of advice on the necessary components of System Safety Specifications and of a Radiation Safety Plan for the PFNA facility, is also given.

1.1 Applicable Radiation Protection Dose Limits

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 manmade sources, not to each source individually. Generally, the exposure from a single source or set of sources controlled by any single entity should be limited to 0.25 mSv annually (NCRP, 1993).

NCRP (2002) recommends that the PFNA system be designed and operated in a manner that ensures that an inadvertently exposed person will receive an effective dose of less than 1 mSv

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[*] 10 mSv is equal to 1 rem in the older system of radiation units.

from a single inadvertent exposure. NCRP (2002) further recommended that this limit can be raised to 5 mSv, if necessary, to achieve national security objectives.

1.2 The ALARA Principle and its Application to the PFNA Facility

The “as low as reasonably achievable” (ALARA) principle 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 smaller and smaller, 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) ensuring that the facility is properly equipped to manage the tritium that is produced in the beam line; (2) minimizing the risk that the target assembly where tritium accumulates over time will rupture during operation; and (3) deciding how to manage tritium produced in the target (*i.e.,* venting tritium to the atmosphere before significant inventories have accumulated, or 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, as described in detail in the previous Presidential Report (NCRP, 2002). For example, sodium-24 (see Section 5 in NCRP, 2002) 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 effective dose recommended in 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.

1.3 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 (refer to Section 1.1), the ALARA principle, and Customs Service policy. Maximum acceptable dose rates at specific locations can be determined based on the applicable annual limit, 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 annual effective dose to an individual not exceed 0.25 mSv.

Area 2 (controlled access) also has an annual effective dose limit of 0.25 mSv, 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), and 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. Dose rates in Area 4 can be substantially above background (*i.e.,* occupancy can result in an annual effective dose above 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 radiation 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.

A summary of the characteristics that define the four types of areas is provided in Table 6.1 (see Section 6).

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 limits. The purpose of personnel monitoring is to confirm that no individual has exceeded the relevant individual effective dose limit. Workers who might receive more than a significant fraction of the appropriate annual limit 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 is notified when the accelerator is about to start, and has quick 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 individual effective doses in excess of 0.25 mSv per year.

The Radiation Safety Plan for a radiation-generating device 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.

1.4 Potential Effects on Nuclear Weapons in Scanned Cargo

The maximum neutron fluence that can be produced by the PFNA accelerator is minuscule compared to the fluence needed to convert a sub-critical assembly of fissionable material into a critical assembly. Thus, neutron irradiation from the PFNA system cannot cause a clandestine nuclear weapon located in the cargo container to detonate by direct action.

2. Introduction

Sensor Concepts and Applications, Inc. (SCA) of Phoenix, Maryland, working with the U.S. Department of Defense (DoD), has asked the National Council on Radiation Protection and Measurements (NCRP) to provide additional recommendations concerning the radiation protection aspects of the PFNA system (Brown et al., 2001). These aspects cover:

1. A description of the relevant concepts of radiation protection that should be applied to the PFNA system. These concepts are justification, the ALARA principle and dose limitation, and can be summarized in the following three questions.
    - Does the overall benefit to society exceed the overall cost? This concept (*i.e.,* justification) refers to the broad societal decision that needs to be made

through appropriate procedures by the law enforcement authority utilizing the PFNA system. NCRP can provide radiation risk estimates and other technical analysis of radiation levels to be taken into consideration by that authority, but cannot render an opinion on the net benefit based on the radiation risk alone.

- Is the detriment from such justified activities or practices maintained as low as reasonably achievable, taking into account economic and social factors (*i.e.,* the ALARA principle)?
- Has the appropriate dose limit been applied to ensure that the procedures of justification and ALARA do not result in individuals or groups of individuals exceeding the level of acceptable risk (*i.e.,* dose limitation)?

2. A critique of the draft System Safety Specifications and the draft Radiation Safety Plan for the PFNA system.

3. A review of the application of the ALARA principle and other radiation related considerations in the draft System Safety Specifications and draft Radiation Safety Plan for the PFNA system, addressing, in particular, tritium releases, short-term and long-term effects resulting from activation of foodstuffs, activation of pharmaceuticals and medical devices, doses to stowaways, doses to the general public (outside the PFNA facility) and accidental activation of a nuclear warhead.

This Presidential Report addresses these additional matters.

3. Review of PFNA Facility

The PFNA system is to be evaluated in a six month test at a port of entry. The objective of the PFNA system is to produce a three-dimensional image of the distribution of atomic composition for the materials in the contents of large cargo containers such as truck trailers. The three-dimensional image of atomic composition makes it possible to identify certain materials, or classes of materials, and allows discrimination between materials even though they may have essentially identical electron density and are, therefore, indistinguishable by conventional x-ray imaging.

In order to achieve resolution of atomic composition, the energy spectra of prompt gamma rays produced by fast neutron absorption are measured. Many elements have significant (n,γ) cross sections for neutrons with energies of several MeV, and the resulting gamma rays have energies that are specific to the atomic number and charge of the target nucleus. Thus the measured γ-ray spectrum can be used to determine atomic composition.

In order to resolve the positions and volumes of materials of different atomic composition, the neutron beam is collimated and scanned in the vertical plane, the container is moved through the plane of the beam, and the time of flight of the neutron from when it was produced to when it was absorbed is used to determine the position along the direction of the beam.

Time of flight is useful because neutrons can be produced in short (10^{-9} second) bursts and their velocity is moderate (on the order of 4×10^{7} m s^{-1}). Furthermore, the (n,γ) reactions of interest are nearly instantaneous, and the gamma rays produced travel at the speed of light in the extant medium. Thus the time when a gamma ray is detected (relative to the start of the neutron pulse) gives the time when the neutron interaction occurred, which in turn gives the distance from the neutron production target, the third dimension in the image of the contents of the container.

The spectrum of gamma rays received at a specific time after the neutron pulse gives the atomic composition at the corresponding point in the container. Sufficient neutron interactions must be detected in each time interval to define the gamma-ray spectrum with sufficient precision to distinguish atomic compositions of interest. The number of gamma rays detected depends on the length of the time interval, the neutron fluence rate, and the efficiency of the gamma-ray detector. The length of the time interval is inversely related to the spatial resolution, so the better the resolution (in cm) the higher the neutron fluence required for a fixed gamma-ray detector array. Conversely, the more efficient the gamma-ray detector, the lower the fluence required to give a specified resolution.

The dose to the contents, and the activity of activation products in scanned containers, is directly related to the neutron fluence, assuming that the neutron spectrum is constant. The neutron spectrum also influences the spatial resolution of the system since low-energy (slow) neutrons will reach a specific distance from the source after the higher-energy neutrons. Thus, the broader the neutron spectrum, the poorer the spatial resolution. The pulse length, neutron energy spread, and total fluence are dependent on the characteristics of the deuteron accelerator and the deuterium target thickness when the $d(d,n)^3He$ reaction is used.

In order to produce a spatially resolved image of the contents of a container, it is important that the neutron energy not change too much as the neutrons traverse the container. This requires that the initial energy of the neutrons be fairly high, and a consequence is that most of the neutrons will not interact in the scanned container. This means that extensive shielding surrounding the scanning system is necessary. The typical PFNA inspection facility would consist of a building (approximately 220 feet by 60 feet) housing the PFNA equipment and several smaller structures for electronic equipment and operators.

When the PFNA system is in routine use, vehicles are selected for inspection from the stream of commerce and are directed to the corridor-like entrance of the test facility. The driver leaves the vehicle and walks to a designated waiting area located at the other side of the PFNA building. A self-powered towing machine slowly pulls the unoccupied vehicle through the facility and past the scanning device located in the tunnel. Once all safety checks are verified, the vehicle is scanned with the neutrons. The pulsed beam moves up and down while the vehicle slowly passes by to ensure that all of the contents are inspected.

Many of the neutrons pass through the vehicle unaffected and are stopped by the shield walls of the tunnel. This shielding, plus surrounding restricted access areas, is designed to minimize exposure to workers and the public to direct radiation from the neutron source or the gamma rays produced by neutron interactions.

Although the neutron production process does not require any radioactive material, the product of the interaction of two deuterium ions can form ^{3}He and a neutron, or can form ^{3}H and a proton. These two outcomes are equally probable, so one tritium atom is formed for every neutron produced. Also, when the neutron is finally absorbed in shielding or other material it often results in the production of a radioisotope. Some of these activation products are formed in the contents of the scanned containers, but the dose that they produce is extremely low and will be discussed in more detail later.

4. Principles of Radiation Protection

The specific objectives of radiation protection are: (1) to prevent the occurrence of clinically significant radiation-induced deterministic effects by adhering to dose limits that are below the apparent threshold levels; and (2) to limit the risk of stochastic effects (*i.e.,* cancer and genetic effects) to a reasonable level in relation to societal needs, values, benefits gained and economic factors (NCRP, 1993).

These objectives can be achieved by ensuring that all exposures are "as low as reasonably achievable" (ALARA) in relation to benefits to be obtained and by applying dose limits for controlling occupational and general public exposures.

4.1 Effects of Concern in Radiation Protection

The serious radiation-induced effects of concern in radiation protection fall into two general categories: deterministic effects and stochastic effects.

4.1.1 *Deterministic Effects*

A deterministic effect is one that increases in severity with increasing radiation dose above a threshold dose. The severity increases because of damage to an increasing number of cells. Deterministic effects occur only after relatively large doses, but the threshold dose and the severity of the effects may be influenced by individual susceptibility and other factors. The question of radiation dose thresholds for deterministic effects is complex and the magnitude of the apparent threshold depends on the specific biological endpoint and the ability to detect it. However, if the endpoints of concern are restricted to those that are clinically significant, dose limits can be selected to be less than the threshold values for these effects (NCRP, 1993).

4.1.2 *Stochastic Effects*

A stochastic effect is one for which the probability of the effect occurring increases with increasing absorbed dose, while the severity of the effect is independent of the magnitude of the absorbed dose to the affected individuals. A stochastic effect is an all-or-none response (*e.g.,* cancer and genetic effects). There are differences in the risk for an effect from a given absorbed dose that are dependent on individual factors such as age and gender. A stochastic effect is assumed to have no dose threshold, although currently available observations in population samples do not exclude the probability of no effect at very low doses. The induction of stochastic effects is considered to be the principal effect that may occur following exposure to low doses of ionizing radiation (NCRP, 1993).

4.2 The Radiation Protection System

For radiation protection purposes, NCRP assumes: (1) that the risk for stochastic effects is proportional to dose without threshold throughout the range of dose and dose rates of importance in routine radiation protection, and (2) that the risk accumulates linearly with dose (NCRP, 1993). When higher doses are received acutely, such as in accidents, more complex (nonlinear) dose-risk relationships may apply.

Given the above assumptions, radiation exposure at any selected dose limit will, by definition, have an associated level of risk. For this reason, NCRP (1993) recommends the following three guiding principles of radiation protection:

> (1) The need to justify any activity that involves radiation exposure on the basis that the expected benefits to society exceed the overall societal cost (*i.e.,* justification).
>
> (2) The need to ensure that the total societal detriment from such justifiable activities or practices is maintained as low as reasonably achievable, economic and social factors being taken into account (*i.e.,* the ALARA principle).
>
> (3) The need to apply individual dose limits to ensure that the procedures of justification and ALARA do not result in individuals or groups of individuals exceeding levels of acceptable risk (*i.e.,* dose limitation).

Principle (1) above (*i.e.,* justification) refers to the broad societal decision that is formally or informally made and based on the conclusion that the expected benefits to society exceed the overall societal cost. NCRP and radiation protection specialists can provide estimates of radiation levels and accompanying radiation risks that are integral to making a societal decision, but cannot render an opinion of the net benefit or cost based on these radiation aspects alone.

4.2.1 *Radiation Workers*

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 continues the use of 50 mSv as the limit on annual effective dose. For the exposure of pregnant women under occupational conditions, NCRP (1993) recommends that there be a limit on the equivalent dose to the embryo-fetus of no more than 0.5 mSv in a month. All dose limits apply to the sum of effective doses from external irradiation and committed effective doses (NCRP, 1993) from internal exposures. In addition, NCRP (1993) recommends that new facilities and the introduction of new practices should be designed to limit annual effective doses to workers to a fraction of the annual limit of 10 mSv implied by the lifetime dose limit given above.

4.2.2 *Members of the Public*

NCRP (1993) recommends that continuous exposure of members of the public be limited to an annual effective dose of 1 mSv. For individuals exposed infrequently, an annual effective dose limit of 5 mSv is recommended. These limits exclude exposures from natural background radiation and radiation exposure associated with medical diagnosis and treatment. The total dose from both internal and external exposure must be less than the stated effective dose limits and should be kept ALARA. It should be noted that the limits apply to the sum of all exposures, not to each source individually.

Whenever the potential exists for exposure of an individual member of the public to exceed 25 percent of the annual effective dose limit as a result of irradiation attributable to a single site, the site operator should ensure that the annual exposure of the maximally exposed individual from all man-made exposures (excepting that individual's medical exposure) does not exceed 1 mSv on a continuous basis. Alternatively, if such an assessment is not conducted, no single source or set of sources under one control should result in an individual being exposed to more than 0.25 mSv annually (NCRP, 1993).

4.2.3 *Negligible Individual Dose*

NCRP (1993) defines an annual Negligible Individual Dose (NID) that establishes a boundary below which the dose can be dismissed from consideration and set the annual NID at 0.01 mSv effective dose. This concept was introduced in NCRP (1987) and was defined as the level of average annual excess risk of fatal health effects attributable to radiation below which efforts to reduce radiation exposure to the individual is unwarranted. This occurs because the random variation in the risk due to all causes other than radiation is much larger than the incremental increase in the risk due to this dose of radiation.

The value of 0.01 mSv is considered an NID per source or practice (NCRP, 1993). Although the

NCRP endorses the nonthreshold hypothesis for the purpose of radiation protection from stochastic effects (NCRP, 2001), making a risk assessment when the individual doses are less than 0.01 mSv is not recommended. Although one cannot exclude the theoretical possibility of a fatal cancer attributable to radiation in a very large population of people exposed to very low doses of radiation, the rate of fatal disease due to other causes is much larger, and the societal impact can be considered to be negligible.

5. As Low as Reasonably Achievable (ALARA) Philosophy

The NCRP radiation protection philosophy is based on the guiding principles of justification, the reduction of dose to levels as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle), and dose limitation. The NCRP set specific upper limits of acceptable dose for occupationally exposed individuals, and the general public, with additional recommendations for the embryo/fetus. The inclusion of the ALARA principle emphasized that adherence only to dose limits was not sufficient (NCRP, 1999).

The ALARA principle has been introduced into radiation safety programs because of the prudent assumption that potential deleterious effects might occur at any level of exposure, while recognizing that as the doses become smaller and smaller, the likelihood of a deleterious effect becomes less and less. The principle of ALARA allows accounting for “social and economic factors” in determining an acceptable level of societal detriment for an activity utilizing ionizing radiation. Although individual doses should be controlled below the dose limits, there is no specific or unique value of dose for a task or occupational category that can be defined as

"ALARA". The principle of ALARA is not a quantitative standard of care for individual workers or individual members of the public (NCRP, 1998).

The ALARA principle is a necessary consequence of the adoption of a non-threshold, dose-response relationship for the purposes of radiation protection from stochastic effects. All non-threshold models dictate that dose reduction always results in a lower probability of harm. These models imply that doses should be "as low as achievable". It is also recognized, however, that the use of radiation can yield direct and indirect benefits to both individuals and populations. Furthermore, not all dose reductions can be achieved with equal ease or resource expenditure. The semantic solution to this problem is to qualify the recommendation such that doses need only be kept to levels which are as low as "reasonably" achievable, or as low as "optimal", in recognition that further reduction below some level cannot be rationally supported because the intended benefit would not be obtained, or because the cost (*i.e.,* the sacrifice of other measurable benefits) would be unreasonable (NCRP, 1990).

A level of radiation protection that is ALARA implies neither maximum protection nor maximum resource expenditure, but rather that detriments and resource expenditures have been optimized to yield the greatest net benefit. As more resources are expended, benefits are gained due to decreased health detriment; at the same time, benefits are lost due to the depletion of resources. In many cases, an optimal resource expenditure level exists which, if either increased or decreased, results in a decrease in net benefit (NCRP, 1990). However, this optimization process is utilized only for exposures below the dose limit values.

The upper limit used for implementing ALARA activities is determined by the applicable dose limit. The lower boundary for implementing ALARA activities is determined by the negligible individual dose (NID). Doses below the NID need not be considered for optimization or any other protective measures. The NID applies to all individuals, both occupationally exposed and members of the public, and applies to all aspects of radiation protection including facility design and operations management (NCRP, 1990).

5.1 Application of ALARA to the PFNA Facility

This Presidential Report is primarily concerned with the second and third principles discussed earlier as applied to a PFNA system, namely, the ALARA principle and dose limits. The dose limit is the upper limit of acceptability rather than a design criterion. For example, it is inappropriate to design a radiation-shielding barrier based on criteria that would allow individuals to be routinely exposed to the annual dose limit. In many applications, use of the ALARA principle is simply the continuation of good radiation protection programs and practices that have been effective in keeping the average and individual exposures well below the dose limits.

Every institution and organization that uses regulated devices that produce ionizing radiation should provide a program plan that specifies the policies and practices that are necessary to control radiation exposures to its employees and the public within the prescribed dose limits and to exposure levels that meet the ALARA principle. The size and scope of the program should be commensurate with the potential hazards (NCRP, 1998).

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 effective doses, 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 encouraged. To prevent unnecessary restrictions and to focus attention on the higher exposures, the NCRP recommends that the procedures and documentation required to implement the ALARA principle be less formally applied as the annual dose to an individual is reduced by progressively larger amounts below the relevant dose limit (NCRP, 1999).

In a well-organized facility, almost all the technical decisions will have been made during planning and design. Many times a small amount of shielding can be added to reduce the dose that workers might receive. Perhaps the most important approach to implementing the ALARA principle is creating the proper “mind set” in managers, supervisors and workers so that they always ask if a particular level of exposure is necessary (NCRP, 1998).

It is left to each institution or organization to adapt the guidance on the ALARA principle to its own particular circumstances (NCRP, 1990).

5.2 Radiation Levels at the Inspection Station

5.2.1 *General Dose Reduction Techniques*

Operation of a PFNA system is based on the use of a radiation-generating device (RGD). There are many ways of reducing radiation exposure to facility workers and to the general public to levels that are below regulatory limits. In each case, the cost, either monetary or in the form of limits on performance of the inspection system, has to be weighed against the reduction in dose to determine if it is reasonably achievable. Dose can clearly be reduced by reducing the time that the system operates or by reducing the neutron fluence used during a scan. However, in the absence of changes to the system sensitivity, a reduction in the time of operation would directly impact the number of containers scanned and a reduction in the neutron fluence per scan would directly impact the resolution in the resulting image (*i.e.,* in terms of identifying the size and atomic composition of the contents).

Dose to the general public and the workers at the facility can also be reduced by increasing shielding or increasing the distance between the source and the nearest occupied spaces. Although increasing shielding may be expensive, in some cases increasing distance may have little cost. Achieving the lowest dose consistent with other requirements requires that radiation protection be a primary concern during the design as well as during the operation of the facility.

5.2.2 *Levels of Tritium Release*

When two deuterium nuclei interact they can produce a neutron and ^{3}He, or they can produce a proton and a tritium atom. The probability of these two products is equal for energies that will be used in the PFNA system. Thus the number of tritium atoms produced is equal to the number of neutrons produced.

Dose to workers or the public due to tritium produced in the d(d,p)^{3}H reaction will occur only after the tritium is released to the atmosphere. The objective of the system is to have the deuteron beam react with deuterium in a sealed target chamber in order to produce a useful neutron beam. Tritium produced in the target chamber will be released only if the target fails and the contents are released, or during cleaning and refilling of the target. ALARA considerations include ensuring that the facility is properly equipped to manage the tritium that might be released, and minimizing the risk that the target assembly will rupture during operation.

Management of tritium should include evaluation of alternatives such as venting it to the atmosphere before significant inventories have accumulated or capturing tritium by a chemical reaction so that it can be managed as a solid or liquid radioactive waste. The risk of significant dose due to an accident in a tritium retention system should be compared with the risk resulting from small releases to the atmosphere over an extended time frame.

The risk of target rupture can be minimized by stringent quality control during target assembly and by changing targets before significant radiation damage to the target windows has occurred. If the target does rupture the deuterium and tritium will be released into the accelerator vacuum system. Part of it will be captured by ion pumps[1], but part of it will reach the turbine pump and be vented to the atmosphere through the roughing pump.

Tritium also may be produced when the beam strikes deuterium deposited on the inside of the accelerator beam line. Tritium produced there also will be captured by the ion pumps used for most of the beam line, or will be vented to the atmosphere by the turbine pump and mechanical roughing pump used to maintain vacuum at the ion source.

Tritium releases to the atmosphere can be minimized by minimizing production of tritium in the beam line, and by conducting maintenance work on the ion pumps in a properly equipped facility. Tritium production in the beam line can be minimized by controlling the deuterium deposited on surfaces in the beam line and by minimizing the amount of beam that strikes those surfaces. Deuterium accumulation can be controlled by periodic bake out of beam line components. The beam striking the beam line walls can be minimized by careful focus and magnetic steering of the beam.

Since good focus and steering are needed to meet accelerator performance specifications, it is unlikely that significant improvements can be made initially. However, as new technology for beam management becomes available, that technology should be evaluated in terms of potential

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[1] It is assumed that the accelerator used for PFNA, like many tandem accelerators, will have ion pumps on the beam line and a turbine pump at the ion source.

for reducing tritium production and release. A determination of whether the dose reductions that can be achieved by controlling deuterium deposition in the beam line are justified should be made based on operational experience with each accelerator installation, including the amount of tritium being produced and the cost of reducing it.

The doses to personnel at the site from tritium can be minimized by venting mechanical vacuum pumps outdoors away from the intake for building ventilation.

Total tritium production in the target resulting from production of 10^{10} neutrons per second for 2,000 hours is 1.3×10^8 Bq (3.5 mCi). Tritium production in the beam line, some of which will be vented as it is produced, will generally be less than 10 percent of that produced in the target, or less than 5.2×10^4 Bq (1.4 μCi) per day when running 8 hours per day. These values can be scaled to the actual neutron production rate and operating time. The dose that would be produced, even in the most extreme accidental release scenario (Bently, 2003) [2, 3], is only 0.1 mSv committed effective dose. Furthermore, periodic venting of the target gas will prevent the tritium inventory from reaching more than a few percent of the amount used in this scenario. Tritium vented from the beam line by vacuum pumps will be at far lower concentrations in air than the concentration used in this scenario.

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[2] Assumes a tritium inventory of 1.3×10^9 Bq distributed in a 1 m diameter sphere of air, and that this air fills the breathing zone of an individual for one minute.

[3] Bently, R. (2003). Personal communication. (Veridan, Falls Church, VA)

5.3 Doses to Stowaways or Others from Inadvertent Exposure

Dose to the inadvertently exposed individual is directly related to the neutron fluence, and therefore to the spatial and compositional resolution of the system if the gamma-ray detector remains constant. Thus, the only ways to reduce dose are to increase the sensitivity of the gamma-ray detection system, or accept reduced resolution of the measurements. Either action would require less neutron fluence. Increasing detector sensitivity becomes progressively more expensive as potential detector locations with good geometric efficiency are exhausted. Future improvements in detector technology may make greater efficiency possible, but probably at a high price which would have to be evaluated in terms of benefit. Reducing the spatial resolution, by increasing the scan speed or reducing the fluence (beam current), may be appropriate for some containers if it is possible to identify those that do not require full resolution imaging.

A major component of ALARA is to avoid the need for repeated scanning of any container. Administrative controls and equipment improvements that might reduce operational errors that result in repeating scans should be considered.

5.4 Activation Products in Food, Pharmaceuticals, Medical Devices and Other Cargo

The effects of neutron irradiation of foodstuffs are similar to those for pharmaceuticals and medical devices, as described in detail in this committee's first Presidential Report (NCRP, 2002). Daily intake of most elements, except hydrogen, oxygen, carbon, and sodium, in the form of food is typically less than the recommended intake in the form of dietary supplements. Thus the doses due to these elements in food will be less than those found previously (NCRP, 2002). The highest dose from activated food would generally be from the sodium-24 produced by the (n,γ) reaction with natural sodium in salty processed foods such as potato chips. Assuming an individual ingests 10 g of sodium from a salty food product immediately after PFNA inspection, the resulting dose would be approximately 1×10^{-6} mGy, or about 10,000 times less than the annual NID. All other elements commonly found in foods would produce much lower doses. Consequently, significant effort or cost to reduce this dose is not warranted.

5.5 Radiation Levels Outside the Facility

Dose to individuals outside the facility can be reduced by reducing the neutron fluence used, by increasing the shielding thickness or the distance between the source and those individuals, or by reducing the amount of time when the PFNA system operates and people are near the facility boundary. The cost or reduction in effectiveness of PFNA scanning produced by each of these actions should be evaluated to determine whether the resulting reduction is reasonably achievable.

6. System Safety Specifications

Safety specifications are intended to set forth the basic requirements for radiological safety of the PFNA system. These specifications need to be consistent with applicable federal and state regulations, recommendations of the NCRP, the ALARA principle and Customs Service policy.

Effective dose limits for radiation workers and for the general public are given in NCRP Report 116 (NCRP, 1993). Effective dose limits for inadvertently exposed individuals are given in the previous Presidential Report from this committee (NCRP, 2002). The policy of the Customs Service for the PFNA facility is to treat its PFNA system and radiation generating device (RGD) operators, and its inspectors, as members of the general public with regard to radiation protection. The application of the NCRP recommended effective dose limits to the Customs Service personnel mentioned above, to visitors at the PFNA facility, and to members of the general public is summarized in Table 6.1. Additional discussion of the radiological area classifications given in Table 6.1 is found in Section 7.1.

It should be noted that the annual exposure to a member of the general public from the routine operation of any single radiation source is limited to one quarter of the annual effective dose limit for that individual (*i.e.,* 0.25 x 1 mSv = 0.25 mSv, see section 4.2.2). This recommendation is based on the assumption that the typical individual may reasonably receive dose from several different radiation sources during each year. This is because the sources are expected to operate year after year, and the typical individual may encounter more than one of them in the course of everyday activities. Individuals inadvertently exposed to the PFNA system will be fully informed of how they were detected, and of the potential effects of repeated exposures. It is assumed that such an individual will be exposed only once because a prudent individual would not repeat the activity that led to the inadvertent exposure.

Maximum acceptable dose rates at specific locations can be determined based on the applicable annual limit, the maximum source operating time per year, and the maximum time any individual

Table 6.1 Summary of the characteristics that define the four types of Areas (1, 2, 3 and 4), giving the area classification, applicable annual effective dose limit, access control, and individuals who have access (including location of inadvertently exposed persons)

Area Classification	Annual Effective Dose Limit	Access Control	Training	Individuals with Access
Area 1 (uncontrolled)	0.25 mSv	none	none	general public
Area 2 (controlled)	0.25 mSv	authorization	GERT[a]	non-radiation workers; escorted visitors
Area 3 (restricted)				
no neutron beam	0.25 mSv	authorization	PFNAT[b]	PFNA operators; escorted visitors
neutron beam	NA	no access	NA	NA
neutron beam	1 mSv[c]	NA	NA	inadvertently exposed persons
Area 4 (RGD room)				
no high voltage	0.25 mSv	authorization	RGDT[d]	RGD operators; escorted visitors
high voltage[e]	50 mSv[f]	limited to radiation workers	RWT[g]	radiation workers
neutron beam	NA	no access	NA	NA

NA, not applicable

[a] GERT, general employee radiation training

[a] PFNAT, PFNA system operator training

[c] The effective dose limit can be raised to 5 mSv, if necessary, for national security objectives (NCRP, 2002)

[d] RGDT, radiation-generating device operator training

[e] Usually only during RGD maintenance

[f] New facilities should be designed to not exceed the 10 mSv per year limit implied by the lifetime limit (NCRP, 1993)

[g] RWT, radiation worker training

would be present in the area per year. For the PFNA test phase, the operation is limited to 6 months and actual operation will not exceed an average of 20 hours per week, for a total of 500 hours. Thus the maximum dose rate in areas that may be occupied by the general public should be limited to 0.5 μSv h^{-1}.

The Customs Service has chosen to operate inspection facilities in a way that limits radiation exposure to inspectors and other employees to the same level as the general public; 0.25 mSv y^{-1}. The safety specifications must establish dose rate limits at the boundary between Area 2 and Area 3 (refer to Table 6.1) that ensure that this annual effective dose limit will not be exceeded considering appropriate work load and occupancy factors. Assuming a workload of 500 hours per year and full time occupancy of the controlled area, the dose rate limit would be 0.5 μSv h^{-1}. It should be noted that routine, year round (*i.e.,* 2,000 hours), use of a PFNA system would result in limiting the dose rate in the controlled area to about 0.12 μSv h^{-1}. Restricted and RGD areas, which would not be occupied by facility employees when the radiation source is operating, could be assigned higher dose rate limits, compatible with the training of individuals who might work in those areas.

A fundamental part of the radiation safety specification should be the requirement that equipment and facilities be designed and operated so that radiation exposures are kept as low as reasonably achievable. It is also appropriate to specify the minimum methods that will be used to achieve the specified dose limits and ALARA objectives. These may include specification of minimum levels of radiation monitoring equipment, shielding effectiveness, interlock protection, and other necessary radiation protection steps. However, it should be recognized that when developing a safety plan for a specific facility it may be necessary to exceed these minimum requirements (*i.e.,* install more shielding, interlocks, and other necessary radiation protection steps) than specified in the safety specification in order to meet the primary objectives of dose limits and ALARA.

7. Radiation Safety Plan

The Radiation Safety Plan is intended to serve as a detailed policy for the implementation of the safety specifications for the PFNA system. By its nature, the plan must be specific to each installation so that allowances can be made for the geographical, architectural, and technical details of the installation. Differences in these features may make it possible to achieve different (lower) dose levels at different sites, resulting in different requirements to meet ALARA objectives. The Radiation Safety Plan should incorporate both engineered and administrative procedures for ensuring that the requirements of the safety specifications are met. However, to the greatest extent possible, engineered controls should be used to minimize the dependence on administrative controls. Major aspects of the plan include definition of the controlled areas for the purpose of radiation protection, access controls to those areas, radiation detection and monitoring, interlocks and emergency switches, shielding, response to emergencies, and training of staff and visitors.

7.1 Radiological Area Classifications

In the case of the PFNA facility, radiological areas are nested, with progressively higher potential radiation exposure rates, and with corresponding requirements for access and training (Table 6.1). Consistent use of nomenclature for these areas is essential in order to avoid unintentional exposure. Generally the facility is located in an uncontrolled area and part of the facility building and grounds may also be an uncontrolled area. There are no restrictions on access to uncontrolled areas. The annual effective dose is limited to that for the general public.

Typically, the majority of a PFNA facility will be designated a controlled access area. Controlled access areas provide a buffer between uncontrolled space and areas where significant radiation exposure can occur. Exposure levels are limited to those acceptable for the general public, but individuals with routine access to controlled areas are required to have an appropriate level of training on the potential hazards of radiation exposure, on recognition of restricted area and RGD area boundaries, and on access controls. The required training is commonly known as "general employee radiation training" and typically requires about one hour. The boundary of the controlled area must be well defined, and secured to prevent access by unauthorized (untrained) individuals. Thus controlled areas are generally buildings, or fence enclosed clusters of buildings, with a receptionist or key controlled entry. Typically visitors can be admitted to a control area after a brief "visitor's training" which emphasizes the need to not enter restricted areas or the RGD room without a trained escort.

Within a controlled area there may be a variety of individual areas with greater radiation exposure potential when the RGD is operating. Within the PFNA facility these can be designated as restricted areas and the RGD room. Entry to these areas requires various levels of training relevant to the maximum hazard that could exist in the area.

The Radiation Safety Plan outlined here is limited to the operation of the PFNA system. A separate Radiation Safety Plan is required for any activities that would result in an annual effective dose in excess of 0.25 mSv. Customs Service policy is to prohibit access of the Customs Service personnel to any area that could result in their exceeding the annual dose limit for the general public. To accomplish this, areas that have elevated dose rates when the PFNA system is operating are designated as restricted areas. When the accelerator is not producing a neutron beam, authorized persons have access to a restricted area. When the accelerator is producing a neutron beam, access is prohibited. The accelerator operator is responsible for ensuring that no one is in the RGD room before starting the accelerator or in the restricted area before generating the neutron beam.

The boundaries of the restricted areas, as well as the RGD room, must be clearly marked and posted. When walls are not present, fences with standard signs, or for temporary situations, standard colored (yellow and magenta) tape or rope is used to mark boundaries. Boundaries are labeled with signs indicating the nature of the enclosed area. If walls are present, doorways are clearly marked and labeled by appropriate signs.

7.2 Access Controls

The level of access control for a given area must be adjusted for the level of risk within the area, and the expected population surrounding the area. In the case of the PFNA system, the major radiation source is the radiation-generating device (RGD), the accelerator. When the accelerator is producing a neutron beam (“operating”), the dose rates in specific areas can be quite high, but when the accelerator is not capable of producing a neutron beam (“turned off”) only the very low dose rates due to activation products remain. Access to a relatively large portion of the PFNA facility must be controlled when the accelerator is operating in order to prevent radiation exposures in excess of the recommended limit, but it is important that access not be unnecessarily restricted when the accelerator is turned off.

Thus, access control systems for the radiation-generating device (RGD) area typically have two or more states. In the first state, defined by the fact that the accelerator is turned off (*i.e.,* cannot produce radiation without significant manipulation of its control circuits), access is not restricted. In the second state, defined by the fact that power is applied so that the accelerator is capable of producing radiation (whether any radiation is being produced or not), access is prevented by physical barriers that are interlocked such that, if opened, power to the accelerator is automatically turned off. The barriers may be shielding walls and shielding doors, but also may be only a wire screen or fence that prevents entry of a person.

In the PFNA system, two levels of accelerator operation can be defined: high voltage on, and deuteron beam on. The “high voltage on” state can be defined as having the chain drive motor of the tandem electrostatic accelerator running. Radiation levels in excess of the maximum rates, established to keep exposures below the annual limit, can be produced in the RGD room with the high voltage on, whether or not the deuteron beam is on. When the deuteron beam is on, as indicated by having the source extraction voltage and inflection magnet current on, neutrons can be produced at the target and in the beam line, and dose rate limits for non-radiation workers can be exceeded in the tunnel (*i.e.,* the area where the container is brought in for scanning) and other restricted areas near the tunnel.

If operation of the RGD is capable of resulting in activation of accelerator or building components that would result in part of the area becoming a radiation area or radioactive material area when the accelerator is not operating, the access control system must also address this issue. Depending on the magnitude of the doses that might be produced, administrative controls (*i.e.,* procedures for determining activation levels and controlling access accordingly) may be sufficient. If activation could lead to producing a high radiation area, fail-safe engineered controls would be desirable.

Design of the barriers for access control and the logic for the transition from controlled access to no access must be addressed in the early stage of design of the facility in order to ensure that there are no unforeseen and uncontrolled avenues of entrance, or possibilities for overlooking potential occupants during the process of preparing the area for operation. Since areas that must be inspected for occupants clearly depend on the architecture of the facility, the building design and access control system must be developed in tandem and must be explicitly addressed in the Radiation Safety Plan.

In the case of the PFNA system, the "tunnel" presents a special access control issue. The central portion is a radiation area when the accelerator is on. In one example, the dose equivalent rates at the entrance and exit of the tunnel are predicted to be 4.0 and 8.7 μSv h^{-1}, respectively (ORNL, 2001). During testing of the PFNA system, the restricted area boundary between Areas 3 and 4 should be defined so that the dose rate inside Area 3 (the restricted area) will not exceed the recommended limit while the accelerator drive motor is on, but the ion source is not delivering ions to be accelerated. When a truck and tow vehicle have entered the restricted area, gates are closed and the area is inspected to ensure that there are no people in the area before access to the area is prohibited (*i.e.,* the deuteron beam can be accelerated). After the vehicle has passed through the scanner, the beam must be turned off before the exit gate can be opened. This procedure limits the beam-on time to a fraction of the system operating time. For routine operation, pairs of sequentially operated gates, spaced so that the largest vehicle can be accommodated between them, may be needed at both ends of the tow vehicle route. The outer gate would open letting the towed truck in, then close for an inspection to ensure that the area is unoccupied before the inner gate opens and the vehicle proceeds into the exclusion area.

7.3 Radiation Detection and Monitoring

A Radiation Safety Plan must address radiation monitoring on several levels. Appropriate methods for personnel monitoring, including designation of individuals to be monitored and detectors to be used, active area monitoring locations and involvement in safety systems, and passive area monitoring for long-term compliance with regulations must be included.

It is considered good radiation protection practice that workers who might receive an appreciable fraction of the annual dose limit be monitored by a personnel radiation dosimeter. Such a dosimeter needs to have reasonable response to all components of the expected radiation field, which includes both photon and neutron components in the case of the PFNA system. All dosimeters have an inherent noise in reading, so, for example, the minimum dose equivalent reported using one commercially available neutron dosimeter is 0.2 mSv. As a result, individuals expected to receive less than 20 percent of the dose limit should generally not be badged, and the processing interval for badges that are used should be as long as possible, consistent with detecting unexpected changes in radiation exposure rates. In the case of radiation-generating devices, those who work near the boundary of the RGD area should generally be badged, while those working at larger distances from the facility, where significant dose reduction is provided by the l/r^2 (*i.e.,* inverse square) relationship between distance and dose rate, would generally not be badged.

Active radiation monitors are often required for radiation-generating devices in order to ensure that the accelerator is operating normally, and that dose rates exceeding specified levels are not being produced. Boundaries of RGD areas are positioned to generally provide a specified dose reduction factor for a radiation source at a specific location, typically by a combination of shielding and distance from the source.

However, malfunction of some components of the accelerator can result in changes in the strength and location of radiation sources. Active monitors can be placed inside or outside the boundary of the RGD area to detect changes in radiation production. Placement inside the accelerator area generally results in higher routine dose rates and therefore in better statistical precision and faster response to changes in operating conditions, but requires provisions to ensure that the effectiveness of the shielding between the measurement location and habitable areas outside the accelerator area will not change. Placement outside the shielding provides a direct measurement of dose rate in habitable spaces, but the stochastic nature of the small number of detected events may prevent detection of transient changes in dose rate unless very large detectors are used.

In either case, selection of detector locations is important, and must be based on the accelerator design and anticipated operational failure modes. For example, a beam collimator or moveable faraday cup may not normally be a source of radiation, but if it becomes coated with deuterium during normal operation and then is hit by a substantial deuteron beam due to failure of a beam control element, it may become a significant neutron source. Depending on shielding design it may be possible to produce unacceptable dose rates outside the RGD area, and detection of such aberrant sources is critical.

Typically, active dosimeters are equipped with a dose rate display and two preset levels. If the lower preset level is exceeded an audible and visible warning is provided to the RGD operator. If the second preset level is exceeded the RGD is shut down, preferably by automatic opening of an interlock circuit. The dosimeter itself should be fail-safe, with proper operation confirmed by periodic automatic monitoring of a test source. Failure to generate the appropriate test reading should result in opening an interlock circuit and terminating accelerator operation.

In most situations, the operator of a RGD is required to prove that annual doses outside the controlled area have not exceeded regulatory limits. This is generally done by placing passive detectors, similar to personnel badges, at selected locations on the boundary of the controlled area.

7.4 Interlocks and Emergency Switches

If the expected dose rate, or procedure, is such that a specific area is not to be occupied during accelerator operation, specific measures must be taken to ensure that those areas are secure. The design of warning and interlock systems used to meet this requirement is described in NCRP Report 88 (NCRP 1986), and this section will only deal with aspects relevant to PFNA installations.

The accelerator and the neutron production target of the PFNA system are capable of producing relatively high dose rates. Thus these areas would be within a radiation-generating device area (accelerator room) which is secured by shielding walls, secure fencing, and locked doors or gates. The region where vehicles are scanned, and where detectors are located (tunnel), is also a restricted area, but with much lower maximum exposure rate (resulting from the distance from the neutron production target source).

The potential for high dose rates in the accelerator room requires access to be limited to times when the accelerator is not operating, or when special procedures (involving interlock bypass) have been developed and approved by radiation protection specialists and management. To ensure that the accelerator does not operate while the accelerator room is occupied, it is necessary to ensure that no one enters while the accelerator is operating, that no one remains in the room when the accelerator is started, and that anyone in the room is adequately notified when the accelerator is about to start and has quick access to a device to prevent the accelerator from starting.

To ensure that no one enters while the accelerator is operating, all potential entrances must be protected by gates or doors with interlock switches that interrupt power to the accelerator, at a point that ensures that no radiation will be produced (*i.e.,* the chain drive motor in the case of an electrostatic accelerator).

In normal operation, the RGD operator must confirm that no one is present in the accelerator room before attempting to start the accelerator. This is most conveniently done by requiring a walk-through of the accelerator room. A thorough walk-through is typically accomplished by requiring closure within a specified time before the accelerator starts of a contact(s) (key switch or push button) located at the critical point(s) of access to the room. The timing must be adjusted for the distance between switches and operating console, but should not be long enough to allow entry after inspection. If accelerator operation has been interrupted by the operator, but accelerator room access controls have not been opened, it is acceptable to restart operation without requiring a walk through.

Finally, to allow a person in the accelerator room to prevent accelerator startup, audible and visible warning devices (typically horns and flashing red lights) must be activated for a significant time (30 to 60 seconds depending on the time needed to reach a panic button from the farthest location in the accelerator room) before the accelerator actually starts (chain drive motor turns on) and "panic buttons" which prevent accelerator startup must be positioned so that they can be easily reached from any location in the accelerator room. All of these devices must be "fail-safe" in the sense that failure of any safety device prevents accelerator startup. Furthermore, panic buttons must require manual reset (can not be the momentary contact type) before the accelerator can be restarted.

In the case of interlocks and panic buttons, they should be wired in series with the coil of a critical relay, such that if any of the switches is open (indicating an open door or pressed panic button) the relay will not activate. These circuits should not involve any active logic elements, unless these elements include automatic fault detection that will detect any error in circuit function and prevent startup. Warning lights should also be fail-safe, in the sense that if any of them does not light, accelerator operation will be prevented.

Because the maximum dose rate in the tunnel is such that radiation protection limits for radiation workers will not be exceeded in a short time, administrative controls, warning devices and access gates provide sufficient access control. Both ends of the tunnel should be posted with warning signs and flashing lights should be placed near the entrance and periodically through the length of the tunnel. The warning system, coupled with video surveillance of the area and gates to prevent individuals from easily walking through the area should be adequate. Any interlock which stops the progress of the container through the tunnel should also stop radiation generation.

7.5 Shielding

Shielding walls of the RGD area should be designed to maintain the dose rate outside the wall below a value required to prevent individual doses to personnel outside the RGD area from exceeding 0.25 mSv per year when the high voltage is on, and doses to personnel outside the restricted area from exceeding 0.25 mSv per year when neutrons are being produced. Furthermore, shielding design should carefully consider opportunities to further reduce dose rates at acceptable costs (ALARA). For example, it is often possible to place generally unoccupied spaces such as storage rooms or mechanical equipment spaces between RGD rooms and frequently occupied spaces such as offices or waiting rooms. If space is available, open spaces can be left between the exterior of shielding and the structures housing frequently occupied spaces.

7.6 Emergency Response

The Radiation Safety Plan for a radiation-generating device needs to include the appropriate responses for radiological emergencies such as accidental exposures or accidental release of radioactive material (rupture of a deuterium target containing significant amounts of tritium), and also for all other types of emergencies that may be exacerbated by the radiation generated. For example, response to a fire should include shutdown of radiation generation, but since the fire may involve the control console, alternative ways of turning off the equipment (for example the main electrical service) from remote locations should be covered in the plan. Furthermore, if there is a chance that fire or natural disaster might disperse activation products in quantities that could produce significant doses, methods for minimizing such releases should be explained in the plan.

7.7 Training

The training of all levels of personnel involved with radiological activities is detailed in NCRP Report 134 (NCRP, 2000). The level of training should be appropriate to the function of the person in the organization, and to the types of exposures they may encounter during their work. The appropriate training of persons with management responsibility is particularly critical.

For the purposes of radiation safety, the primary objectives of training are: (1) to provide awareness of radiation risks; (2) to provide enough radiation physics to understand that facility changes can result in changes in radiation exposure; (3) to convey basic information on radiation protection regulations; and (4) to instill a sense of individual responsibility for radiation safety. Many organizations, particularly the National Laboratories of the Department of Energy, have developed radiation safety training materials for all levels of employees. General employee radiation training is often available electronically. It may be possible to take advantage of some of the existing resources at much less cost than required to develop them de novo.

8. Potential effects on Nuclear Weapons in Scanned Cargo

The potential effects of PFNA inspection on weapons concealed in containers are an additional concern. The low doses of radiation delivered by the PFNA system result in only a fraction of a degree increase in temperature of the scanned materials, so thermal effects cannot cause detonation of chemical explosives. Similarly, the charge generated by ionization of air surrounding electric conductors is small, and tends to neutralize accumulated charges, so the probability of generating an electrostatic discharge which would detonate an explosive or trigger an electronic circuit is vanishingly small.

Nuclear weapons might be assumed to be a special case because neutrons play a special role in fission reactions. However, the mechanism underlying the detonation of all nuclear devices is the conversion of a sub-critical assembly of fissionable material into a critical assembly. The maximum neutron fluence that can be produced by the PFNA accelerator is minuscule compared to the fluence needed to effect such a transformation. Thus, neutron irradiation from the PFNA system cannot cause a nuclear weapon to detonate by direct action.

At lower neutron fluence than discussed above, neutrons will cause some atoms of the weapon to fission, and there will be a "neutron multiplier" action. In extreme cases, this neutron multiplier response can release enough energy to produce mechanical damage in the weapon, which renders it inactive. However, inactivation of weapons depends strongly on the specific weapon design, and generally requires in the range of 10^{16} to 10^{18} neutrons incident on the device is less than one second. This range is at least 100,000 times more the number of neutrons produced by the PFNA system per second.

9. Conclusions

The following conclusions underlie the radiation protection advice provided in this Presidential Report on the PFNA system and the facility in which it is located.

9.1 Characteristics of the PFNA System

1. The spectrum of gamma rays received at a specific time after the neutron pulse from the PFNA system gives the atomic composition at the corresponding point in the cargo container. Because the number of gamma rays detected determines the spatial resolution, the more efficient the gamma-ray detector is, the lower the neutron fluence required to give a specified resolution.
2. The dose to the cargo contents, and the activity (in becquerels) of activation products in scanned containers, is directly related to the magnitude of the neutron fluence, assuming that the neutron spectrum is constant.
3. Most of the neutrons will not interact in the scanned container. This means that extensive shielding surrounding the scanning system is necessary.

4. This shielding, plus surrounding controlled access areas, is designed to minimize exposure to workers and the public to direct radiation from the neutron source or the gamma rays produced by neutron interactions.
5. The interaction of two deuterium ions (that generates the neutrons in the beam) also produces one tritium atom for every neutron produced. Also, when the neutron is finally absorbed in shielding or other material it often results in the production of an activation product (*i.e.,* a radionuclide). Some of the activation products are formed in the contents of the scanned containers, but the dose that they would produce either by contact with or use of the contents (such as pharmaceuticals or medical devices) or ingestion of foodstuff is negligible.

9.2 Radiation Protection Considerations

1. The objectives of the NCRP radiation protection principles are to prevent the occurrence of clinically significant radiation-induced deterministic effects[4] and to limit the risk of stochastic effects (*i.e.,* cancer and genetic effects) to a reasonable level in relation to societal needs, values, benefits gained, and economic factors. These objectives are achieved by ensuring that all exposures are "as low as reasonably achievable" (ALARA) in relation to benefits to be obtained and by applying dose limits for controlling occupational and general public exposures.
2. For radiation protection purposes, NCRP assumes: (a) that the risk for stochastic effects is proportional to dose without threshold throughout the range of dose and dose rates of

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[4] Deterministic effects do not occur at the radiation levels encountered during the normal operation of the PFNA system.

importance in routine radiation protection, and (b) that the risk accumulates linearly with dose.

3. NCRP and radiation protection specialists can provide estimates of radiation levels and accompanying radiation risks that are integral to making a societal decision, but cannot render an opinion of the net benefit or cost based on the radiation aspects alone. This justification of the use of a radiation source is the responsibility of the implementing U.S. Government Agency.
4. The Customs Service has chosen to operate the inspection facilities under its control in a way that limits the annual effective dose to operators, inspectors and other employees to the same level as the general public (*i.e.,* 0.25 mSv). The System Safety Specifications need to establish dose rate limits that ensure that this annual effective dose limit will not be exceeded considering appropriate work load and occupancy factors. For the initial 6-month test period of the PFNA system, the Custom Service assumes a workload of 500 hours per year and full time occupancy of the controlled area. The dose rate at the boundary that would meet the condition of 0.25 mSv per year would be 0.5 μSv h^{-1}. However, It should be noted that routine, year round, use of a PFNA system would result in limiting the dose rate in the controlled area to about 0.12 μSv h^{-1}.
5. The level of access control for a given area needs to be adjusted for the level of risk within the area, and the expected population surrounding the area. In the case of the PFNA system, the major radiation source is the radiation-generating device (*i.e.,* the accelerator).
6. In the case of the PFNA system, the "tunnel" presents a special access control issue. The central portion of the tunnel is a radiation area when the accelerator is on.

7. The accelerator and the neutron production target of the PFNA system are capable of producing relatively high dose rates within the radiation-generating device area (accelerator room), which is secured by shielding walls, secure fencing, and locked doors or gates. The region where vehicles are scanned, and where detectors are located (tunnel), is also a RGD area, but with much lower maximum exposure rate (resulting from the distance from the neutron production target source).
8. Because the maximum dose rate in the tunnel is such that radiation protection limits for radiation workers will not be exceeded in a short time, administrative controls, warning devices and access gates provide sufficient access control.

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