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LETTER REPORT ON RADIATION PROTECTION ADVICE FOR PULSED FAST NEUTRON ANALYSIS SYSTEM USED IN SECURITY SURVEILLANCE

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Preface

This letter 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 PFNA system is being evaluated as a security surveillance device. Specific questions on which NCRP's advice was requested are the following.

a) What is the appropriate dose limit for persons inadvertently irradiated by the PFNA system?
b) What are the proper methods to determine the dose received?
c) In the opinion of NCRP, can 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.

This letter report addresses these three questions.

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Thomas S. Tenforde
President

Radiation Protection Advice for Pulsed Fast Neutron Analysis System Used in Security Surveillance

1. Summary

The National Council on Radiation Protection and Measurements (NCRP) has been asked by the U.S. Department of Defense (DoD) to provide radiation protection advice on a pulsed fast neutron analysis (PFNA) system that may be used to do security surveillance on trucks transiting United States Ports of Entry. 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
- to 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.

1.1 The Appropriate Dose Limit

NCRP 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. NCRP 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 principles of keeping exposures "as low as reasonably achievable" (ALARA).

In forming this recommendation, NCRP 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 Determination of Effective Dose

The radiation protection quantity of interest for an exposed individual is the effective dose (*E*). The method for obtaining values of *E* is described in Sections 4.1 and 4.2, and is derived from previous recommendations (ICRP, 1991; ICRU, 1993; NCRP, 1993; NCRP, 2000). The effective dose (*E*) can be evaluated for a series of likely PFNA system scenarios

[1] Throughout this Letter Report, 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).

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

NCRP 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.

2. Introduction

The U.S. Department of Defense (DoD) has asked the National Council on Radiation Protection and Measurements (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 has been 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.

This Letter Report addresses each of these requests.

3. The Appropriate Dose Limit

3.1 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, 2000); and detailed recommendations have been made on limiting radiation exposure to the skin (NCRP, 1999; NCRP, 2001a).

For workers, the system of dose limitation is based on constraining 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 4 percent Sv^{-1} (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 mSv" (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 5 percent Sv^{-1} (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 each source of exposure be constrained to 0.25 mSv y^{-1} unless it is known that there are no other sources of exposure. This limit 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 limit 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).

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 fetus potentially exposed in the occupational environment, NCRP recommended an occupational equivalent dose rate limit of 0.5 mSv per month to the fetus or a cumulative dose of 4.5 mSv during the entire period of gestation. The limitation on the equivalent dose rate to the fetus was developed in consideration of the two-month period (8^{th} to 15^{th} 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 the 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.

3.2 Recommendations for the Pulsed Fast Neutron Analysis System

NCRP 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 is allowed for 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 (or 0.025 percent for the 5 mSv limit) percent 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, NCRP 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. NCRP 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, with economic and social issues taken into account (NCRP, 1993). NCRP 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.

4. Determination of Effective Dose

4.1 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 risk due to 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. 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 sum pf the products of H_T and w_T yields the quantity effective dose (E). The w_T values are the

same for all radiations. The dosimetric approach and the specific formulas showing how these modifying factors are applied for this more complicated case are given later in this Section.

The quantity used to express the radiation level received by an exposed individual is the effective dose (E) (NCRP, 1993). 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 these 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). 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 radiation spectra at each selected point 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 [$Q(L)$] relationship (ICRP, 1991; ICRU, 1993; 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.

If a simulated person with simulated organs and tissues is located inside the container, the resulting organ dose equivalent ($\overline{H}_T$) (ICRU, 1993; NCRP, 2002) to each internal organ or tissue of the individual can be calculated utilizing the $Q(L)$ relationship, and the dose-limit quantity E can be estimated. The evaluation of $\overline{H}_T$ can be performed with computerized anthropomorphic models in conjunction with an appropriate radiation transport code. In this way, a value of a conversion coefficient (*i.e.*, E divided by a unit 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 likely range of radiation environments at various locations 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 E values 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, 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 incident on the cargo container for fixed neutron beam conditions.

NCRP expects to further develop the methods given above in a follow-up report.

4.2 Dosimetry Formulation

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

The public dose limits for delayed stochastic effects are expressed in E, where:

$$E = \sum_{T} w_T H_T \ , \tag{4.1}$$

H_T is the equivalent dose and w_T is the tissue weighting factor (ICRP, 1991; NCRP, 1993).

The equivalent dose (H_T) for stochastic effects is usually obtained as:

$$H_T = \sum_{R} w_R D_{T,R} \ , \tag{4.2}$$

where D_T is the mean absorbed dose in an organ or tissue T (*i.e.,* $D_{T,R}$ for a given type of radiation R), and w_R is a nominal radiation weighting factor used in most radiation protection situations that accounts for the biological effectiveness of radiation type R. The radiation weighting factor (w_R) applies to the radiation type incident on the body.

For the complex radiation spectra of photons and neutrons that result from the PFNA system inside the cargo container, the practice for the radiation transport approach is to obtain point values of D and H [*i.e.*, using D and the appropriate $Q(L)$ relationship, rather than w_R, to obtain H]. Therefore, NCRP recommends that the quantity H and the

currently recommended $Q(L)$ relationship be used to evaluate the complex radiation distribution inside the body resulting from the PFNA scan.

The dose equivalent (H) is defined at a point (ICRU, 1993) and also can be evaluated based on appropriate measurements. The quantity H is given by:

$$H = \int_L Q(L)\, D(L)\, \mathrm{d}L, \tag{4.3}$$

where $Q(L)$ is the quality factor for radiation with linear energy transfer L and $D(L)$ is the spectral distribution in terms of L of the absorbed dose at the point.

When an average value over an organ or tissue is required, it can be obtained by means of computational models or measurements using anthropomorphic phantoms and defined sites for organs or tissues. In this case, the point quantity H at multiple locations in an organ or tissue can be used to obtain the organ dose equivalent $\left(\overline{H}_{\mathrm{T}}\right)$ (ICRU, 1993). The quantity $\overline{H}_{\mathrm{T}}$ was adopted by NCRP as an acceptable approximation for H_{T}(NCRP, 2000).

Therefore, in general terms:

$$\overline{H}_{\mathrm{T}} = \frac{1}{M_{\mathrm{T}}} \int_{\mathrm{x}} \int_{\mathrm{L}} Q(L)\, D(L)\, \mathrm{d}L\, \mathrm{D}(x)\, \mathrm{d}x, \tag{4.4}$$

where there is a second integration over the points x in tissue T with tissue density $D(x)$ and

total mass M_T. The special name of the unit for the quantities E, H, H_T and $\overline{H}_T$ is sievert (Sv).

The quality factor relationship as a function of linear energy transfer [$Q(L)$] is given in ICRP (1991), ICRU (1993), and NCRP (1993), where:

$$\begin{aligned} Q(L) &= 1 && \text{for } L < 10 \text{ keV } :\text{m}^{-1} \\ Q(L) &= 0.32\,L - 2.2 && \text{for } L = 10 \text{ to } 100 \text{ keV } :\text{m}^{-1} \\ Q(L) &= 300\,L^{-1/2} && \text{for } L > 100 \text{ keV } :\text{m}^{-1} \end{aligned} \tag{4.5}$$

For example, for a value of L equal to 20 keV $:\text{m}^{-1}$, the value of $Q(L)$ would be 4.2.

Since $\overline{H}_T$ is an acceptable approximation for H_T, E can be obtained from:

$$E = \sum_T w_T H_T \approx \sum_T w_T \overline{H}_T \tag{4.6}$$

5. Neutron Activation in Pharmaceuticals and Medical Devices

5.1 Approach to Analysis of Neutron Activation Products

Since the application of the PFNA system is based on the interaction of neutrons with the nuclei of the atoms being inspected, it is unavoidable that some atoms will be converted to radioactive nuclides. When ingested, or kept in close proximity to the consumer, these activation products deliver a low value of absorbed dose (D) to the individual. NCRP has been asked to "provide an opinion as to whether the level of activation that the PFNA system imparts to pharmaceuticals and medical devices would likely result in unsafe radiation exposure in or to persons consuming or using these items." Other items, including shipments of food and the transportation equipment (truck) will also be irradiated, but are not the subject of this analysis. A detailed evaluation of D delivered to the maximally exposed individual through consumption or use of activated products would be complex and time consuming, requiring extensive neutron transport calculations as well as detailed evaluation of intake and retention of specific elements in pharmaceuticals and medical devices. However, an informed opinion of the significance of the D values received from activation products can be developed by considering those component elements of pharmaceuticals and medical devices that are likely to produce the highest values for D to consumers, and evaluating the conservatively safe estimate of D to organs and tissues from those elements against the established E limit for the general public.

The factors that determine which elements result in the highest values for D include the neutron activation cross sections for fast and thermal neutrons, the amount of D delivered per transformation of the activation product, the concentration of the element in pharmaceuticals and devices, the amount of the pharmaceutical consumed, how long the activation product is retained in the body, and the half-life of the radionuclide. For example, a product with a half-life of only a few minutes will not produce an exposure of concern for consumers because it will have decayed to a very low level before it can travel to a distributor and be delivered to a customer. Similarly, a radionuclide that has a long half-life but is produced by irradiation of an element that occurs only at very low concentrations will not produce significant values for D.

5.2 Neutron Activation Products for the PFNA System

Tables 1 and 2 list the significant thermal and fast neutron activation products of elements with atomic number between 1 and 60, plus gold, platinum, iridium and bismuth, high-Z elements that occur in pharmaceuticals and medical devices. For fast neutron activation, a narrow neutron energy distribution, with a peak at 8.5 MeV and a total fluence of 6.4×10^5 neutrons cm^{-2} was assumed. This is the specified neutron fluence at the surface of a container scanned by the PFNA System. This approximation for the fluence is expected to give activation levels to within a factor of two even though it neglects the fact that some neutrons will scatter as they penetrate the container, reducing the total fluence with depth, and introducing some lower energy neutrons. The approximation was used because a detailed evaluation of the neutron spectrum as a function of position in the container would require extensive, time-consuming calculations that could be justified only if there were a real chance that a significant exposure might be missed as a result of using

TABLE 1—*Absorbed Dose from activation products uniformly distributed.*[1]

Target Element[2]	Reaction[3]	Half-Life ($T_{½}$ in hours)	Fast Neutrons		Thermal Neutrons	
			Activity[4] (Bq mg^{-1})	Absorbed Dose Rate[5] (mGy h^{-1} per wppm[6])	Activity[4] (Bq mg^{-1})	Absorbed Dose Rate[5] (mGy h^{-1} per wppm[6])
Lithium	$^{6}Li(n,")^{3}H$	1.08×10^{5}	7.15×10^{-8}	2.34×10^{-16}	9.48×10^{-5}	3.10×10^{-13}
Sodium	$^{23}Na(n,()^{24}Na$	1.50×10^{1}	1.21×10^{-8}	3.27×10^{-14}	1.01×10^{-4}	8.94×10^{-11}
Magnesium	$^{24}Mg(n,p)^{24}Na$	1.50×10^{1}	5.87×10^{-6}	1.58×10^{-11}		
Aluminum	$^{27}Al(n,")^{24}Na$	1.50×10^{1}	2.87×10^{-6}	7.70×10^{-12}		
Phosphorus	$^{31}P(n,p)^{31}Si$	2.63	2.22×10^{-7}	7.61×10^{-15}		
Chlorine	$^{35}Cl(n,p)^{35}S$	2.09×10^{3}	7.85×10^{-8}	2.21×10^{-15}	2.35×10^{-7}	6.58×10^{-15}
Potassium	$^{41}K(n,()^{42}K$	1.24×10^{1}	5.38×10^{-9}	5.28×10^{-16}	3.93×10^{-6}	3.85×10^{-12}
Scandium	$^{45}Sc(n,()^{46}Sc$	2.01×10^{3}	6.82×10^{-10}	8.32×10^{-16}	1.95×10^{-5}	2.22×10^{-11}
Titanium	$^{46}Ti(n,p)^{46}Sc$	2.01×10^{3}	1.34×10^{-8}	1.63×10^{-14}		
	$^{47}Ti(n,p)^{47}Sc$	8.21×10^{1}	1.09×10^{-7}	1.71×10^{-14}		
	$^{48}Ti(n,p)^{48}Sc$	4.37×10^{1}	2.62×10^{-7}	5.37×10^{-13}		
Manganese	$^{55}Mn(n,()^{56}Mn$	2.58	6.00×10^{-10}	8.71×10^{-16}	9.76×10^{-6}	1.42×10^{-11}
Iron	$^{54}Fe(n,p)^{54}Mn$	7.50×10^{3}	4.90×10^{-9}	2.37×10^{-15}		
	$^{56}Fe(n,p)^{56}Mn$	2.58	3.38×10^{-8}	4.92×10^{-14}		
Cobalt	$^{59}Co(n,()^{60}Co$	4.62×10^{4}	2.30×10^{-11}	3.43×10^{-17}	9.00×10^{-7}	1.35×10^{-12}
	$^{59}Co(n,p)^{59}Fe$	1.07×10^{3}	2.87×10^{-8}	2.14×10^{-14}		
	$^{59}Co(n,")^{56}Mn$	2.58	6.53×10^{-9}	9.47×10^{-15}		
Nickel	$^{58}Ni(n,p)^{58}Co$	1.70×10^{3}	3.02×10^{-7}	1.49×10^{-13}		
Copper	$^{63}Cu(n,()^{64}Cu$	1.27×10^{1}	6.85×10^{-5}	2.03×10^{-15}	5.50×10^{-8}	2.51×10^{-12}
	$^{63}Cu(n,")^{60}Co$	4.62×10^{4}	3.50×10^{-10}	5.24×10^{-16}		
Zinc	$^{64}Zn(n,p)^{64}Cu$	1.27×10^{1}	2.37×10^{-6}	8.69×10^{-14}		
Arsenic	$^{75}As(n,()^{76}As$	2.63×10^{1}	3.57×10^{-8}	3.06×10^{-14}	7.62×10^{-5}	6.55×10^{-11}

Table 1. (cont.)

Bromine	$^{81}Br(n,()^{82}Br$	3.53×10^{1}	3.24×10^{-8}	5.81×10^{-14}	2.15×10^{-5}	3.44×10^{-11}
Rubidium	$^{85}Rb(n,()^{86}Rb$	4.48×10^{2}	4.62×10^{-9}	2.03×10^{-15}	5.50×10^{-7}	2.40×10^{-13}
Molybdenum	$^{98}Mo(n,()^{99}Mo$	6.60×10^{1}	3.73×10^{-9}	1.18×10^{-15}	2.48×10^{-7}	7.83×10^{-14}
Silver	$^{109}Ag(n,()^{110m}Ag$	6.05×10^{3}	3.68×10^{-10}	5.93×10^{-16}	2.00×10^{-7}	3.21×10^{-13}
Antimony	$^{123}Sb(n($	^{124}Sb	1.44×10^{3}	3.43×10^{-10}	4.42×10^{-16}	6.83×10^{-7}	8.79×10^{-13}
Lutetium	$^{176}Lu(n,()^{177}Lu$	1.61×10^{2}	4.02×10^{-10}	4.20×10^{-17}	2.00×10^{-4}	2.08×10^{-11}
Tantalum	$^{181}Ta(n,()^{182}Ta$	2.76×10^{3}	1.21×10^{-9}	1.02×10^{-15}	2.77×10^{-6}	2.33×10^{-12}
Tungsten	$^{186}W(n,()^{187}W$	2.39×10^{1}	2.88×10^{-6}	1.26×10^{-15}	8.00×10^{-5}	3.50×10^{-11}
Iridium	$^{193}Ir(n,()^{194}Ir$	1.93×10^{1}	5.31×10^{-9}	2.68×10^{-15}	5.63×10^{-4}	2.84×10^{-10}
Platinum	$^{198}Pt(n,()^{199}Pt$	5.13×10^{-1}	3.56×10^{-19}	1.92×10^{-27}	1.69×10^{-18}	9.13×10^{-25}
Gold	$^{197}Au(n,()^{198}Au$	6.47×10^{1}	2.62×10^{-9}	1.11×10^{-15}	3.95×10^{-4}	1.67×10^{-10}
Bismuth	$^{209}Bi(n,()^{210}Bi$	1.20×10^{2}	1.28×10^{-9}	6.37×10^{-16}	6.18×10^{-8}	3.06×10^{-14}

[1]Activation calculated based on 6.42×10^{5} neutrons cm^{-2} (fast, 8.5 MeV) or 6.42×10^{5} neutrons cm^{-2} (thermal plus 1/E neutron spectrum).
[2] Elements listed in order of atomic number.
[3] Reactions are given in the format "target nuclide (particle in, particle out) product nuclide." The symbols used are n for neutron, p for proton, " for alpha particle, and (for gamma ray.
[4] Activity calculated at 24 h post PFNA. Activity at other times can be calculated using $N/N_0 = e^{-.693t/T_{1/2}}$, where t is the elapsed time and $T_{½}$ is the half-life in hours for radioactive decay of the product radionuclide. No entry indicates no significant cross section for this reaction.
[5] Absorbed dose rate calculated at 24 h post PFNA. Absorbed dose rate at other times is proportional to the activity at those times. No entry indicates no significant absorbed dose due to this reaction.
[6] wppm is weight part per million.

TABLE 2—*Absorbed Dose from activation products in localized sources.*[1]

Target Element[2]	Reaction[3]	Half-Life ($T_{½}$ in hours)	Fast Neutrons		Thermal Neutrons	
			Activity[4] (Bq mg^{-1})	Absorbed Dose Rate[5] (mGy h^{-1} mg^{-1})	Activity[4] (Bq mg^{-1})	Absorbed Dose Rate[5] (mGy h^{-1} mg^{-1})
Magnesium	$^{24}Mg(n,p)^{24}Na$	1.50×10^{1}	5.87×10^{-6}	1.34×10^{-7}		
Aluminum	$^{27}Al(n,")^{24}Na$	1.50×10^{1}	2.87×10^{-6}	6.58×10^{-13}		
Scandium	$^{45}Sc(n,()^{46}Sc$	2.01×10^{3}	6.82×10^{-10}	7.60×10^{-17}	1.95×10^{-5}	2.18×10^{-12}
Titanium	$^{46}Ti(n,p)^{46}Sc$	2.01×10^{3}	1.34×10^{-8}	1.48×10^{-15}		
	$^{47}Ti(n,p)^{47}Sc$	8.21×10^{1}	1.09×10^{-7}	7.08×10^{-16}		
	$^{48}Ti(n,p)^{48}Sc$	4.37×10^{1}	2.62×10^{-7}	4.87×10^{-14}		
Manganese	$^{55}Mn(n,()^{56}Mn$	2.58	6.00×10^{-10}	5.89×10^{-17}	9.76×10^{-6}	9.57×10^{-13}
Chromium	$^{50}Cr(n,()^{51}Cr$	6.65×10^{2}	6.62×10^{-11}	1.16×10^{-19}	1.29×10^{-6}	2.25×10^{-15}
Iron	$^{54}Fe(n,p)^{54}Mn$	7.50×10^{3}	4.90×10^{-9}	2.27×10^{-16}		
	$^{56}Fe(n,p)^{56}Mn$	2.58	3.38×10^{-8}	3.33×10^{-15}		
	$^{58}Fe(n,()^{58}Fe$	1.07×10^{3}	3.30×10^{-12}	2.17×10^{-19}	3.62×10^{-9}	2.38×10^{-16}
Cobalt	$^{59}Co(n,()^{60}Co$	4.62×10^{4}	2.30×10^{-11}	3.19×10^{-18}	9.00×10^{-7}	1.25×10^{-13}
	$^{59}Co(n,p)^{59}Fe$	1.07×10^{3}	2.87×10^{-8}	1.89×10^{-15}		
	$^{59}Co(n,")^{56}Mn$	2.58	6.53×10^{-9}	6.43×10^{-16}		
Nickel	$^{58}Ni(n,p)^{58}Co$	1.70×10^{3}	3.02×10^{-7}	1.38×10^{-14}		
Copper	$^{63}Cu(n,()^{64}Cu$	1.27×10^{1}	6.85×10^{-5}	5.93×10^{-16}	5.50×10^{-8}	7.38×10^{-13}
	$^{63}Cu(n,")^{60}Co$	4.62×10^{4}	3.50×10^{-10}	4.87×10^{-17}		
Zinc	$^{64}Zn(n,p)^{64}Cu$	1.27×10^{1}	2.37×10^{-6}	2.55×10^{-14}		
Arsenic	$^{75}As(n,()^{76}As$	2.63×10^{1}	3.57×10^{-8}	7.38×10^{-16}	7.62×10^{-5}	1.58×10^{-12}
Rubidium	$^{85}Rb(n,()^{86}Rb$	4.48×10^{2}	4.62×10^{-9}	2.42×10^{-17}	5.50×10^{-7}	2.88×10^{-15}
Molybdenum	$^{98}Mo(n,()^{99}Mo$	6.60×10^{1}	3.73×10^{-9}	5.57×10^{-17}	2.48×10^{-7}	3.69×10^{-15}
Silver	$^{109}Ag(n,()^{110m}Ag$	6.05×10^{3}	3.68×10^{-10}	4.92×10^{-17}	2.00×10^{-7}	2.67×10^{-14}

Table 2. (cont.)

Indium	$^{115}In(n,()^{116}In$	4.49	1.37×10^{-14}	1.86×10^{-21}	9.70×10^{-10}	1.32×10^{-16}
	$^{115}In(n,n')^{115m}In$	4.49	9.92×10^{-7}	8.34×10^{-15}		
Antimony	$^{123}Sb(n,()^{124}Sb$	1.44×10^{3}	3.43×10^{-10}	3.46×10^{-17}	6.83×10^{-7}	6.88×10^{-14}
Lutetium	$^{176}Lu(n,()^{177}Lu$	1.61×10^{2}	4.02×10^{-10}	3.62×10^{-19}	2.00×10^{-4}	1.80×10^{-13}
Tantalum	$^{181}Ta(n,()^{182}Ta$	2.76×10^{3}	1.21×10^{-9}	7.49×10^{-17}	2.77×10^{-6}	1.72×10^{-13}
Tungsten	$^{186}W(n,()^{187}W$	2.39×10^{1}	2.88×10^{-9}	8.08×10^{-17}	8.00×10^{-5}	2.24×10^{-12}
Iridium	$^{193}Ir(n,()^{194}Ir$	1.93×10^{1}			5.63×10^{-4}	1.06×10^{-11}
Gold	$^{197}Au(n,()^{198}Au$	6.47×10^{1}	2.62×10^{-9}	5.86×10^{-17}	3.95×10^{-4}	8.85×10^{-12}

[1]Activation calculated based on 6.42×10^{5} neutrons cm^{-2} (fast, 8.5 MeV) or 6.42×10^{5} neutrons cm^{-2} (thermal plus 1/E neutron spectrum).
[2] Elements listed in order of atomic number.
[3] Reactions are given in the format "target nuclide (particle in, particle out) product nuclide." The symbols used are n for neutron, p for proton, " for alpha particle, and (for gamma ray.
[4] Activity calculated at 24 h post PFNA. Activity at other times can be calculated using $N/N_0 = e^{-.693t/T_{1/2}}$, where t is the elapsed time in hours and $T_{½}$ is the half-life in hours for radioactive decay of the product radionuclide. No entry indicates no significant cross section for this reaction.
[5]Absorbed dose rate calculated at 5 cm from a point source, 24 h post PFNA. Absorbed dose rate at other times is proportional to the activity at those times. No entry indicates no significant absorbed dose due to this reaction.

the approximation. For many of the fast neutron activation reactions that produce the largest values for D, the activation cross section has a very broad peak extending from about 5 to 14 MeV. For higher-Z elements the threshold energy tends to increase so that the lower energy neutrons become an insignificant contributor to the absorbed dose. It is estimated that the calculated activation rates for 8.5 MeV neutrons are within a factor of two of the activation rates produced by the actual energy distributions of the neutrons at various locations in the container. If the values for D that result from this monoenergetic approximation are very small compared to D values of concern, a more detailed analysis using the actual neutron energy distribution is unnecessary.

For thermal neutron activation, a Maxwellian distribution with a 1/E tail extending up to about 0.1 MeV was assumed.[3] Again, a neutron fluence of 6.4×10^5 was assumed, equivalent to assuming that every fast neutron was reduced to thermal energy in the container, or was scattered back into it after being thermalized in the surrounding shielding. This energy distribution provides a reasonable representation of the spectrum between thermal and fast neutrons (*i.e.*, epithermal neutrons), although the fluence is probably a significant overestimate since many of the low-energy neutrons will not interact within the scanned container and not contribute to activation.

[3] Thermal neutrons have an energy distribution that is dependent on the thermal motion of the atoms making up their environment. The shape of this distribution is Maxwellian, and the most probable energy at 20 ºC is 0.025 eV. As fast neutrons slow down their rate of energy loss decreases, so the energy distribution in shielding material contains many thermal neutrons but extends to higher energies, with the number per unit energy decreasing in proportion to 1/E, where E is the energy of the neutron.

The activity (transformations per second) (becquerel) of each product is calculated per unit mass of the naturally occurring target element using a computer algorithm (Greenwood, 2002).[4] For example, five stable isotopes of titanium occur naturally, but only three of them have activation products. The calculated activities and absorbed dose rates for each of the activation products (^{46}Sc, ^{47}Sc, and ^{48}Sc) are per milligram of the natural mixture of all five isotopes of titanium, that is, per milligram of total titanium in the PFNA-scanned material.

Table 1 lists target elements that might be included in pharmaceuticals or whose activation products might become uniformly distributed throughout the body of the consumer. In this uniform, whole-body irradiation situation where the quality factor of the radiation is one (gamma rays and beta particles) the equivalent dose for each organ or tissue is numerically equal to the absorbed dose (D). To estimate the values for D that these products would produce, D was calculated based on the assumption that one weight part per million (wppm) of the target element was uniformly distributed in an infinite, homogeneous medium. To avoid unrealistic values for D that might be calculated for very short-lived radionuclides, D was determined at 24 h after PFNA scanning. The result is listed separately for fast neutron activation and thermal neutron activation. When these data were used to calculate D to an individual, all of the radionuclide remaining at 24 h postirradiation was assumed to contribute to the value of D; that is, the material was assumed to be ingested and to remain in the body permanently. Because the recommended

[4] Greenwood, L. (2002). Personal communication (Battelle Pacific Northwest National Laboratory, Richland, Washington).

dosage[5] of over the-counter medications and dietary supplements are not normally adjusted for body weight of adults, the concentration will be highest in the person with minimum mass. For these calculations, a mass of 50 kg was assumed. The recommended dosage of most medications is reduced for children, resulting in similar concentrations of activation products in children and adults.

Table 2 includes target elements that may be components of medical devices that would be implanted in the body and expose only a limited tissue volume to significant absorbed dose rates. For example, cobalt and manganese may be components of stainless steel fasteners used in orthopedic reconstruction, copper and gold are common components of electronic devices such as pacemakers, and titanium is often used in artificial joints. These materials are typically inert in the body, or are packaged in inert materials so that they will not become distributed. Such devices can be treated as localized sources and the absorbed dose rate is given at 5 cm from the source, per milligram of target element.

From these lists, a few problematic reactions have been identified that lead to radionuclides with long enough half-life to make it to the consumer, combined with high enough cross section or high enough concentration in products to produce significant absorbed doses. These include $^{24}Mg(n,p)^{24}Na$, $^{23}Na(n,\gamma)^{24}Na$, $^{64}Zn(n,p)^{64}Cu$, and $^{59}Co(n,\gamma)^{60}Co$ (the reaction format and symbols are defined in Table 1). These reactions were identified primarily on the basis of their relatively high product of decay energy and activity per gram

[5] The word “dosage” is used to describe the quantity of a pharmaceutical or other material consumed by an individual.

of irradiated target element. The half-life of the product radionuclide and the abundance of the target element in pharmaceuticals were also considered.

5.3 Activation Products in Pharmaceuticals Uniformly Distributed in the Body

In the case of pharmaceuticals, the $^{24}Mg(n,p)^{24}Na$ reaction is likely to produce the highest absorbed dose due to a fast neutron reaction because relatively large amounts of magnesium, as MgOH (milk of magnesia, recommended dosage 2.7 g $d^{-1}$of magnesium), may be consumed. Assuming 10 g of magnesium, the amount ingested would be 200 weight parts per million (wppm) of the body mass. From Table 1, the absorbed dose rate is 1.58×10^{-11} mGy h^{-1} per wppm, and the mean lifetime (1/decay constant) is 21.64 h. Thus, the absorbed dose would be 6.84×10^{-8} mGy. Some other reactions may produce radionuclides with only slightly lower absorbed dose rate per wppm, but they are consumed in much lower quantities, so the absorbed dose is substantially less. Other reactions may produce higher absorbed dose rates per wppm immediately after activation, but the products of these reactions typically have such short half-lives that the absorbed dose delivered is lower.

The highest absorbed dose from a thermal neutron activated product may result from the $^{23}Na(n,\gamma)^{24}Na$ reaction because of the relatively high amounts of sodium that might be consumed. For example, isotonic saline administered intravenously contains 3.45 g L^{-1} of sodium. Assuming treatment with three liters (L), this would contribute approximately 10 g of sodium, or 200 wppm. From Table 1, the absorbed dose rate is 8.94×10^{-11} mGy h^{-1} per wppm, so the total absorbed dose, if the sodium is retained in the body is 3.87×10^{-7} mGy.

Other thermal neutron reactions occur with similar absorbed dose rates per wppm, for example $^{55}Mn(n,\gamma)^{56}Mn$, $^{59}Co(n,\gamma)^{60}Co$, and $^{64}Zn(n,p)^{64}Cu$, but the amounts of these elements consumed are much less. For example, the recommended daily dosage of manganese as a mineral supplement is 2 mg. The absorbed dose from 0.1 g of manganese (50 times the recommended dosage) distributed uniformly throughout the body is 1.06×10^{-10} mGy.

Of course, there will be both thermal and fast neutron activation of sodium and some other elements, but the absorbed dose due to fast neutron activation of sodium is 0.034 percent of the absorbed dose due to thermal activation. For a compound such as NaCl, the contribution from chlorine should also be considered, but it makes an even smaller contribution.

In some situations, the irradiated element and resulting radionuclide may not be uniformly distributed throughout the body. For example, significant quantities of bismuth may be ingested as bismuth subsalicylate, an ingredient in an over the counter digestive remedy. Bismuth probably is retained in the contents of the intestinal tract. The recommended maximum dosage is equal to 2.5 g of bismuth in 48 h, and the weight of the colon is about 1 kg, resulting in a concentration of 2,500 wppm. The resulting absorbed dose is 1.32×10^{-8} mGy if the bismuth is retained until it has all decayed. In this case, the contribution to the effective dose (E) is less because w_T for the colon is 0.12.

All of the absorbed doses calculated for activated soluble products are below 1×10^{-6} mGy. Since the gamma and beta radiations from these radionuclides have a w_R of one, the result is one one-millionth (1/1,000,000) of the recommended limit for E of 1 mSv.

Therefore, these absorbed doses would contribute minimally to the value of E compared to the limit for E for the general public (NCRP, 1993), and need not be considered further.

5.4 Activation Products in Implanted Medical Devices

The significance of activation of implanted medical devices can be evaluated based on the absorbed dose rate at a distance from the device (see Table 2). For example, 1 g of cobalt, perhaps in the form of a stainless steel part used for orthopedic reconstruction, would deliver an absorbed dose of 1.25×10^{-10} mGy h^{-1} at 5 cm. Other elements likely to be included in implanted mechanical and electronic devices, such as gold and iridium, produce higher absorbed doses per gram but would typically occur only in much smaller quantities. Materials such as copper and titanium, which might occur in larger than 1 g quantities, produce lower absorbed dose rates or have shorter half-lives, resulting in lower absorbed doses. In all cases, the absorbed doses to organs and tissues would result in very low effective doses, and are not of further concern.

Thus, the opinion of NCRP is that activation of pharmaceuticals and medical devices by a PFNA system would not result in effective doses of concern to public health.

6. Conclusions

6.1 The Appropriate Dose Limit

The recommended effective dose (E) limit for inadvertent exposure of people from the PFNA system is 1 mSv, but may be raised to 5 mSv, if necessary, to achieve National Security objectives. In addition, the effective dose should be kept ALARA below the limit, considering inspection requirements. Any individual that is exposed by the PFNA system should be fully informed of the radiation exposure, where practicable.

6.2 Determination of Effective Dose

The value for E delivered by the PFNA system under various irradiation scenarios should be determined by mathematical simulation and confirmed by experimental measurement.

It should be possible to evaluate, prior to the routine use of a PFNA system, the potential unintended values for E to individuals associated with a range of irradiation conditions likely to be encountered during implementation of the PFNA system.

It should be possible to monitor appropriate performance characteristics during routine use of the PFNA system that would enable an adequate estimate of E to an individual, who is actually exposed, to be made using the data obtained for the range of irradiation conditions noted.

A more detailed description of the dose assessment approach (including procedures and measurements) outlined in this Letter Report requires further evaluation, in order to provide more specific technical advice on how to implement the dose assessment approach noted above.

6.3 Neutron Activation in Pharmaceuticals and Medical Devices

Analysis of neutron activation of the constituent elements in pharmaceuticals and medical equipment shows that it is extremely unlikely that any radiation exposure of concern could be produced by consumption or use of material that had been activated by the PFNA system. The absorbed dose received by people consuming PFNA-irradiated medications or using irradiated medical equipment will result in effective doses several factors of 10 times lower than the effective dose limit for the general public.

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