A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota

MODULE 3

METHODS DERIVATION

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1 Introduction and Basis for the Approach

The Department of Energy (DOE) currently has in place a radiation dose limit of 1 rad/d (10 mGy/d) for the protection of aquatic organisms (DOE Order 5400.5), and has proposed dose limits for both aquatic and terrestrial organisms. These limits are: 1 rad/d (10 mGy/d) for aquatic animals; 1 rad/d (10 mGy/d) for terrestrial plants; and 0.1 rad/d (1 mGy/d) for terrestrial animals. Because the biota protection limits are dose-based, a calculational method is needed to demonstrate compliance. In theory, derived radionuclide concentration limits for environmental media (e.g., Biota Concentration Guides, BCGs, for water, sediment, or soil) provide a relatively straightforward and simple means to do so. However, because of the inherent complexity of environmental systems, and the vast array of biota that can potentially be exposed to any radionuclide contamination level, it was decided that a graded approach to evaluating compliance would be the most appropriate.

The first step in evaluating compliance would be to compare measured environmental concentrations with very conservative (i.e., very restrictive or protective) BCGs in a general screening process. To be useful in general screening, the concentration limits (BCGs) must be set so that real biota exposed to such concentrations are not expected to ever exceed the biota Dose Rate Guidelines. Since the screening limits would be chosen to protect “all biota, everywhere” they would, by their nature be restrictive, and in many circumstances conservative with regards to specific environments. Consequently, the graded approach for evaluating compliance had to allow site users to examine and revise, if appropriate, the screening limits to more realistically reflect the conditions at their site. This approach parallels methods currently used to protect human health from residual levels of radionuclides in the environment (e.g., site-specific conditions can be considered in deriving residual radionuclide concentration levels).

This Module provides detailed descriptions of the dose models, equations, and default parameters used in the graded approach for evaluating doses to biota. Topics presented include: (1) selection of pathways, media, organism types, and target radionuclides; (2) derivation and selection of lumped parameters; (3) derivation of internal and external dose conversion factors; (4) equations and models for calculating dose to biota and deriving BCGs; and (5) default parameters and their sources.

1.1 Pathways, Media Types, and Organism Types Addressed

The Biota Dose Assessment Committee (BDAC) had to consider several factors in developing the general screening methodology. The method had to be simple, defensible, and user-friendly. It also had to have broad applicability - from aquatic animals through terrestrial species. It also had to address radiation dose in small organisms (e.g., mice) and large carnivores (e.g., cougars). The method had to provide a logical and consistent departure point should additional in-depth evaluation of dose be required. Should additional analysis be required, the method had to utilize existing data - either from the technical literature or from

site-specific monitoring - whenever possible. Lastly, the method had to be useful in evaluating the potential impacts of combined media: water, sediment, and soil.

The BDAC's choice of organisms for the methodology evolved from consideration of the existing and proposed radiation dose limits for biota. Biota dose limits had been set for aquatic animals, and were being considered for terrestrial plants and animals. Accordingly, the screening methodology had to accommodate these three general categories. A fourth, riparian animal, was added after recognizing that the riparian pathways of exposure combined aspects of both the terrestrial and aquatic systems.

The pathways of exposure evaluated for each of the four organism types were developed based on consideration of the likelihood of dose occurring through a specific route, or "pathway." Based on the potential pathways of exposure, BCGs were derived for surface water, sediment, and soil. Calculated using conservative assumptions, the BCGs are intended to preclude the relevant biota from being exposed to radiation levels in excess of the relevant existing or recommended biota dose limits.

1.2 Selection of Target Radionuclides

Biota Concentration Guides (BCGs) that are considered to be conservatively protective of non-human biota were derived for twenty-three radionuclides. These BCGs are provided for radionuclide concentrations in water, sediment, and soil. They have been calculated based on limiting the potential radiological dose rate to the most sensitive receptors: aquatic, terrestrial, and riparian animals, and terrestrial plants. These radionuclides (see Module 1, Tables 6.1-6.4) were selected because they are relatively common constituents in past radionuclide releases to the environment from DOE facilities. This list is not meant to imply particular concern for biotic impact from these twenty-three specific radionuclides. Rather, it is a starting point for application of the methodology. The list was developed in consultation with BDAC members, and health physics and radioecological staff at several Federal facilities. It represents a general consensus as to the most prevalent radionuclides in environmental releases.

1.3 Overview of the Technical Approach for Deriving the BCGs

The derivation of BCGs used to demonstrate compliance with the biota dose limits is based on the fact that biota dose is a function of the contaminant concentration in the environment, and is the sum of internal and external contributions. It is possible, given a unit concentration (i.e., 1 Bq kg^{-1}) of a contaminant in a single media (e.g., soil) to estimate the potential dose rate to a receptor from both internal and external exposures (admittedly, several assumptions must be made to do so, and these are described in the following sections). Once the dose rate has been calculated, it can be ratioed to the dose rate limit, and used to back-calculate a concentration of the contaminant in the media that could generate a dose rate at the specified biota dose limit. If multiple contaminated media are present then the dose evaluation can be performed for each, and the results individually ratioed to the standard. This "sum of fractions"

approach is commonly used in evaluating compliance for humans exposed to radionuclides discharged to air, soil and water.

Once the target radionuclides had been selected, external dose coefficients (also called dose conversion factors, DCFs) were developed which relate environmental concentrations of the contaminants in water, sediment and soil to projected organism dose rate. Internal dose coefficients (DCFs) were also developed to estimate dose rate from internally deposited radionuclides.

General Dose Equation and Approach Used to Derive BCGs

$$\text{Limiting Concentration} = \frac{\text{Dose Rate Limit}}{(\text{Internal Dose Rate}) + (\text{External Dose Rate}_{\text{soil/sed.}}) + (\text{External Dose Rate}_{\text{water}})}$$

The limiting concentration in an environmental medium was calculated by first setting a target total dose (e.g., 1 rad/d for aquatic organisms and terrestrial plants, or 0.1 rad/d for riparian and terrestrial animals) and then back-calculating to the medium concentration (i.e., the BCG) necessary to produce the applicable dose from radionuclides in the organism (internal dose), plus the external dose components from radionuclides in the environment (external dose). The denominator of the generic equation may be broken down into the base components of internal and external dose. Internal doses originate from radionuclides inside the organism's body. The internal dose is calculated as the product of the internal radionuclide concentration and the internal dose conversion factor. External doses originate from radionuclides external to the organism and are calculated as the product of the radionuclide concentration in the environmental medium in which the organism resides and an appropriate dose conversion factor.

1.4 Selection of the Most Limiting BCGs for Use in General Screening

As discussed, BCGs were derived for a matrix of radionuclides and media types for each of four organism types. That is, BCGs were derived for twenty-three radionuclides within water, sediment, and soil media for aquatic animal, riparian animal, terrestrial plant, and terrestrial animal organism types. The resulting BCGs from this matrix of radionuclides, media types, and organism types were then reviewed to determine the most limiting (i.e., most conservative or protective) values that could be summarized in two tables for the general screening phase of the graded approach: one for aquatic systems and one for terrestrial systems. The logic flow for selecting the BCG values for use in the general screening phase of the graded approach is illustrated in Figure 1.1.

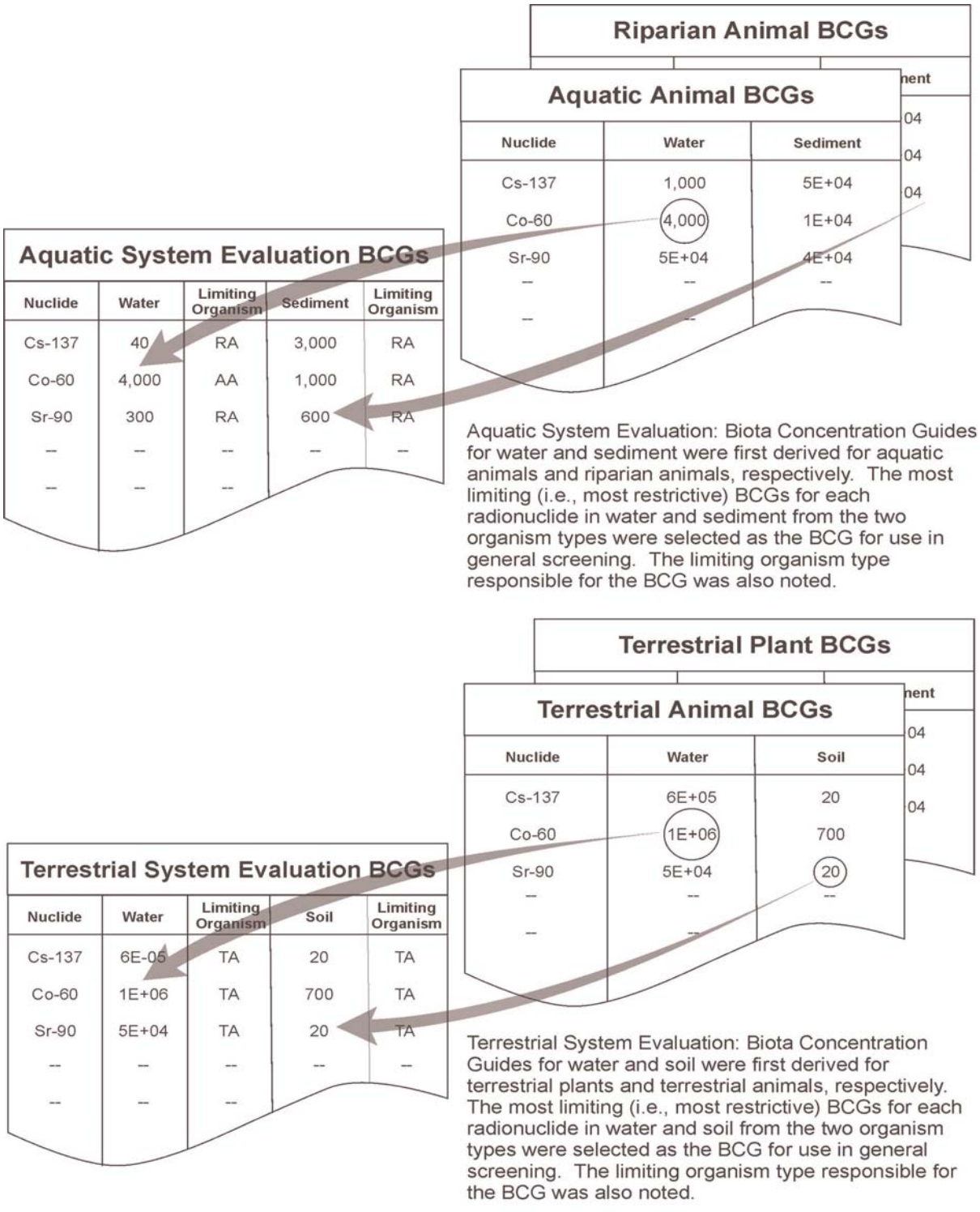

Figure 1.1 Selection of Biota Concentration Guides (BCGs) for Use in Aquatic and Terrestrial System Evaluations.

2 Dose Coefficients

2.1 External Dose Coefficients

This section describes a simple approach to calculating external dose coefficients for aquatic and terrestrial biota that can be used for purposes of screening in demonstrating compliance with specified limits on absorbed dose rates to biota, and it presents tables of screening-level external dose coefficients for exposure of aquatic and terrestrial biota to selected radionuclides in the environmental media of concern.

2.1.1 Introduction

External dose coefficients (also called external dose rate conversion factors or external dose conversion factors) give dose rates from external exposure per unit concentration of radionuclides in environmental media. For external exposure to radionuclides in the environment, only penetrating radiations (photons and electrons) are of concern, and non-penetrating radiations (e.g., alpha particles) need not be considered. The environmental (source) media of concern are contaminated water and sediments for exposure of aquatic animals and contaminated soil and water for exposure of terrestrial biota. Contaminated air (i.e., the active air pathway) is not an important source medium for terrestrial biota, because the limits on allowable concentrations of radionuclides in air based on requirements for protection of on-site workers and members of the public would result in absorbed dose rates to terrestrial biota that are far less than specified limits (see Module 2, Section 2.2).

The essence of screening-level external dose coefficients for aquatic and terrestrial biota is that they clearly must provide conservative overestimates of absorbed dose rates from external exposure to given concentrations of radionuclides in the environment. Screening-level dose coefficients thus provide a means of demonstrating compliance with specified limits on absorbed dose rate for aquatic and terrestrial biota that can be used at any DOE site, without the need for a detailed exposure pathway analysis based on site-specific considerations of the important species at risk and the important exposure pathways.

2.1.2 Approach to Calculating External Dose Coefficients

The approach to calculating external dose coefficients for aquatic and terrestrial biota for use in general screening should be simple and transparent, so that it can be easily implemented and understood. Furthermore, as indicated above, the approach must clearly result in conservative estimates of external dose rates to aquatic and terrestrial biota for given concentrations of radionuclides in the environment. The approach to calculating screening-level external dose coefficients for aquatic and terrestrial biota is based on the following assumptions:

- First, the source medium (water, sediment, or soil) is assumed to be infinite in extent and to contain uniform concentrations of radionuclides. This assumption results in reasonably realistic estimates of dose rates for radionuclides which are dispersed in the

source medium, because the range of electrons emitted in radioactive decay is no more than a few cm and the mean-free-path of emitted photons is no more than a few tens of centimeters (Shleien et al. 1998).

- Second, the exposed organism is assumed to be very small (less than the mean free path of the electron emitted in decay). This assumption results in overestimates of external dose rates for any finite-sized organism, because the attenuation of photons and electrons in transport through an organism is ignored. In addition, the assumption of a very small organism combined with the assumption of an infinitely large and uniformly contaminated source medium leads to a particularly simple approach to calculating screening-level external dose coefficients developed in the following section. Specifically, because all of the energy emitted by radionuclides in a uniformly contaminated and infinite source medium is absorbed uniformly throughout the medium, the dose rate in the organism is essentially the same as the dose rate in the medium itself, and the absorbed dose rate can be calculated directly from the energy of photons and electrons emitted per disintegration of the radionuclides in the medium.

- Third, because the organism is assumed to be very small, the energies of all photons and electrons emitted by radionuclides are taken into account in calculating the screening-level external dose coefficients. This approach is particularly conservative for electrons when the irradiated tissues of concern lie below the body surface of an organism and lower-energy electrons could not penetrate to the location of these tissues. Taking into account the energies of all photons and electrons in radioactive decay is tantamount to assuming that the radiosensitive tissues of concern (i.e., the reproductive tissues) lie on the surface of a very small organism.

Based on the foregoing discussions, the approach to calculating screening-level external dose coefficients is simple, because the dose coefficients are calculated based only on the known energies and intensities of photons and electrons emitted in the decay of radionuclides, and it is evidently conservative in providing overestimates of external dose rates to the reproductive tissues of finite-sized organisms. The calculations of screening-level external dose coefficients for aquatic and terrestrial biota based on this approach are described in the following sections.

2.1.2.1 Screening-Level External Dose Coefficients for Aquatic Animals

Screening-level external dose coefficients for exposure of aquatic animals to radionuclides in sediments and water are calculated based on the assumptions described in the previous section and the additional conservative assumption that the organism is located 100 percent of the time at the water-sediment interface. Thus, it is assumed that the organism was exposed at the boundary of two semi-infinite and uniformly contaminated media. The assumption of exposure at the boundary of a semi-infinite medium results in an absorbed dose rate in the organism that is one-half of the dose rate in an infinite source volume. The calculation of the screening-level external dose coefficients for aquatic animals then proceeds as follows.

The total energies of all photons and electrons emitted in the decay of radionuclides are assumed to be given in units of MeV per disintegration. For exposure to contaminated sediments, the desired units for the external dose coefficients are rad/d per pCi/g. The emitted energy in MeV per disintegration (i.e., per Bq-s) is expressed in terms of the desired units for the external dose coefficients by multiplication of the known factors relating energy in MeV to ergs, absorbed energy in ergs/g to rads, time in seconds to days, and activity in Bq to pCi:

$$\left(1\ \frac{\text{MeV}}{\text{Bq\&s}}\right)\left(1.6\text{E\&06}\ \frac{\text{ergs}}{\text{MeV}}\right)\left(0.01\ \frac{\text{g\&rad}}{\text{erg}}\right)\left(8.64\text{E\%04}\ \frac{\text{s}}{\text{d}}\right)\left(0.037\frac{\text{Bq}}{\text{pCi}}\right)\ '\ 5.12\text{E\&05}\ \frac{\text{rad/d}}{\text{pCi/g}}$$

If SI units are used for absorbed dose (Gy), activity (Bq), and mass (kg), and the unit of time is taken to be the year, the factor for converting emitted energy to the external dose coefficient is obtained by a similar calculation as:

$$\left(1\ \frac{\text{MeV}}{\text{Bq\&s}}\right)\ '\ 5.04\text{E\&06}\ \frac{\text{Gy/y}}{\text{Bq/kg}}$$

As noted above, the external dose coefficient at the sediment-water interface is one-half of the value for exposure in an infinite medium. Therefore, given the total energies (E) of photons and electrons in MeV per disintegration of a radionuclide, the external dose coefficient (d_{ext}) for exposure to contaminated sediments is given by:

$$(d_{ext})_{\text{sediments}}\left(\frac{\text{rad/d}}{\text{pCi/g}}\right)\ '\ (2.56\text{E\&05})E_{\text{photons\%electrons}}\left(\frac{\text{MeV}}{\text{dis}}\right)$$

If the desired units for the external dose coefficients are Gy/y per Bq/kg, the factor by which the decay energy is multiplied is 2.52E-06.

For exposure to contaminated water, the desired units for the external dose coefficients are rad/d per pCi/L. If the density of water is assumed to be 1 g/cm^3, the external dose coefficient for exposure to contaminated water at the sediment-water interface is obtained from a calculation similar to that for contaminated sediments given above as:

$$(d_{ext})_{\text{water}}\left(\frac{\text{rad/d}}{\text{pCi/L}}\right)\ '\ (2.56\text{E\&08})E_{\text{photons\%electrons}}\left(\frac{\text{MeV}}{\text{dis}}\right)$$

Similarly, if the desired units for the external dose coefficients are Gy/y per Bq/m^3, the factor by which the decay energy is multiplied is 2.52E-09.

The screening-level external dose coefficients for exposure of aquatic animals to selected radionuclides in contaminated sediments calculated as described above are given in Table 2.1,

and the values for exposure to contaminated water are given in Table 2.2. The energies of all photons and electrons per disintegration of the radionuclides are obtained from the compilation by Kocher (1980), which summarizes the data contained in a handbook of decay data tables (Kocher 1981). For most radionuclides, the decay data compiled by Kocher are in good agreement with the data compiled by the ICRP (1983).

2.1.2.2 Screening-Level External Dose Coefficients for Terrestrial Biota

Screening-level external dose coefficients for exposure of terrestrial biota to radionuclides in soil are calculated based on the assumption that the organism is immersed 100% of the time in an infinite and uniformly contaminated source region. This assumption takes into account that some terrestrial animals reside well below ground for a substantial fraction of the time, and it is appropriately conservative for purposes of screening.

For exposure to contaminated soil, the desired units for the external dose coefficients are rad/d per pCi/g. Therefore, based on the calculations for contaminated sediments discussed in the previous section, the external dose coefficient for exposure to contaminated soil is given by:

$$(d_{ext})_{soil}\left(\frac{\text{rad/d}}{\text{pCi/g}}\right) \text{ ' } (5.12E\&05)E_{photons\%electrons}\left(\frac{\text{MeV}}{\text{dis}}\right)$$

If the desired units for the external dose coefficients are Gy/y per Bq/kg, the factor by which the decay energy is multiplied is 5.05E-06.

The screening-level external dose coefficients for exposure of terrestrial biota to selected radionuclides in contaminated soil calculated as described above are given in Table 2.3. The values for contaminated soil are twice the values for contaminated sediments in Table 2.1.

2.1.3 Discussion of Results

Several points about the screening-level external dose coefficients in Tables 2.1-2.3 should be noted. The first point concerns the treatment of radioactive decay chains in obtaining the results.

Several radionuclides - including Sr-90, Zr-95, Sb-125, Cs-137, Ce-144, Pb-210, Ra-226, Ra-228, Ac-227, Th-228, Th-229, U-235, U-238, Np-237, and Am-243 - have radioactive decay products that are sufficiently short-lived that the decay products are assumed to be in secular equilibrium with the parent radionuclide in each environmental medium. For these radionuclides, the external dose coefficients are the sum of the values for the parent and its indicated short-lived decay products, taking into account the branching fractions in the decay of the parent.

For several radionuclides, however, the external dose coefficients do not include possible contributions from decay products that are sufficiently long-lived that they may not be in activity

equilibrium with the parent radionuclide, even though the contributions from the decay products may be significant. The radionuclides of concern (with the decay products in parentheses) include Ra-226 (Pb-210), Ra-228 (Th-228), Th-232 (Ra-228 and Th-228), Pa-231 (Ac-227), and U-232 (Th-228). If separate data on the concentrations of the shorter-lived decay products in sediments, water, or soil are not available, the decay products could be assumed to be in activity equilibrium with the parent, and the dose coefficients for the parent and the decay products should be added. This approach may or may not be conservative, depending on differences in the environmental behavior of the parent and its decay products.

The second point concerns the importance of the external dose coefficients for exposure to contaminated water in Table 2.2. For most radionuclides, the concentration in aquatic animals relative to the concentration in water should be considerably greater than unity (Kennedy and Strenge 1992). Therefore, the dose rate from internal exposure calculated for purposes of screening by assuming that all radiations emitted in the decay of radionuclides in an organism are absorbed in the organism, usually would be considerably higher than the screening-level dose rate from external exposure. In addition, for most radionuclides, the solid/solution distribution coefficient (K_d) in sediments should be considerably greater than unity (Onishi et al. 1981). Therefore, for the assumption of exposure at the sediment-water interface, the screening-level dose rate from external exposure to contaminated sediments should be higher in most cases than the corresponding dose rate from external exposure to contaminated water.

Based on these arguments, the screening-level external dose coefficients for exposure of aquatic animals to contaminated water in Table 2.2 are unlikely to be important for most radionuclides in determining screening-level concentrations in water. Rather, the screening-level concentrations of most radionuclides in aquatic environments should be based on considerations of external exposure to contaminated sediments and internal exposure.

The third point concerns a comparison of the screening-level external dose coefficients obtained in this technical standard with values given by Amiro (1997). The calculations of Amiro assumed that the organism is located 0.1 m below the surface of a semi-infinite, uniformly contaminated body of sediment, water, or soil. Compared with the assumptions of exposure in an infinite medium (soil) or at the boundary of a semi-infinite medium (sediments and water) used in this technical standard, Amiro's assumption is less conservative for exposure to contaminated soil but more conservative for exposure to contaminated sediments and water. In addition, the external dose coefficients of Amiro were calculated for a human phantom, rather than a point receptor, and the calculated values for photons apply at the body surface and the calculated values for electrons apply at a depth of 70 µm in tissue (an aerial thickness of 0.7 mg/cm^2). For high-energy photon emitters, the photon dose rate at the body surface of a human phantom is slightly higher than the dose rate in the source medium itself, but the difference is not significant. However, the depth in tissue for calculating the electron dose rate assumed by Amiro is considerably less conservative than the assumption in this technical standard of exposure at the surface of a very small organism, because the minimum electron energy that results in a non-zero dose at a depth of 70 µm is about 70 keV (Kocher and Eckerman 1981) but all such lower-energy electrons are taken into account in obtaining the

present results. Finally, in the approach to screening developed by Amiro, the external dose coefficients cannot be calculated simply on the basis of the energies of photons and electrons in radioactive decay, and results for radionuclides not considered by Amiro are not readily obtainable.

Table 2.1 Screening-Level External Dose Coefficients for Exposure of Aquatic Animals to Contaminated Sediments (These values were also used for exposure of riparian animals to contaminated sediments.)

Radionuclide[a]	Decay Energy (MeV)[b]	External Dose Coefficient	
		rad/d per pCi/g	Gy/y per Bq/kg
^{3}H	0.0057	1.5E-07	1.4E-08
^{14}C	0.0495	1.3E-06	1.2E-07
^{32}P	0.6949	1.8E-05	1.8E-06
^{60}Co	2.6016	6.7E-05	6.6E-06
^{59}Ni	0.0067	1.7E-07	1.7E-08
^{63}Ni	0.0171	4.4E-07	4.3E-08
^{65}Zn	0.5904	1.5E-05	1.5E-06
$^{90}Sr + {}^{90}Y$	1.1305	2.9E-05	2.8E-06
$^{95}Zr + {}^{95}Nb$	1.6614	4.3E-05	4.2E-06
^{94}Nb	1.7027	4.4E-05	4.3E-06
^{99}Tc	0.0846	2.2E-06	2.1E-07
$^{125}Sb + {}^{125m}Te$	0.5670	1.5E-05	1.4E-06
^{129}I	0.0789	2.0E-06	2.0E-07
^{131}I	0.5715	1.5E-05	1.4E-06
^{134}Cs	1.7171	4.4E-05	4.3E-06
^{135}Cs	0.0563	1.4E-06	1.4E-07
$^{137}Cs + {}^{137m}Ba$	0.7966	2.0E-05	2.0E-06
$^{144}Ce + {}^{144}Pr$	1.3517	3.5E-05	3.4E-06
^{154}Eu	1.5269	3.9E-05	3.8E-06
^{155}Eu	0.1224	3.1E-06	3.1E-07
$^{210}Pb + {}^{210}Bi$	0.4279	1.1E-05	1.1E-06
$^{226}Ra + D^{C}$	2.7023	6.9E-05	6.8E-06
$^{228}Ra + {}^{228}Ac^{d}$	1.3677	3.5E-05	3.4E-06
$^{227}Ac + D^{e}$	1.4916	3.8E-05	3.8E-06
$^{228}Th + D^{f}$	2.4310	6.2E-05	6.1E-06
$^{229}Th + D^{g}$	1.2282	3.1E-05	3.1E-06
^{230}Th	0.0143	3.7E-07	3.6E-08
$^{232}Th^{h}$	0.0121	3.1E-07	3.0E-08
$^{231}Pa^{i}$	0.0727	1.9E-06	1.8E-07
$^{232}U^{j}$	0.0162	4.1E-07	4.1E-08
^{233}U	0.0037	9.5E-08	9.3E-09
^{234}U	0.0128	3.3E-07	3.2E-08
$^{235}U + {}^{231}Th$	0.3729	9.5E-06	9.4E-07
$^{238}U + D^{k}$	0.9154	2.3E-05	2.3E-06
$^{237}Np + {}^{233}Pa$	0.5049	1.3E-05	1.3E-06

Table 2.1 (Continued) Screening-Level External Dose Coefficients for Exposure of Aquatic Animals to Contaminated Sediments (These values were also used for exposure of riparian animals to contaminated sediments.)

Radionuclide[a]	Decay Energy (MeV)[b]	External Dose Coefficient	
		rad/d per pCi/g	Gy/y per Bq/kg
^{238}Pu	0.0099	2.5E-07	2.5E-08
^{239}Pu	0.0056	1.4E-07	1.4E-08
^{240}Pu	0.0098	2.5E-07	2.5E-08
^{241}Pu	0.0052	1.3E-07	1.3E-08
^{241}Am	0.0575	1.5E-06	1.4E-07
^{243}Am + ^{239}Np	0.4990	1.3E-05	1.3E-06
^{242}Cm	0.0092	2.4E-07	2.3E-08
^{243}Cm	0.2547	6.5E-06	6.4E-07
^{244}Cm	0.0079	2.0E-07	2.0E-08

(a) Short-lived decay products assumed to be in activity equilibrium are listed with parent radionuclide, and "D" denotes multiple decay products listed in separate footnote. Contributions to dose coefficient from decay products take into account branching fractions in decay of parent radionuclide (Kocher 1981).
(b) Total energy of all photons and electrons emitted per decay of radionuclide from Kocher (1980).
(c) Short-lived decay products include ^{222}Rn, ^{214}Pb, ^{214}Bi, and ^{214}Po. Possible contributions to dose coefficient from ^{210}Pb decay product are not included, but dose coefficient for decay product is listed separately.
(d) Possible contributions to dose coefficient from ^{228}Th decay product are not included, but dose coefficient for decay product is listed separately.
(e) Short-lived decay products include ^{227}Th, ^{223}Fr, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, and ^{207}Tl.
(f) Short-lived decay products include ^{224}Ra, ^{220}Rn, ^{212}Pb, ^{212}Bi, and ^{208}Tl.
(g) Short-lived decay products include ^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{209}Tl, and ^{209}Pb.
(h) Possible contributions to dose coefficient from ^{228}Ra and ^{228}Th decay products are not included, but dose coefficients for decay products are listed separately.
(i) Possible contributions to dose coefficient from ^{227}Ac decay product are not included, but dose coefficient for decay product is listed separately.
(j) Possible contributions to dose coefficient from ^{228}Th decay product are not included, but dose coefficient for decay product is listed separately.
(k) Short-lived decay products include ^{234}Th, ^{234}Pa, and ^{234}Pa.

Table 2.2 Screening-Level External Dose Coefficients for Exposure of Aquatic Animals to Contaminated Water (These values were also used for exposure of riparian animals to contaminated water.)

Radionuclide[a]	Decay Energy (MeV)[b]	External Dose Coefficient	
		rad/d per pCi/L	Gy/y per Bq/m^3
^{3}H	0.0057	1.5E-10	1.4E-11
^{14}C	0.0495	1.3E-09	1.2E-10
^{32}P	0.6949	1.8E-08	1.8E-09
^{60}Co	2.6016	6.7E-08	6.6E-09
^{59}Ni	0.0067	1.7E-10	1.7E-11
^{63}Ni	0.0171	4.4E-10	4.3E-11
^{65}Zn	0.5904	1.5E-08	1.5E-09
^{90}Sr + ^{90}Y	1.1305	2.9E-08	2.8E-09
^{95}Zr + ^{95}Nb	1.6614	4.3E-08	4.2E-09
^{94}Nb	1.7027	4.4E-08	4.3E-09
^{99}Tc	0.0846	2.2E-09	2.1E-10
^{125}Sb + ^{125m}Te	0.5670	1.5E-08	1.4E-09
^{129}I	0.0789	2.0E-09	2.0E-10
^{131}I	0.5715	1.5E-08	1.4E-09
^{134}Cs	1.7171	4.4E-08	4.3E-09
^{135}Cs	0.0563	1.4E-09	1.4E-10
^{137}Cs + ^{137m}Ba	0.7966	2.0E-08	2.0E-09
^{144}Ce + ^{144}Pr	1.3517	3.5E-08	3.4E-09
^{154}Eu	1.5269	3.9E-08	3.8E-09
^{155}Eu	0.1224	3.1E-09	3.1E-10
^{210}Pb + ^{210}Bi	0.4279	1.1E-08	1.1E-09
^{226}Ra + D[c]	2.7023	6.9E-08	6.8E-09
^{228}Ra + ^{228}Ac[d]	1.3677	3.5E-08	3.4E-09
^{227}Ac + D[e]	1.4916	3.8E-08	3.8E-09
^{228}Th + D[f]	2.4310	6.2E-08	6.1E-09
^{229}Th + D[g]	1.2282	3.1E-08	3.1E-09
^{230}Th	0.0143	3.7E-10	3.6E-11
^{232}Th[h]	0.0121	3.1E-10	3.0E-11
^{231}Pa[i]	0.0727	1.9E-09	1.8E-10
^{232}U[j]	0.0162	4.1E-10	4.1E-11
^{233}U	0.0037	9.5E-11	9.3E-12
^{234}U	0.0128	3.3E-10	3.2E-11
^{235}U + ^{231}Th	0.3729	9.5E-09	9.4E-10
^{238}U + D[k]	0.9154	2.3E-08	2.3E-09
^{237}Np + ^{233}Pa	0.5049	1.3E-08	1.3E-09

Table 2.2 (Continued) Screening-Level External Dose Coefficients for Exposure to Aquatic Animals to Contaminated Water (These values were also used for exposure of riparian animals to contaminated water.)

Radionuclide[a]	Decay Energy (MeV)[b]	External Dose Coefficient	
		rad/d per pCi/L	Gy/y per Bq/m^3
^{238}Pu	0.0099	2.5E-10	2.5E-11
^{239}Pu	0.0056	1.4E-10	1.4E-11
^{240}Pu	0.0098	2.5E-10	2.5E-11
^{241}Pu	0.0052	1.3E-10	1.3E-11
^{241}Am	0.0575	1.5E-09	1.4E-10
^{243}Am + ^{239}Np	0.4990	1.3E-08	1.3E-09
^{242}Cm	0.0092	2.4E-10	2.3E-11
^{243}Cm	0.2547	6.5E-09	6.4E-10
^{244}Cm	0.0079	2.0E-10	2.0E-11

(a) Short-lived decay products assumed to be in activity equilibrium are listed with parent radionuclide, and "D" denotes multiple decay products listed in separate footnote. Contributions to dose coefficient from decay products take into account branching fractions in decay of parent radionuclide (Kocher 1981).
(b) Total energy of all photons and electrons emitted per decay of radionuclide from Kocher (1980).
(c) Short-lived decay products include ^{222}Rn, ^{214}Pb, ^{214}Bi, and ^{214}Po. Possible contributions to dose coefficient from ^{210}Pb decay product are not included, but dose coefficient for decay product is listed separately.
(d) Possible contributions to dose coefficient from ^{228}Th decay product are not included, but dose coefficient for decay product is listed separately.
(e) Short-lived decay products include ^{227}Th, ^{223}Fr, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, and ^{207}Tl.
(f) Short-lived decay products include ^{224}Ra, ^{220}Rn, ^{212}Pb, ^{212}Bi, and ^{208}Tl.
(g) Short-lived decay products include ^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{209}Tl, and ^{209}Pb.
(h) Possible contributions to dose coefficient from ^{228}Ra and ^{228}Th decay products are not included, but dose coefficients for decay products are listed separately.
(i) Possible contributions to dose coefficient from ^{227}Ac decay product are not included, but dose coefficient for decay product is listed separately.
(j) Possible contributions to dose coefficient from ^{228}Th decay product are not included, but dose coefficient for decay product is listed separately.
(k) Short-lived decay products include ^{234}Th, ^{234}Pa, and ^{234}Pa.

Table 2.3 Screening-Level External Dose Coefficients for Exposure of Terrestrial Biota to Contaminated Soil

Radionuclide[a]	Decay Energy (MeV)[b]	External Dose Coefficient	
		rad/d per pCi/g	Gy/y per Bq/kg
^{3}H	0.0057	2.9E-07	2.9E-08
^{14}C	0.0495	2.5E-06	2.5E-07
^{32}P	0.6949	3.6E-05	3.5E-06
^{60}Co	2.6016	1.3E-04	1.3E-05
^{59}Ni	0.0067	3.4E-07	3.4E-08
^{63}Ni	0.0171	8.8E-07	8.6E-08
^{65}Zn	0.5904	3.0E-05	3.0E-06
$^{90}Sr + {}^{90}Y$	1.1305	5.8E-05	5.7E-06
$^{95}Zr + {}^{95}Nb$	1.6614	8.5E-05	8.4E-06
^{94}Nb	1.7027	8.7E-05	8.6E-06
^{99}Tc	0.0846	4.3E-06	4.3E-07
$^{125}Sb + {}^{125m}Te$	0.5670	2.9E-05	2.9E-06
^{129}I	0.0789	4.0E-06	4.0E-07
^{131}I	0.5715	2.9E-05	2.9E-06
^{134}Cs	1.7171	8.8E-05	8.7E-06
^{135}Cs	0.0563	2.9E-06	2.8E-07
$^{137}Cs + {}^{137m}Ba$	0.7966	4.1E-05	4.0E-06
$^{144}Ce + {}^{144}Pr$	1.3517	6.9E-05	6.8E-06
^{154}Eu	1.5269	7.8E-05	7.7E-06
^{155}Eu	0.1224	6.3E-06	6.2E-07
$^{210}Pb + {}^{210}Bi$	0.4279	2.2E-05	2.2E-06
^{226}Ra + Dc	2.7023	1.4E-04	1.4E-05
$^{228}Ra + {}^{228}Ac$[d]	1.3677	7.0E-05	6.9E-06
^{227}Ac + D[e]	1.4916	7.6E-05	7.5E-06
^{228}Th + D[f]	2.4310	1.2E-04	1.2E-05
^{229}Th + D[g]	1.2282	6.3E-05	6.2E-06
^{230}Th	0.0143	7.3E-07	7.2E-08
^{232}Th[h]	0.0121	6.2E-07	6.1E-08
^{231}Pa[i]	0.0727	3.7E-06	3.7E-07
^{232}U[j]	0.0162	8.3E-07	8.2E-08
^{233}U	0.0037	1.9E-07	1.9E-08
^{234}U	0.0128	6.6E-07	6.5E-08
$^{235}U + {}^{231}Th$	0.3729	1.9E-05	1.8E-06
^{238}U + D[k]	0.9154	4.7E-05	4.6E-06
$^{237}Np + {}^{233}Pa$	0.5049	2.6E-05	2.5E-06

Table 2.3 (Continued) Screening-Level External Dose Coefficients for Exposure of Terrestrial Biota to Contaminated Soil

Radionuclide[a]	Decay Energy (MeV)[b]	External Dose Coefficient	
		rad/d per pCi/g	Gy/y per Bq/kg
^{238}Pu	0.0099	5.1E-07	5.0E-08
^{239}Pu	0.0056	2.9E-07	2.8E-08
^{240}Pu	0.0098	5.0E-07	4.9E-08
^{241}Pu	0.0052	2.7E-07	2.6E-08
^{241}Am	0.0575	2.9E-06	2.9E-07
^{243}Am + ^{239}Np	0.4990	2.6E-05	2.5E-06
^{242}Cm	0.0092	4.7E-07	4.6E-08
^{243}Cm	0.2547	1.3E-05	1.3E-06
^{244}Cm	0.0079	4.0E-07	4.0E-08

(a) Short-lived decay products assumed to be in activity equilibrium are listed with parent radionuclide, and "D" denotes multiple decay products listed in separate footnote. Contributions to dose coefficient from decay products take into account branching fractions in decay of parent radionuclide (Kocher 1981).
(b) Total energy of all photons and electrons emitted per decay of radionuclide from Kocher (1980).
(c) Short-lived decay products include ^{222}Rn, ^{214}Pb, ^{214}Bi, and ^{214}Po. Possible contributions to dose coefficient from ^{210}Pb decay product are not included, but dose coefficient for decay product is listed separately.
(d) Possible contributions to dose coefficient from ^{228}Th decay product are not included, but dose coefficient for decay product is listed separately.
(e) Short-lived decay products include ^{227}Th, ^{223}Fr, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, and ^{207}Tl.
(f) Short-lived decay products include ^{224}Ra, ^{220}Rn, ^{212}Pb, ^{212}Bi, and ^{208}Tl.
(g) Short-lived decay products include ^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{209}Tl, and ^{209}Pb.
(h) Possible contributions to dose coefficient from ^{228}Ra and ^{228}Th decay products are not included, but dose coefficients for decay products are listed separately.
(i) Possible contributions to dose coefficient from ^{227}Ac decay product are not included, but dose coefficient for decay product is listed separately.
(j) Possible contributions to dose coefficient from ^{228}Th decay product are not included, but dose coefficient for decay product is listed separately.
(k) Short-lived decay products include ^{234}Th, ^{234}Pa, and ^{234}Pa.

2.2 Internal Dose Coefficients

This section presents the approach used to calculate internal dose coefficients that can be used in general screening for internal exposure of aquatic and terrestrial biota to selected radionuclides. A table of screening-level internal DCFs is provided.

2.2.1 Approach to Calculating Internal Dose Coefficients

Internal dose conversion factors (Gy y^{-1} per Bq kg^{-1}) were derived for unit concentrations of each of the target radionuclides in tissue. Reference decay energies and abundances were taken from ICRP 38 (1983) for each of the target radionuclides and its progeny The default dose factor includes buildup of progeny with half-lives less than 100 y. The calculations assume all of the energies of radioactive decay were retained in the tissue of the organism (i.e., the organism was presumed to be very large in size). The radionuclides were presumed to be homogeneously distributed in the tissue. The default internal dose factors include a dose-

modifying factor of 20 (i.e., Q or w_R = 20) for alpha particles and the alpha-emitting progeny of chain-decaying nuclides. However, the RAD-BCG Calculator is constructed such that the dose-modifying factor can be modified. See Module 2, Section 7 for a detailed discussion on the rationale for the radiation weighting factor selected.

The RAD-BCG Calculator Provides the Capability to Modify the Internal DCFs

Internal DCFs. The default internal DCFs used in the graded approach include the contribution from build-up of progeny with half-lives less than 100y. A user can select whether or not the energy of the progeny will be included in the calculations. This is done in the Dose Factors and Common Parameters Spreadsheet.

Radiation Weighting Factor for Alpha Emitters. The default value of the radiation weighting factor (default = 20) for alpha particles and the alpha-emitting progeny of chain-decaying radionuclides can be modified in the Dose Factors and Common Parameters Spreadsheet.

The dose factors were calculated as the sum of all decay energies and multiplied by appropriate unit conversion factors. The equation used to calculate an internal dose factor for a specific radionuclide is shown below. The resultant dose factors are presented in Table 2.4. For internal exposure to contaminants, the units for the dose coefficients were calculated as Gy/y per Bq/kg of wet tissue.

$$DCF_{internal,i} = \left(\frac{1dis(s^{-1})}{Bq}\right)\left(\Sigma\Sigma_{i\ j} Y_j E_j Q_j\right)\left(1.6022E{-}13\ J\ MeV^{-1}\right)\left(3.1536E07s(y^{-1})\right)\frac{1Gy}{1J(kg^{-1}}$$

where the following terms apply:

$DCF_{internal,i}$ = Gy/y per Bq/kg of wet tissue for radionuclide i;

Y_j = yield (abundance) of radiation j per disintegration of nuclide i;

E_j = energy (MeV) of radiation j for nuclide i; and

Q_j is the radiation weighting factor (quality factor, also called W_R) for radiation j of nuclide i.

The dose factors can also be expressed in rad/d per pCi/g, where all other factors have been defined:

$$DCF_{internal,i} = \left(\frac{1dis(s^{-1})}{Bq}\right)\frac{0.037Bq}{pCi}\left(\Sigma\Sigma_{i\ j} Y_j E_j Q_j\right)(1.6022E{-}06\ erg(MeV^{-1})(8.64E04s(d^{-1})\frac{0.01g(rad}{erg}$$

Table 2.4 Screening Level Internal Dose Factors

Radionuclide	Internal dose with progeny[a]		Internal dose without progeny	
	Gy/y per Bq/kg (wet)	Rad/d per pCi/g (wet)	Gy/y per Bq/kg (wet)	Rad/d per pCi/g (wet)
^{241}Am	5.6E-04	5.7E-03	5.6E-04	5.7E-03
^{144}Ce	6.8E-06	6.9E-05	5.6E-07	5.7E-06
^{135}Cs	3.4E-07	3.4E-06	3.4E-07	3.4E-06
^{137}Cs	4.3E-06	4.3E-05	9.4E-07	9.6E-06
^{60}Co	1.3E-05	1.3E-04	1.3E-05	1.3E-04
^{154}Eu	7.6E-06	7.7E-05	7.6E-05	7.7E-05
^{155}Eu	6.2E-07	6.3E-06	6.2E-07	6.3E-06
^{3}H	2.9E-08	2.9E-07	2.9E-08	2.9E-07
^{129}I	4.5E-07	4.5E-06	4.5E-07	4.5E-06
^{131}I	2.9E-06	2.9E-05	2.9E-06	2.9E-05
^{239}Pu	5.3E-04	5.4E-03	5.3E-04	5.4E-03
^{226}Ra	3.0E-03	3.1E-02	4.9E-04	5.0E-03
^{228}Ra	3.6E-03	3.7E-02	8.5E-08	8.6E-07
^{125}Sb	2.7E-06	2.7E-05	2.7E-06	2.7E-05
^{90}Sr	5.7E-06	5.8E-05	9.9E-07	1.0E-05
^{99}Tc	5.1E-07	5.2E-06	5.1E-07	5.2E-06
^{232}Th	4.1E-03	4.1E-02	4.1E-04	4.2E-03
^{233}U	4.9E-04	5.0E-03	4.9E-04	5.0E-03
^{234}U	4.9E-04	5.0E-03	4.9E-04	5.0E-03
^{235}U	4.5E-04	4.6E-03	4.5E-04	4.6E-03
^{238}U	4.4E-04	4.5E-03	4.3E-04	4.4E-03
^{65}Zn	3.0E-06	3.0E-05	3.0E-06	3.0E-05
^{95}Zr	8.4E-06	8.5E-05	4.3E-06	4.4E-05

(a) Includes listed radiations (α β γ, X) and an RBE of 20 for alpha particles. Progeny with half-lives less than 100 y are included at 100% abundance.