4. Bioconcentration of Radionuclides in Marine Food-Web Organisms

W. Templeton[a], F. Harrison[b], J. Knezovich[b], N. Fisher[c], and D. Layton[b]

[a]Battelle Pacific Northwest Laboratories, Richland, WA

[b]Lawrence Livermore National Laboratory, Livermore, CA

[c]State University of New York, Stony Brook, NY

Concentrations of radionuclides in seawater, particles, and marine species are important inputs to radiological assessments involving the health and ecological impacts of radionuclide releases to the marine environment. In our assessment of the potential consequences of nuclear wastes in the Arctic Ocean, the RAIG focuses primarily on future releases. Therefore, predicted concentrations of nuclides in Arctic waters must be translated to the associated possible concentrations in marine species. Historically, radiological assessments have used a derived parameter, termed a concentration factor or bioconcentration factor (BCF), that links the concentration of a nuclide in the whole body or a tissue of a marine organism to its concentration in seawater. This section describes the basis of such factors and analyzes applicable values for the principal radionuclides addressed in this assessment (i.e., ^{90}Sr, ^{137}Cs, ^{241}Am, and ^{239}Pu) and for naturally occurring radionuclides that are reported to deliver the greatest dose to the organisms. Finally, the RAIG uses the BCFs along with measured and predicted concentrations of radionuclides in Arctic waters to estimate levels of radionuclides in marine species.

4.1 Definition of Bioconcentration Factors

Marine organisms accumulate exogenous substances present in food, water, and particles by various mechanisms. For example, the consumption of contaminated foods (i.e., food-chain transfer), direct uptake from water, and ingestion/filtration of contaminated particulate matter each may contribute to the exposure of an organism to radionuclides. The term bioaccumulation is used to acknowledge that organisms exposed to contaminants in the field derive their body burdens from a variety of sources. While it may be possible to simulate bioaccumulation processes for some organisms under controlled conditions, it is simply not possible to characterize accurately such processes over a suite of marine species and environments.

A simpler approach is to determine a contaminant's concentration in a given organism as a function of its concentration in water. More specifically, the basic approach for determining a bioconcentration factor (BCF) has been to calculate it as the ratio of a contaminant's concentration in the whole body or target tissue of interest (e.g., muscle) to the concentration of the contaminant in water. A BCF can be expressed as a unitless ratio if the radionuclide concentrations are expressed on a mass basis (e.g., Bq/kg wet weight in tissue ÷ Bq/kg of seawater), or it can be expressed in units of L/kg (e.g., Bq/kg wet weight in tissue ÷ Bq/L of seawater) or m^3/kg (e.g., Bq/kg wet weight in tissue ÷ Bq/m^3 of seawater). In this risk assessment, the units are presented both as traditional unitless ratios and in units of m^3/kg, which are consistent with the circulation models developed to predict the concentrations in seawater. These latter BCF values are 1/1,000 of that of the unitless quantity found in most publications.

A BCF is thus a parameter that represents the net effects of all bioaccumulation and elimination processes affecting the transfer of a radionuclide from food, water, and particles to an organism. The application of this approach is based on the assumption that organisms, their prey items, and particulate matter are at or near steady state with the dissolved fraction of a contaminant. This is a reasonable assumption for the assessment of future releases of radionuclides expected to result in relatively small spatial and temporal variations in their dissolved concentrations. Some authors also have calculated BCFs from radionuclide concentrations in food-chain organisms and in sediments. The use of BCFs based on specific biotic and abiotic components is appropriate when sufficient data are available indicating the component is the actual source of the radionuclide to the organism of interest. Because relatively little information is available for BCFs based on exposure media other than water, only water-derived BCFs were used for our assessments.

Three idealized patterns of BCFs have been described by Vanderploeg et al. (1975). The first pattern is that the BCF of a nuclide in biological material is constant (i.e., is unaffected by the concentration of the nuclide in the water). This pattern is shown by nuclides that are not under homeostatic control (regulated to a specific concentration); an example is the behavior of plutonium in marine invertebrates and fishes. The second pattern is that the BCF of the nuclide is inversely proportional to its concentration in the water. This is characteristic of nuclides that are under homeostatic control (e.g., ^{131}I in whales). The third pattern is that the BCF for the nuclide is inversely proportional to the concentration of a non-isotopic carrier element (i.e., chemically similar to but occurring in higher concentrations than the stable-element analog). The classical example of this pattern is cesium in freshwater animals; the non-isotopic carrier element is potassium in this case. This pattern is shown by very few radionuclides in marine organisms.

Scientists have directed considerable attention to the determination of BCFs. They have calculated values from analyses of stable and radioactive nuclides in field samples, have assessed them in laboratory experiments, and have determined wide ranges in BCFs for some organisms (Jackson et al., 1983; Noshkin, 1985; Harrison, 1986, Gomez et al., 1991; Radioactive Waste Management Center, 1996). A number of factors may contribute to the large variability in BCF values for the same group of organisms (Harrison, 1986). Important among these for the water include (1) the concentration being determined from filtered v. unfiltered water, (2) the differences in physicochemical form of nuclides among ecosystems, and (3) the absence of steady-state conditions from changing source terms. Metabolic demands and physiological state may result in differences in the BCF with season. Also, part of the variability in BCFs can be attributed to the samples being collected in ecosystems where steady-state conditions with abiotic and biotic components were not present.

The International Atomic Energy Agency (IAEA, 1978, 1985) compiled listings of values and ranges for sixty elements in surface water fishes, crustaceans, mollusks, macroalgae, zooplankton, phytoplankton, cephalopods, and mesopelagic fishes. The approach used in the 1985 assessment was "to review the literature in order to select the most appropriate BCFs for radionuclides in marine biological materials based, whenever possible, on field data." The data base upon which their recommended values were obtained differed greatly among the sixty elements.

4.2 Bioconcentration Factors for Radionuclides Derived from FSU Sources

In the initial stages of ANWAP, some concern was expressed that because the IAEA-recommended BCF values were not derived from measurements of Arctic biological materials but were obtained in organisms from temperate and tropical regions, the BCFs may be inappropriate. Some laboratory experiments for specific organisms, i.e., the brown seaweed (*Fucus vesiculosus*) and the brittle star (*Ophiothrix fragilis*), were conducted (Povinec et al., 1996). Scientists from both the IAEA and the IAEA's Marine Environment Laboratory reviewed these experiments and other data and concluded that no evidence indicates any significant difference between BCFs derived from organisms indigenous to temperate and Arctic waters. A larger database, however, must substantiate this conclusion.

In 1995 the IAEA convened a panel of consultants who reviewed all of the available data and recommended BCFs for use in the Arctic ecosystems. One of the authors of this report (N. Fisher) was a member of that group (IAEA Working Group papers, 1995). The recommended BCF values for radionuclides in muscles of Arctic fish are given in Table 4-1, for marine mammals in Table 4-2, and for seabirds in Table 4-3. The BCF data for seabirds is based on the assumption that their exposures to radionuclides were primarily from prey items that were in contact with seawater. The majority of seawater and biological samples were collected in the eastern Arctic. ANWAP has sponsored the collection of samples from the western Arctic, particularly the Beaufort, Chukchi, and Bering Seas. However, the data are not yet available from which to calculate site-specific BCFs for organisms from Alaskan waters.

Table 4-1. Recommended bioconcentration factors for fish flesh in temperate and Arctic waters.

	Recommended Bioconcentration Factors				
	Temperate waters[a]		Arctic waters[b]		
Element	m^3/kg	Unitless	m^3/kg	Unitless	Species[c]
Sr	2×10^{-3}	2×10^{0}	2×10^{-3}	4×10^{0}	Cod, Plaice, Halibut, Haddock, Saithe, Seawolf, Red Fish, Ray, Salmon
Cs	1×10^{-1}	1×10^{2}	1×10^{-1}	1×10^{2}	Cod, Plaice, Haddock, Saithe, Seawolf, Red Fish, Ray, Halibut, Salmon, Polar Cod, Char
Pu	4×10^{-2}	4×10^{1}	4×10^{-2}	4×10^{1}	Haddock, Sea Scorpion, Cod
Am	5×10^{-2}	5×10^{1}			
Po	2×10^{0}	2×10^{3}			

[a] Values recommended for fish in temperate waters are from the IAEA (1985).
[b] Values recommend for fish in Arctic waters are from IAEA Working Group.
[c] Species addressed in the review of the IAEA Working Group.

Table 4-2. Actual and recommended bioconcentration factors for sea mammal muscle (from the IAEA Working Group).

	Bioconcentration Factors				
			Recommended Values		
Element	Range m^3/kg	Mean m^3/kg	m^3/kg	Unitless	Species
Sr	4×10^{-4} to 1.2×10^{-3}	7×10^{-4}	1×10^{-3}	1×10^{0}	Seal
	2×10^{-4} to 3×10^{-3}	1.1×10^{-3}	1×10^{-3}	1×10^{0}	Whale
Cs	1.3×10^{-2} to 1.8×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{2}	Seal
	4×10^{-1} to 1.3×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{2}	Whale
Pu		$<3 \times 10^{-3}$	3×10^{-3}	3×10^{0}	Seal
		4×10^{-3}	3×10^{-3}	3×10^{0}	Walrus

Table 4-3. Actual and recommended bioconcentration factors for seabirds in the Arctic (from IAEA Working Group).

Element	Range m^3/kg	Bioconcentration Factors Mean m^3/kg	Recommended Values m^3/kg	Unitless	Species
Cs	4×10^{-2} to 1.1×10^{0}	4×10^{-1}	1×10^{-1}	1×10^{2}	Auk, Great Black Backed Gull, Common Gull, Great Skus, Spotted Redshank, Sandpiper and Goosander. Goosander has the lowest BCF, 4×10^{-1}
Pu	$<2 \times 10^{-2}$ to 1.5×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{2}	Guillemot and Eider

4.3 Bioconcentration Factors for Naturally Occurring Radionuclides

Naturally occurring radionuclides in the marine environment contribute significantly to the background doses received by some marine organisms (IAEA, 1976, 1985). Dose rates calculated for a series of natural radionuclides in phytoplankton, zooplankton, mollusks, crustacea, and fishes indicated that the significant doses were contributed from internal emitters ^{40}K and ^{210}Po. The radionuclide ^{40}K is of limited interest because it is an isotope of an essential element that is under homeostatic control and its concentrations are determined primarily by body build and type. ^{210}Po is of special interest because it is the decay product of ^{210}Bi, which is the daughter of naturally occurring ^{210}Pb ($^{210}Pb \longrightarrow {}^{210}Bi \longrightarrow {}^{210}Po$) and has a relatively short half-life of 140 d.

Data are available indicating that ^{210}Po is accumulated in different tissues of marine organisms to levels greater than those resulting from the decay of its long-lived precursor ^{210}Pb (Noshkin et al., 1984; Noshkin et al., 1994; and Aarkrog et al., 1997). Holtzman (1980) provided information on the normal dietary levels of ^{210}Po for individuals from different countries and attributed the higher intake for Japanese to be due to the high seafood consumption and that from Arctic dwellers to be due to consumption of reindeer and caribou meat. In an in-depth study of the concentrations of ^{210}Po and ^{210}Pb in the diet of the Marshallese, Noshkin et al. (1994) provided mean values and ranges in values of ^{210}Po in fishes, invertebrates, seabirds, and vegetation. The data on fishes show large variation in concentrations with species. Comparable variability was shown for invertebrates and seabirds. Noshkin et al. (1994) and Aarkrog et al. (1997) discuss the variability among species and within the same species. They note that the differences do not appear to be related to trophic level, but may be related to the differences in the types of tissue consumed, citing the large variability in ^{210}Po content of the viscera.

The comprehensive review by Aarkrog et al. (1997), an international group of scientists, summarized published data on the two radionuclides ^{137}Cs and ^{210}Po, providing not only BCFs but also doses to persons in different geographical areas. Their recommended BCF values for ^{137}Cs were 100 and 30 and for ^{210}Po were 2,000 and 30,000 for fish and shellfish, respectively. The water concentrations they used for ^{210}Po was 1 Bq/m^3. Noshkin et al. (1994) calculated the BCF for flesh from all fish in the Marshall Islands to be 1.2×10^4; their BCFs were based on the water concentration of ^{210}Po for the equatorial Pacific (i.e., 1.15 Bq/m^3). The Noshkin et al. (1994) value is six times greater than that of Aarkrog et al. (1996) and two times greater than the mean value computed by Carvalho (1988) for muscle of epipelagic teleosts from the Atlantic (Noshkin et al., 1994). It should be taken into consideration that Noshkin et al. (1994) obtained all their data using the same methodology, which had been calibrated with international standards, and the BCFs were all based on filtered seawater. Thus, the high variability undoubtedly is real and represents physiological or chemical factors that still are unresolved. In consideration of the doses received from ^{210}Po by native Alaskans, it is important to recognize not only the large differences in concentrations among food sources but also that the time between the collection and consumption of the material becomes significant because of ^{210}Po's relatively short half-life.

4.4 Variabilities in Bioconcentration Factors

Previous reviews of BCFs (Jackson et al., 1983; Noshkin, 1985; Harrison, 1986; Gomez et al., 1991; RWMC, 1996), have demonstrated that BCF values are highly variable and that they usually fit log normal probability distributions rather than normal distributions. As a means of characterizing this variability, the RAIG has prepared log probability plots of the BCF values for ^{137}Cs in fish and birds (Tables 4-4 and 4-5), and for ^{90}Sr in fish (Table 4-4). Figure 4-1 shows the resulting probability plots. The geometric means of the BCF values for ^{137}Cs in fish and birds are 120 and 340, respectively. The geometric standard deviation (GSD) of the BCF for fish was 1.6, while that for seabirds was larger (i.e., 2.7). The geometric mean value of the BCF values for ^{90}Sr in fish is 4.33, with a GSD of 2.4.

The degree of variability that surrounds the BCF data presented in Figure 4-1 is reasonable in light of the variabilities associated with the age, sex, and exposure history of each species. The GSD for ^{137}Cs accumulation in fish is relatively low (i.e., 1.6), which indicates that water-based exposures represent a reasonable approximation of exposure for this radionuclide. Although the GSD for ^{90}Sr accumulation in fish is higher (i.e., 2.4), the accumulation of this radionuclide is relatively low. The relatively high variability of ^{137}Cs accumulation in birds most likely is due to the fact that these species have limited contact with seawater. Their exposure, therefore, largely is due to the ingestion of prey items. Because prey items and other food sources can have terrestrial as well as marine sources, and be from different trophic levels, the use of water-based BCF values could be expected to yield variable results.

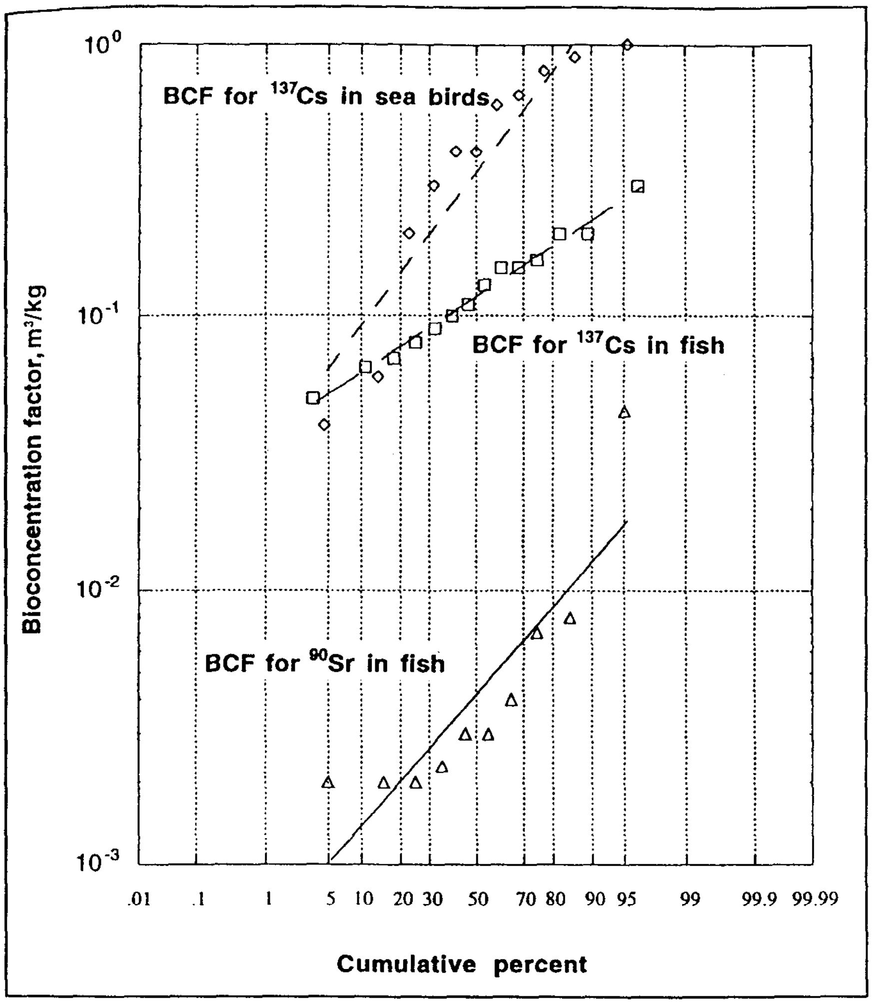

Figure 4-1. Log probability plots of the bioconcentration factors for ^{137}Cs in seabirds and fish, and for ^{90}Sr in fish. Data are from Tables 4-4 and 4-5.

Table 4-4. **Bioconcentration factors for fish tissues based on measured values of nuclides in water and fish for Arctic Waters (from IAEA Working Group).**

Nuclide/ Element	Area	Species	Bioconcentration Factor m^3/kg	Bioconcentration Factor Unitless
^{90}Sr	Barents Sea	Cod Muscle	8×10^{-3}	8×10^{0}
		Plaice Muscle	2×10^{-3}	2×10^{0}
		Haddock Muscle	4×10^{-3}	4×10^{0}
		Saithe Muscle	3×10^{-3}	3×10^{0}
		Seawolf Muscle	2×10^{-3}	2×10^{0}
		Red Fish Muscle	7×10^{-3}	7×10^{0}
		Ray Muscle	3×10^{-3}	3×10^{0}
	Around Greenland	Salmon Muscle	2×10^{-4} to 9×10^{-2}	2×10^{-1} to 9×10^{1}
		Halibut Muscle	3×10^{-4} to 2×10^{-3}	3×10^{-1} to 2×10^{0}
		Cod Muscle	2×10^{-3}	2×10^{0}
^{137}Cs	Barents Sea	Cod Muscle	1.6×10^{-1}	1.6×10^{2}
		Plaice Muscle	1.1×10^{-1}	1.1×10^{2}
		Haddock Muscle	1.0×10^{-1}	1.0×10^{2}
		Saithe Muscle	9×10^{-2}	9×10^{1}
		Seawolf Muscle	8×10^{-2}	8×10^{1}
		Red Fish Muscle	2×10^{-1}	2×10^{2}
		Ray Muscle	1.5×10^{-1}	1.5×10^{2}
		Halibut Muscle	1.5×10^{-1}	1.5×10^{2}
	Barents Sea	Fish Muscle	3×10^{-2} to 2×10^{-1}	3×10^{1} to 2×10^{2}
	Abrosimov Fjord	Polar Cod Muscle	3×10^{-1}	3×10^{2}
		Char Muscle	2×10^{-1}	2×10^{2}
	Around Greenland	Salmon Muscle	5×10^{-4} to 1.3×10^{-1}	5×10^{-1} to 1.3×10^{2}
		Halibut Muscle	4×10^{-2} to 6×10^{-2}	4×10^{1} to 6×10^{1}
		Cod Muscle	7×10^{-2}	7×10^{1}
$^{239,240}Pu$	Barents Sea	Ray, Muscle	1.8×10^{0}	1.8×10^{3}
		Other Fish Species, Muscle	$<5 \times 10^{-1}$	$<5 \times 10^{2}$
		Haddock, Liver	4×10^{0}	4×10^{3}
	Greenland Thule	Sea Scorpion and Cod, Muscle	8×10^{-2}	8×10^{1}

Table 4-5. Bioconcentration factors for seabirds (from IAEA Working Group).

Nuclide	Area	Species	Bioconcentration Factor m^3/kg	Bioconcentration Factor Unitless
^{137}Cs	Around Greenland Kola Peninsula	Auk, Muscle	5×10^{-2} to 7×10^{-2}	5×10^{1} to 7×10^{1}
		Gt. Black-Backed Gull, Muscle	5×10^{-1} to 1.1×10^{0}	5×10^{2} to 1.1×10^{3}
		Gt. Black-Backed Gull, Liver	4×10^{-1} to 9×10^{-1}	4×10^{2} to 9×10^{2}
		Common Gull, Muscle	2×10^{-1}	2×10^{2}
		Common Gull, Liver	2×10^{-1}	2×10^{2}
		Great Skus, Muscle	6×10^{-1}	6×10^{2}
		Great Skus, Liver	4×10^{-1}	4×10^{2}
		Spotted Redshank, Muscle	9×10^{-1}	9×10^{2}
		Spotted Redshank, Liver	1×10^{0}	1×10^{3}
		Sandpiper, Muscle	3×10^{-1}	3×10^{2}
		Sandpiper, Liver	4×10^{-1}	4×10^{2}
		Goosander, Muscle	4×10^{-2}	4×10^{1}
$^{239,240}Pu$	Greenland Thule	Guillemot and Eider, Muscle	$<2 \times 10^{-2}$ to 1.5×10^{-1}	$<2 \times 10^{1}$ to 1.5×10^{2}
		Guillemot and Eider, Liver	6×10^{-2} to 2×10^{0}	6×10^{1} to 2×10^{3}

Table 4-6. Bioconcentration factors (unitless) selected for use in risk assessment for different groups of marine organisms in Arctic seas. The bioconcentration factors were those in IAEA (1985), except where noted.

Group	Radionuclides ^{90}Sr	^{137}Cs	^{210}Po	$^{239,240}Pu$	^{241}Am
	Bioconcentration Factor (unitless)				
Macroalgae	5×10^0	5×10^1	1×10^3	2×10^3	8×10^3
Phytoplankton	3×10^0	2×10^1	3×10^4	1×10^5	2×10^5
Zooplankton	1×10^0	3×10^1	3×10^4	1×10^3	2×10^3
Annelids	—	3×10^1 [a]		—	1×10^3 [a]
Mollusks	1×10^0	3×10^1	3×10^4 [b] 5×10^4 [d]	3×10^3	2×10^4
Large crustaceans	2×10^0	3×10^1	3×10^4 [b] 1×10^4 [d]	3×10^2	5×10^2
Fish muscle	4×10^0	1×10^2	2×10^3 [b] 1.2×10^4 [d]	4×10^1	5×10^1
Fish liver	—	4×10^1 [c]	5×10^5 [d]	4×10^3 [c]	1×10^2 [c]
Mammal muscle	1.1×10^0 [e]	1×10^2 [e]	1.7×10^3 [f]	3×10^0 [e]	—
Mammal liver	—	6×10^1 [g]	2.2×10^4 [f]	—	—
Marine bird muscle		1×10^2 [e]	3×10^4 [d]	1×10^2 [e]	—
Marine bird liver	—	2×10^2 to 1×10^3 [e]	—	6×10^1 to 2×10^3 [e]	—
Marine bird eggs			4.6×10^4 [d]		

a Harrison (1986); BCF approximated from laboratory data.
b Aarkrog et al. (1997)
c Noshkin (1985)
d Noshkin (1994)
e IAEA Working Group
f Data from Roos et al. (1992) assuming a dry/wet ratio of 0.2 and a water concentration of 1 Bq/m^3.
g Data from Dahlgaard, personal communication, assuming a water concentration of 6 Bq/m^3.

Table 4-7. Bioconcentration factors (m^3/kg) selected for use in risk assessment for different groups of marine organisms in Arctic seas. The bioconcentration factors were those in IAEA (1985), except where noted.

Group	Radionuclides ^{90}Sr	 ^{137}Cs	 ^{210}Po	 $^{239,240}Pu$	 ^{241}Am
	Bioconcentration Factor (m^3/kg)				
Macroalgae	5×10^{-3}	5×10^{-2}	1×10^{0}	2×10^{0}	8×10^{0}
Phytoplankton	3×10^{-3}	2×10^{-2}	3×10^{1}	1×10^{2}	2×10^{2}
Zooplankton	1×10^{-3}	3×10^{-2}	3×10^{1}	1×10^{0}	2×10^{0}
Annelids	—	$3 \times 10^{-2,\,a}$		—	$1 \times 10^{0,\,a}$
Mollusks	1×10^{-3}	3×10^{-2}	$3 \times 10^{1,\,b}$ $5 \times 10^{1,\,d}$	3×10^{0}	2×10^{1}
Large crustaceans	2×10^{-3}	3×10^{-2}	$3 \times 10^{1,\,b}$ $1 \times 10^{1,\,d}$	3×10^{-1}	5×10^{-1}
Fish muscle	$4 \times 10^{-3,\,e}$	1×10^{-1}	$2 \times 10^{0,\,b}$ $1.2 \times 10^{1,\,d}$	4×10^{-2}	5×10^{-2}
Fish liver	—	$4 \times 10^{-2,\,c}$	$5 \times 10^{2,\,d}$	$4 \times 10^{0,\,c}$	$1 \times 10^{-1,\,c}$
Mammal muscle	$1.1 \times 10^{-3,\,e}$	$1 \times 10^{-1,\,e}$	$1.7 \times 10^{0,\,f}$	$3 \times 10^{-3,\,e}$	—
Mammal liver	—	$6 \times 10^{-2,g}$	$2.2 \times 10^{1,\,f}$	—	—
Marine bird muscle		$1 \times 10^{-1,\,e}$	$3 \times 10^{1,\,d}$	$1 \times 10^{-1,\,e}$	—
Marine bird liver	—	2×10^{-1} to $1 \times 10^{0,\,e}$	—	6×10^{-2} to $2 \times 10^{0,\,e}$	—
Marine bird eggs			$4.6 \times 10^{1,\,d}$		

[a] Harrison (1986)
[b] Aarkrog et al. (1997)
[c] Noshkin (1985)
[d] Noshkin (1994)
[e] IAEA Working Group
[f] Data from Roos et al. (1992) assuming a dry/wet ratio of 0.2 and a water concentration of 1 Bq/m^3.
[g] Data from Dahlgaard, personal communication, assuming a water concentration of 6 Bq/m^3.

4.5 Estimated and Measured Concentrations of Radionuclides in Marine Species

Because data on the levels of radionuclides in marine species found in Alaskan waters are extremely limited, few opportunities exist to validate the BCFs selected for use in the risk assessment. There are, however, some measurements for marine organisms collected in the 1960s and 1990s for ^{137}Cs. Based on the review in Section 3, concentrations of ^{137}Cs were as high as 14 Bq/m^3 in the early 1960s in the Chukchi Sea because of global nuclear fallout, declining to under 2 Bq/m^3 in the 1990s. With a BCF of 0.1 m^3/kg for the muscle of fish, marine mammals, and seabirds, the levels of ^{137}Cs in muscle would range from about 0.2 to 1.4 Bq/kg for species collected during those years. For comparison, Baskaran et al. (1991) reported a concentration of 0.57 Bq/kg in muscle tissue of a bowhead whale obtained from the Chukchi Sea in 1987. This value is close to the geometric mean of 0.53 Bq/kg calculated from the predicted range of ^{137}Cs concentrations in muscle.

4.6 Summary

- The relationship between the radionuclide concentrations in marine species and that in the seawater in which they live is reviewed, and the importance of a derived parameter, bioconcentration factor (BCF), is described. BCF is commonly defined as a unitless parameter providing an indication at steady-state conditions of the bioaccumulation processes resulting from the transfer of radionuclides from ecosystem components (water, particulate matter, and food) to an organism. Information is provided on the principal radionuclides addressed in this assessment, i.e., ^{90}Sr, ^{137}Cs, ^{241}Am, and ^{239}Pu, and for the naturally occurring radionuclide ^{210}Po, which may be significant in some risk considerations.

- Bioconcentration factors of radionuclides were demonstrated to have a wide range from one group of organisms to another and from one radionuclide to another. Because the morphology and physiology of organisms may differ greatly, temporally and spatially, this variability is not unexpected. The RAIG constructed log normal probability plots for some radionuclides and characterized this variability in terms of the geometric mean and standard deviations of the BCFs.

- In its data compilation, the RAIG provides recommended BCFs (unitless and in m^3/kg) for groups of marine organisms from different trophic levels in Arctic ecosystems. In addition, a more extensive database on BCFs is provided for fishes from both temperate and Arctic waters, for sea mammals, and for seabirds.