

RADIONUCLIDES IN MARINE FISHES AND BIRDS FROM AMCHITKA AND KISKA ISLANDS IN THE ALEUTIANS: ESTABLISHING A BASELINE

Joanna Burger,^{*†‡} Michael Gochfeld,^{†‡§} David Kosson,^{†**} Charles W. Powers,^{†‡§} Barry
Friedlander,^{†‡§} Michael Stabin,^{†**} Derek Favret,^{†**} Stephen Jewett,^{†,††} Daniel
Snigaroff,^{‡‡} Ronald Snigaroff,^{‡‡} Tim Stamm,^{§§} James Weston,^{***} Christian Jeitner,^{*†}
and Conrad Volz^{†,†††}

En1

Abstract—Amchitka Island (51° N lat, 179° E long) was the site of three underground nuclear tests from 1965–1971. There have been no substantive studies of radionuclides in marine fishes and birds in the area since the mid-1970's. In this study, levels of ⁶⁰Co, ⁵²Eu, ⁹⁰Sr, ⁹⁹Tc, ¹²⁹I, ¹³⁷Cs, and the actinides (²⁴¹Am, ²³⁸Pu, ^{239,240}Pu, ²³⁴U, ²³⁵U, ²³⁶U, and ²³⁸U) were studied in ten marine fish species (including Pacific Cod *Gadus macrocephalus* and Pacific Halibut *Hippoglossus stenolepis*) and five marine bird species (including Glaucous-winged Gulls *Larus glaucescens*, Tufted Puffins *Fratercula cirrhata*, and Common Eider Ducks *Somateria mollissima*) from Amchitka. The same species were collected at a reference site, Kiska Island (52° N lat; 177° E long), about 130 km west of Amchitka. Each sample was a composite of edible muscle from five or more individual fish or birds of similar size ($\pm 15\%$) from the same sampling station. The null hypotheses of no differences among species or between Amchitka and Kiska were tested. Most analytic results were below the minimum detectable activity (MDA), even when 1,000 g sizes and 72 h counting times were used. The only radionuclides detected above the MDA were ¹³⁷Cs, ²⁴¹Am, ^{239,240}Pu, ²³⁴U, ²³⁵U, and ²³⁸U. There were significant differences in ¹³⁷Cs as a function of species, but not location, for top predatory fishes. Of the fishes, eight of ten species had ¹³⁷Cs values above the MDA for some samples; only one bird, Glaucous-winged Gull, had ¹³⁷Cs values above the MDA. The highest concentrations of ¹³⁷Cs were in Dolly Varden [*Salvelinus malma*, 0.780 (Bq kg⁻¹ wet weight)] and Pacific Cod (0.602

Bq kg⁻¹). In aggregate for any actinides, 73 of 234 (31%) composites for fish were above the MDA, compared to only 3 of 98 (3%) for birds. ²³⁴U and ²³⁸U, radionuclides that are primarily natural in origin, were routinely detected in these biological samples, but there were no significant differences in mean concentrations between Amchitka and Kiska. The concentrations of all radionuclides examined at Amchitka are similar to those of other uncontaminated Northern Hemisphere sites, and are lower than those reported for fishes and birds from the Irish Sea in the vicinity of the Sellafield nuclear reprocessing facility, an area with known contamination. *Health Phys.* 92(3):265–279; 2007

Key words: biological indicators; ¹³⁷Cs; plutonium; radioactivity, environmental

INTRODUCTION

THE MANAGEMENT of radioactive wastes and the protection of humans and the environment from residual wastes and nuclear accidents is an important element of radiation protection and public policy. Information on radionuclide concentrations in organisms at different nodes on the food chain, and in the foods that are eaten by people, is thus essential to understanding and quantifying potential risks from population exposures to these radionuclides. While models are useful in predicting what concentrations might be expected in different biota compartments in marine ecosystems (Kryshchuk et al. 2001; Matishov et al. 2001; Hakanson 2005), measurements of actual concentrations in biota and foods consumed are clearly more directly useful in predicting intake rates and ultimately doses, particularly when the public is included in determining what species and foods are tested (Burger et al. 2005). Further, using concentration factors to estimate concentrations in fishes and shellfish is not as direct as providing the data, and in any case, has proven not to be predictive for Arctic fishes (and thus presumably for subarctic fishes of similar behavior; Sazykina 1998).

AQ: A

* Division of Life Sciences, Rutgers University, 604 Allison Road, Piscataway, NJ 08854-8082; † Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Piscataway, NJ; ‡ Environmental and Occupational Health Sciences Institute (EOHSI), Piscataway, NJ; § Environmental and Occupational Medicine, UMDNJ-Robert Wood Johnson Medical School, Piscataway, NJ; ** Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN; †† School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, AK; ††† Village of Atka, Aleutians, Alaska; §§ Village of Nikolski, Aleutians, AK; *** Department of Biology, University of Mississippi, Oxford, MS; †††† Department of Environmental and Occupational Health, Graduate School of Public Health, University of Pittsburgh, Pittsburgh, PA.

For correspondence contact: J. Burger, Division of Life Sciences, Rutgers University, 604 Allison Road, Piscataway, NJ 08854-8082, or email at burger@biology.rutgers.edu.

(Manuscript accepted 15 September 2006)

0017-9078/07/0

Copyright © 2007 Health Physics Society

Amchitka Island was the site of three underground nuclear tests from 1965 to 1971, and although considerable biological and radiological work was conducted in the early 1970's (Merritt and Fuller 1977), there has been little evaluation of radionuclides in marine biota since then. In a primarily terrestrial study, Dasher et al. (2002) used the brown algae (*Fucus*) collected from Amchitka shores as a bioindicator of $^{240}\text{Pu}/^{239}\text{Pu}$ ratios and reported that the ratios were above the value of 0.18 indicative of global fallout (Krey et al. 1976; Buesseler and Halverson 1987), but noted that because of small sample sizes and potential analytical issues, more research was necessary. Amchitka has posed a challenge for the U.S. Department of Energy (DOE), state and federal regulators, and other stakeholders including the Aleuts and other people living in the Aleutian Islands. People were primarily concerned about the concentrations of radionuclides and mercury in marine biota and subsistence foods. Controversy also existed at the time of the tests because of concerns about the disruptive role of earthquakes and other geologic events on the nuclear residue remaining in the underground test cavities (Greenpeace 1996; U.S. DOE 1997, 2000; Kohlhoff 2002; Eichelberger et al. 2002).

The aims of the present study were to examine the concentrations of a wide range of radionuclides in fishes and birds in the marine ecosystem surrounding Amchitka Island, and to compare them to a reference site (Kiska Island). Specific objectives were to determine whether there were inter-specific (differences between species) and inter-island differences in radionuclide concentrations, and to determine the relative concentrations among radionuclides in biota from this region. These data can be used to examine seafood safety, to determine whether the concentrations found in fishes and birds at Amchitka were similar to those found in other regions of the Northern Hemisphere, and to establish a baseline for future monitoring. This work is part of a larger multidisciplinary project by the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) to provide the information to assure the protection of human health and the environment, and to provide a baseline for monitoring in the context of a long-term stewardship plan for Amchitka (Powers et al. 2005, 2006; Burger et al. 2006a). While these data are critical for the development of long-term protection and surveillance on Amchitka Island, they can also be used to provide baseline radionuclide data for fishes and birds in this region of the Northern Pacific Ocean and Bering Sea.

Although the human population density in the immediate vicinity is relatively low, the Bering Sea ecosystem provides a large percentage of the fish and shellfish for commercial sale in the United States and elsewhere (AFSC 2003). Understanding baseline concentrations is

particularly important for the Bering Sea region, where there is intense commercial fishing. Dutch Harbor in the Aleutians, the port for commercial fish in the Bering Sea, had the highest tonnage of fish landings in the world in 2003, and provides 17% of Alaska's \$811 million fish landings (2.3 million metric tons of fish; NOAA 2004). Over 90% of the world's fish catch comes from 10% of the world's oceans (including the Bering Sea; Waldichuk 1974). Thus, having baseline data from the Aleutians is important, even without any interest in Amchitka as an underground nuclear test site. Many of the fish examined are relatively sedentary (i.e., greenling, sole, rockfish), others regularly move short distances (i.e., cod simply move seasonally inshore and offshore along the same continental shelf region; Simenstad et al. 1977). Likewise, the seabirds are mobile, but resident year-round in the Aleutians, remaining within the same general area (White et al. 1977).

MATERIALS AND METHODS

Study sites

Amchitka Island (Fig. 1, 51° N lat; 179° E long), in the Aleutian chain of Alaska, is part of the Alaska Maritime National Wildlife Refuge system under the aegis of the U.S. Fish & Wildlife Service (U.S. FWS) and contains important ecological resources (Merritt and Fuller 1977; Burger et al. 2005). Amchitka Island is the only island where underground tests were conducted, making it difficult to assess and technically impossible to remove the residual radionuclide levels. It is unusual

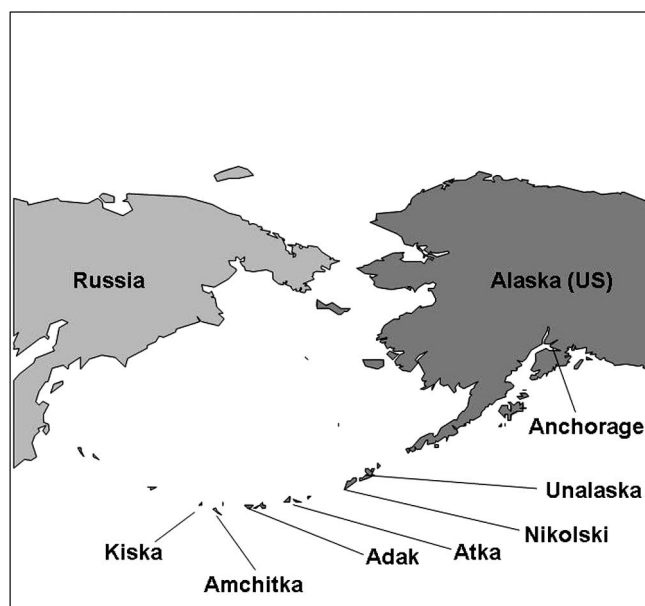


Fig. 1. Map of Amchitka and Kiska Islands in the Aleutian Chain of Alaska.

among DOE-contaminated sites because of its combination of remoteness, depth below ground surface of the contamination, and the importance of its ecological resources and seafood productivity that could be at risk if there were significant seepage of radionuclides from the test cavities to the marine environment. It is believed that most of the radioactive material from the Amchitka tests is trapped in the vitreous matrix created by the intense heat of the blasts, and is therefore permanently immobilized. This, however, is only an assumption, and some model results indicate that breakthrough of radionuclides into the marine environment will eventually occur (U.S. DOE 2002a and b; Powers et al. 2005). Data on radionuclide residues and conditions in the cavities remain classified.

After extensive consultation with the U.S. FWS and the Alaska Department of Environmental Conservation (ADEC), Kiska Island (51° N lat; 177° E long) was selected as the reference site. The reference had to be far enough away to be uninfluenced by Amchitka, yet close enough to share its geologic and biologic features. Both islands are bordered on the south by the North Pacific and on the north by the Bering Sea (Fig. 1). Kiska Island contains many of the same terrestrial and benthic environments and species composition as Amchitka (Burger et al. 2006b, c). The collection sites on Kiska and Amchitka were at least 130 km apart, a sufficient distance that most fish and birds remained within the vicinity of each island. Because of the ice free waters of the region, many of the sea birds do not migrate away from the area in the winter, but are residents in waters around their breeding island; many of the fish are sedentary (rock greenling, sole, rockfish) or move from

inshore to offshore seasonally (cod) (Simenstad et al. 1977). Although it did not experience any underground nuclear tests, Kiska Island was occupied by both the Japanese and later the U.S. military during World War II, and Amchitka was a military base at the time.

Protocol

Fishes and birds were collected under appropriate federal and state permits from both Amchitka and Kiska Islands from late June–July 2004. Dolly Varden were only collected at Amchitka. Species collected, shown with their scientific names in Table 1, had a wide distribution, are reported as subsistence foods of the Unangan (Aleut) people, and some of the fishes are commercially important for the region. All specimens were tracked from field collection to their ultimate analytic destinations with chain-of-custody forms. Our overall protocol was to collect the same number of individuals of each species from near each of Amchitka's three test areas (*Long Shot*, *Milrow*, *Cannikin*) and from Kiska. Fishes were collected by Aleut fishermen using rods and reels, by the diving team using spears, and by a fisheries biologist on a National Oceanographic and Atmospheric Administration (NOAA) vessel by trawling. Adult birds were shot by the Aleut members of our team, and bird eggs and fledglings were collected from nesting colonies by hand (Burger et al. 2005; Jewett et al. 2006). The diving team consisted of four divers who worked in pairs at depths ranging from 5 to 27 m. The NOAA trawl was part of a standardized biennial fish survey in the Aleutians. Marine algae and invertebrates were collected at the same time (Burger et al. 2006b, d).

Fishes and birds were scanned on deck with a Ludlum Model 44-10 NaI gamma and a Ludlum Model

Table 1. List of species, with scientific name of organism collected at Amchitka and Kiska.

Common name	Scientific name	Eaten by Aleuts
Lower predators		
Dolly Varden	<i>Salvelinus malma</i>	Yes
Atka Mackerel	<i>Pleurogrammus monopterygius</i>	Yes
Red Irish Lord	<i>Hemilepidotus hemilepidotus</i>	Yes
Yellow Irish Lord	<i>Hemilepidotus jordani</i>	Yes
Northern Rock Sole	<i>Lepidopsetta polyxystra</i>	Yes
Rock Greenling	<i>Hexagrammos lagocephalus</i>	Yes
Pacific Ocean Perch	<i>Sebastes alutus</i>	Yes
Black Rockfish	<i>Sebastes melanops</i>	Yes
Common Eider adults (birds)	<i>Somateria mollissima</i>	Yes
Common Eider (eggs)	<i>Somateria mollissima</i>	Yes
Higher trophic level		
Walleye Pollock	<i>Theragra chalcogramma</i>	Yes
Glaucous-Winged Gull (bird)	<i>Larus glaucescens</i>	No
Glaucous-Winged Gull (eggs)	<i>Larus glaucescens</i>	Yes
Pigeon Guillemot	<i>Cephus columba</i>	Yes
Tufted Puffin	<i>Fratercula cirrhata</i>	Yes
Top trophic level		
Pacific Halibut	<i>Hippoglossus stenolepis</i>	Yes
Pacific Cod	<i>Gadus macrocephalus</i>	Yes
Bald Eagle	<i>Haliaeetus leucocephalus</i>	No

44-9 alpha, beta, gamma pancake type halogen quenched G-M detector, both attached to a Ludlum Model 2241-2 ratemeter (Ludlum Instruments, Inc., 501 Oak Street, P.O. Box 810, Sweetwater, TX 79556). The instrument was factory calibrated on 23 May 2004, before expedition use. Scanning was accomplished to identify any specimens with high radioactivity that might contaminate the ship or personnel. Such specimens would have been stored in lead bags. However, none of the samples scanned during the expedition exceeded background readings, so the lead-bag contingency was not activated. The scanning was for safety only, and the results were not recorded.

Processing the fish and bird samples included filling in the chain of custody forms, and measuring, weighing, dissecting, packaging, labeling and freezing muscle and organs. The 100-g composites contained five similarly sized individual ($\pm 15\%$) fish or birds of one species from one sampling station that were prepared for analysis. To enhance the sensitivity for ^{137}Cs we prepared 1,000-g composites that required up to 24 individuals for small

species (Table 2). Samples were prepared for analysis and homogenized in a radio-clean and metal-clean laboratory at Rutgers University and subsequently analyzed for radionuclides at Vanderbilt University and Idaho National Laboratory (INL). Since one of the study objectives was to assess whether there was any cause for concern about human health, we analyzed the tissues that would be expected to have the highest concentrations (bioaccumulate the highest levels) as a screen (e.g., muscle for ^{137}Cs and bone for ^{90}Sr).

Wipe samples of laboratory table tops and blenders were taken every day in the laboratory and read in a Ludlum Model 44-9 detector. No wipe samples were above background or blanks. The filter paper discs were then archived in scintillation vials, marked with the date and time taken, and were sent to Vanderbilt University for corroborative analysis by liquid scintillation analysis (LSA). All wipe samples were below the minimum detectable activity (MDA) level (see Powers et al. 2005, appendices).

Our radionuclide analysis design was based on trophic level considerations and sample availability and

Table 2. Radionuclide analysis conducted for human health screen. Total analyses run by species and radionuclide for 100 g samples. For cesium the number of 1,000 g samples is shown in parentheses. This is a complete species list for all analyses.

Species	Tissue	Number of 100 g composite samples for analysis						
		^{137}Cs	^{129}I	^{60}Co	^{152}Eu	^{90}Sr	Alpha ^a analyses	^{99}Tc
Lower predators								
Dolly Varden	muscle	8 (2)		8	8			
Atka Mackerel	muscle	1 (3)	1	1	1	2		2
Atka Mackerel	bone	1 (3)		1	1	1	1	
Red Irish Lord	muscle	8		8	8			
Yellow Irish Lord	muscle	15 (3)	4	15	15	4		4
Yellow Irish Lord	bone	3	1	3	3	3	3	
Northern Rock Sole	muscle	(2)						
Rock Greenling	muscle	23 (5)	9	23	23	4		4
Rock Greenling	bone	4	4	4	4			
Pacific Ocean Perch	muscle	2 (3)	2	2	2	2		2
Pacific Ocean Perch	bone	1	1	1	1	1	1	
Black Rockfish	muscle	12 (3)	4	12	12	4		4
Black Rockfish	bone	3	2	3	3	1	1	
Eider adults (birds)	muscle	4 (2)		4	4			
Eider (eggs)	eggs	6 (2)	3	6	6	3		3
Higher trophic level								
Walleye Pollock	muscle	(2)				2		2
Walleye Pollock	bone					2	2	
Gull (birds)	muscle	18 (2)	8	18	18	8		8
Gull (birds)	bone	8		8	8	8	8	
Gull (eggs)	egg	(2)						
Pigeon Guillemot	muscle	7	3	7	7	3		3
Pigeon Guillemot	bone	3		3	3	3	3	
Tufted Puffin	muscle	6 (2)	3	6	6	3		3
Tufted Puffin	bone	3		3	3	3	3	
Top trophic level								
Pacific Halibut	muscle	(4)						
Pacific Halibut	bone						4	
Pacific Cod	muscle	14 (14)	5	14	14	5		6
Pacific Cod	bone	3		3	3		14	
Bald Eagle	muscle	(2)						

^a The actinides analyzed were ^{241}Am , ^{238}Pu , $^{239,240}\text{Pu}$, ^{234}U , ^{235}U , ^{236}U , ^{238}U .

quantity. Desired detection sensitivity was initially set using a lifetime human cancer risk level of 10^{-6} , and sample numbers, counting times, and quantities were selected based on achieving detection levels well below this risk level. We used this process to determine how many samples we needed to run of each species (and thus how many to collect in the field). However, when we found that most samples were below the MDA for ^{137}Cs , we shifted to larger quantities (1,000 g) and longer counting times (72 h) to provide quantitative results useful for bioindicator selection.

Detailed analytic and quality assurance (QA) methods are provided for Vanderbilt (2005) and INL (INEEL 2005). Both laboratories shared and reviewed their proposed analytic methods. The Data Quality Objectives were established in advance of sample collection (CRESP 2003) and informed the establishment of target MDAs and numbers of samples. The MDA was derived following the method originally proposed by Currie (1968). Isotopes analyzed included radioactive cesium (^{137}Cs), iodine (^{129}I), cobalt (^{60}Co), europium (^{152}Eu), strontium (^{90}Sr), technetium (^{99}Tc), americium (^{241}Am), plutonium (^{238}Pu , $^{239,240}\text{Pu}$), and uranium (^{234}U , ^{235}U , ^{236}U , ^{238}U). Analyses at Vanderbilt and INL provided inter-laboratory validation (Powers et al. 2005). Samples below the MDA in one laboratory were below the MDA in the other. Samples above the MDA were within 20%, except for one sample that was re-analyzed.

Gamma emitters (^{137}Cs , ^{152}Eu , ^{60}Co) were analyzed using homogenized samples loaded into 0.5 L Marinelli

beakers and counted on high purity germanium detectors (HPGe) calibrated to the container geometry for 24–72 h. ^{99}Tc was “trapped” on an Eichrom TEVA resin (Eichrom Technologies, Inc., 8205 S. Cass Ave., Suite 106, Darien, IL 60561) to preconcentrate the analyte and remove potential interferences prior to measurement by inductively coupled plasma-mass spectrometry (ICP-MS). The method uses rhenium spikes as a recovery surrogate. ^{129}I was analyzed with a HPGe detector optimized for low energy photon counting. Solid phase extraction was used for selective separation of strontium, americium, plutonium, and uranium using a serial configuration of Eichrom TRU resin and TEVA columns. The beta emitter, ^{90}Sr , was separated by sulfate precipitation and analyzed at Vanderbilt by LSC of its decay product ^{90}Y . The actinides (uranium, plutonium, and americium) were quantified radiochemically using co-precipitation with neodymium fluoride, followed by alpha spectroscopy (INEEL 2001 Method ACM 3816).

Counts were adjusted for background counts, and evaluated against detection limits based on the method of Currie (1968). All values are presented in Bq kg^{-1} , wet weight. Average MDAs ranged from 0.029 Bq kg^{-1} for ^{241}Am to 0.102 Bq kg^{-1} for ^{235}U . Initially for gamma emitters, 100-g samples were counted for 24 h, but all results were below the MDA; thus, to enhance sensitivity, 1,000-g samples were analyzed for 72 h. MDAs for ^{137}Cs ranged from $5.57\text{--}6.25 \text{ Bq kg}^{-1}$ for 100-g samples and $0.18\text{--}0.36 \text{ Bq kg}^{-1}$ for 1,000-g samples (Table 3).

AQ: F

AQ: G

AQ: H

Table 3. Examination of predators for use as bioindicators for ^{137}Cs . Given are the values in Bq kg^{-1} (wet weight) for 1,000 gram samples only. For comparative purposes, all predators are listed. Trophic levels were based on previous information. Low trophic levels eat mainly invertebrates. Medium trophic levels eat small fish. Higher trophic levels eat medium-sized fish. These distinctions are not absolute; for example, smaller or younger individuals feed at a lower trophic level than older or larger individuals of the same species.

Species	Number of 1,000 g analyses	Mean MDA Bq kg^{-1} (wet weight)	Percent above the MDA	All values above the MDA are shown below in Bq kg^{-1} (wet weight)
Low trophic level				
	(Total number of individuals)			
Dolly Varden	2 (46)	0.12	100	0.697, 0.780
Atka Mackerel	3 (30)	0.10	33	0.102
Rock Greenling	5 (37)	0.25	0	—
Yellow Irish Lord	3 (15)	0.10	33	0.131
Northern Rock Sole	2 (10)	0.10	0	—
Pacific Ocean Perch	3 (15)	0.12	33	0.108
Black Rockfish	3 (31)	0.10	100	0.189, 0.130, 0.111
Eider (birds)	2 (10)	0.23	0	—
Eider (eggs)	2 (29)	0.10	0	—
Medium trophic level				
Walleye Pollock	2 (10)	0.32	50	0.461
Gulls (birds)	2 (18)	0.26	50	0.094
Gulls (eggs)	2 (14)	0.24	0	—
Tufted Puffin	2 (15)	0.12	0	—
Top trophic level				
Pacific Halibut	4 (14)	0.15	75	0.190, 0.315, 0.446
Pacific Cod	14 (71)	0.28	57	0.176, 0.200, 0.209, 0.315, 0.323, 0.399, 0.472, 0.602
Bald Eagle	2 (2)	0.66	0	—

Sample results above the MDA are referred to as “detects” and values below the MDA are “non-detects” (Helsel 2005). For calculating the means, “non-detects” were assigned half their respective MDA, a common but not ideal convention in environmental chemistry (Helsel 2005). This is the least biased statistical approach, although if the concentration of an analyte is truly zero, it introduces an upward bias (Gochfeld et al. 2005). Because of the large number of values for composites that fell below the MDA, the actual values for “detects” is given in Table 3.

RESULTS

The raw data tables for this study are available at <http://www.cresp.org/Amchitka/RadionuclideData.html>. For analytic quality assurance see Vanderbilt (2005) and INEEL (2005). For fishes and birds, there were no values above the MDA for several radionuclides, including ¹²⁹I, ⁶⁰Co, ¹⁵²Eu, ⁹⁰Sr, and ⁹⁹Tc. The remainder of the paper focuses on radiocesium (¹³⁷Cs) and the actinides.

Actinides

There were significant inter-specific differences among the actinide radionuclides, in terms of percent of samples above MDA and activities measured for “detects.” For fishes, 73 composites of 234 (31%) were above the MDA (Table 4). For birds, only 3 composites of 98 (3%) had results above the MDA. There were no composites above the MDA for ²³⁸Pu or ²³⁶U in fishes or birds. For ²⁴¹Am, there were only three out of 36 composites above the MDA for fishes and none for birds. Only three samples exceeded the MDA for ^{239,240}Pu (one each for Walleye Pollock, Halibut, and Pigeon Guillemot), and only four composites were above the MDA for ²³⁵U (one each for Atka Mackerel, Black Rockfish, Walleye Pollock, and Pacific Cod) (Table 4).

²³⁴U and ²³⁸U, radionuclides that are primarily natural in origin, had the greatest number of samples that were above the MDA. All fish species had some composites above the MDA for both ²³⁴U and ²³⁸U, but birds only had detectable concentrations of ²³⁸U. Most composites of Halibut and Pacific Cod had values above the

Table 4. Number of composites, number above the maximum actinides level (MDA) and highest value above the MDA for radionuclides in biota from Amchitka and Kiska. Top line is the number of composites above the MDA/number of composites. Lower line for each species is the maximum level in Bq kg⁻¹ wet weight. For Source, A = anthropogenic and N = naturally occurring. X = no analyses conducted.

Species	¹³⁷ Cs	²⁴¹ Am	²³⁸ Pu	^{239,240} Pu	²³⁴ U	²³⁵ U	²³⁶ U	²³⁸ U
Main source	A	A	A	A	N	A	A	N
Lower predators								
Dolly Varden	3/3 0.78	X	X	X	X	X	X	X
Atka Mackerel	1/3 0.102	0/1	0/1	0/1	1/1 0.963	1/1 0.065	0/1	1/1 0.94
Rock Greenling	0/5 0.16	X	X	X	X	X	X	X
Yellow Irish Lord	1/3 0.25	0/3	0/3	0/3	3/3 0.567	0/3	0/3	3/3 0.607
Northern Rock Sole	0/2	X	X	X	X	X	X	X
Pacific Ocean Perch	1/3 0.108	0/1	0/1	0/1	1/1 0.655	0/1	0/1	1/1 0.654
Black Rockfish	3/3 0.189	1/1 0.029	0/1	0/1	1/1 2.18	1/1 0.116	0/1	1/1 1.83
Eider (birds)	0/2	X	X	X	X	X	X	X
Eider (eggs)	0/2							
Higher trophic level								
Walleye Pollock	1/2 0.461	1/2 0.022	0/2	1/2 0.02	2/2 0.857	1/2 0.053	0/2	2/2 0.779
Gulls (birds)	1/2 0.094	0/8	0/8	0/8	0/8	0/8	0/8	1/8 0.449
Gulls (eggs)	0/2	X	X	X	X	X	X	X
Pigeon Guillemot	X	0/3	0/3	1/3 0.312	0/3	0/3	0/3	0/3
Tufted Puffin	0/2	0/3	0/3	0/3	0/3	0/3	0/3	1/3
Top trophic level								
Pacific Halibut	3/4 0.445	0/7	0/7	1/7 0.017	6/7 1.2	1/7 0.048	0/7	7/7 0.179
Pacific Cod	8/14 0.602	1/21 0.015	0/21	0/21	17/21 0.29	0/21	0/21	17/21 0.2575
Bald Eagle	0/2	X	X	X	X	X	X	X

MDA for ²³⁴U (means ± standard error of 0.289 ± 0.15 and 0.109 ± 0.01 Bq kg⁻¹ wet weight, respectively) and ²³⁸U (means ± standard error of 0.21 ± 0.12 and 0.112 ± 0.01 Bq kg⁻¹, respectively).

For most radionuclides the relatively low percentage of composites above the MDA precluded examining inter-island and inter-specific differences. However, it is clear that a higher percent of fishes accumulated actinides than birds, and that all trophic levels of fishes had detectable concentrations of the naturally-occurring ²³⁴U and ²³⁸U. Halibut and cod combined had sufficient composites above the MDA to examine inter-island differences for the naturally-occurring uranium isotopes. Using Kruskal Wallis non-parametric One-Way Analysis of Variance there were no significant inter-island differences in concentrations for ²³⁴U ($X^2 = 1.22, p = 0.27$) or ²³⁸U ($X^2 = 2.29, p = 0.138$). Nor were there inter-island differences in the MDAs for ²³⁴U ($X^2 = 1.12, p = 0.29$) or ²³⁸U ($X^2 = 0.93, p = 0.33$).

There were also no significant differences between cod and halibut for ²³⁴U in either of the concentrations ($X^2 = 1.43, p = 0.23$) or the MDAs ($X^2 = 0.77, p = 0.38$). Also, there were no differences between cod and halibut for ²³⁸U in concentrations ($X^2 = 0.44, p = 0.51$) or MDAs ($X^2 = 0.31, p = 0.58$). Combined, these data indicate that the concentrations of naturally-occurring uranium isotopes were higher than the anthropogenic radionuclides, and that there were no differences among islands or species for cod and halibut, the species with the largest number of composites analyzed and with detectable concentrations.

Radiocesium

None of the ¹³⁷Cs values for fishes and birds were above the MDA for the 100-g samples counted for 24 h ($N = 173$ composites), so 1,000-g samples were then counted for 72 h (Table 3). Most of these samples were either below or close to the MDA. Except for one gull sample, all 1,000-g bird samples were below the MDA ($N = 12$ samples representing 88 birds or eggs).

The percent of values above the MDA for fishes ranged from 0% (Rock Greenling and Northern Sole) to

100% (for Dolly Varden, Black Rockfish). The highest values were for Dolly Varden, Walleye Pollock, Pacific Halibut, and Pacific Cod. The mean ± standard error for ¹³⁷Cs value in the species with the most composites are as follows (values below the MDA were entered as half the MDA): Black Rockfish = 0.143 ± 0.04, Halibut = 0.24 ± 0.14, Pacific Cod = 0.29 ± 0.20, Walleye Pollock = 0.311 ± 0.311, and Dolly Varden = 0.74 ± 0.04 Bq kg⁻¹. Pacific Cod, the species with the most composites analyzed, did not show any difference in ¹³⁷Cs as a function of the size of the individual fish sampled, although the mean total fish lengths in composites varied from 42 to 92 cm.

When fish were compared, there was not a significant difference in either the percent of values above the MDA or in the mean value of ¹³⁷Cs for fish collected at Amchitka and Kiska (Table 5). Dolly Varden was excluded from this analysis because it was collected only from Amchitka.

DISCUSSION

Establishing baselines

Radionuclides in the environment come from natural sources, from fallout from historic nuclear weapons testing (Duran et al. 2004), from nuclear facility accidents (Baeza et al. 1994; Cooper et al. 1998; Livingston and Povinec 2000), and from discarded nuclear wastes (Fisher et al. 1999; IAEA 1999), as well as other nuclear accidents (UNSCEAR 2000; Sanchez-Cabeza and Molero 2000; Amundsen et al. 2002; Aumento et al. 2005). A total of 543 atmospheric nuclear weapons tests were conducted from 1945–1980, primarily in the Northern Hemisphere (UNSCEAR 2000), although radionuclides have been found in fishes from as far away as the Antarctic (Marzano et al. 2000). The disposal of large quantities of radioactive wastes in the Arctic Seas by the former Soviet Union prompted interest in radionuclides in the Bering Sea ecosystem as well (Fisher et al. 1999). Early on, Moscati and Erdmann (1974) recognized the implications of accidental releases of radioactivity into the marine environment, often noting the importance of

Table 5. Comparison of ¹³⁷Cs levels in fishes between Amchitka and Kiska. Comparison for Black Rockfish, Pacific Halibut, Pacific Cod, Walleye Pollock, Pacific Ocean Perch, Atka Mackerel and Yellow Irish Lord (1,000 gram samples only, fish species where cesium was detected in at least one composite sample). Dolly Varden is not included because samples came only from Amchitka.

	Amchitka	Kiska	Statistical test
Number of composites	20	12	
Number positive (%)	10	8	0.84, $p < 0.36$
Mean ± SD (using 1/2 MDA for non detects) (range)	0.152 ± 0.160 (<0.05–0.602)	0.184 ± 0.139 (0.069–0.461)	0.61, $p < 0.43$
Mean ± SD for detects only	0.257 ± 0.167	0.252 ± 0.120	0.08, $p < 0.93$

^{137}Cs , ^{239}Pu , and other radionuclides in producing adverse health impacts.

Because of the importance of fish and shellfish consumption throughout the world, and the occurrence of atmospheric deposition into marine environments, a number of monitoring programs have been established in Asia (Duran et al. 2004), in the Sea of Japan (Togawa et al. 1999; JCAC 2003, 2004), in the Irish Sea (RPII 2003, 2004), and in the Black Sea (Bologa 2000). Other biomonitoring programs have been established to evaluate possible exposure from nuclear facility operations (Poon and Au 2002; Shinohara 2004), as well as exposure due to dumping by the former Soviet Union (Togawa et al. 1999; Yamada et al. 1999; Matishov et al. 2001). Some of this biomonitoring is ongoing near decommissioned nuclear power plants and reprocessing plants (e.g., Sellafield in the UK, Sanchez-Cabeza and Molero 2000; and in Taiwan, Hung et al. 1998). The present data set can serve as a baseline for the Northern Pacific/Bering Sea ecosystem for possible future seepage from the Amchitka underground nuclear test shots and for nuclear waste dumping or accidents from the former Soviet Union. While fishes and birds often have relatively low concentrations of radionuclides (Skwarzec 1997), they are key species both for the ecosystem and (except for the eagle) for both subsistence and commercial human consumption. All of the fishes and most birds we studied are regularly eaten by native people of the Aleutians (Hamrick and Smith 2003).

Inter-specific and inter-island differences

There were inter-specific differences in concentrations of radionuclides for fishes and birds: 1) for actinides, 31% of the fish composites exceeded the MDA, while only 3% of the bird composites had concentrations above the MDA; 2) for ^{234}U and ^{235}U , some fish composites were above the MDA, but no bird composites were above the MDA; 3) for ^{238}U , a higher percent of composites for fishes were above the MDA than for birds; 4) for ^{137}Cs , 46% of the composites were above the MDA for fishes, compared to 8% for birds, and 5) some species of fishes had no composites above the MDA, while others had up to 100% above the MDA. Thus, there were inter-specific differences in the radionuclide concentrations both among fishes and birds, and within fish species. For birds, ^{234}U was below MDA even when ^{238}U was detectable. This unexpected result is most likely related to the generally low levels of ^{238}U in the bird tissues, not to some fundamental toxicokinetic difference between fish and birds.

Inter-specific differences in concentrations of contaminants, including radionuclides, are usually due to differences in trophic level (Denton and Burdon-Jones 1986; Jackson 1991; Kasamatsu and Tshikawa 1997; Watras et al. 1998; Wiener and Spry 1996; Wiener et al. 2003; Burger et al. 2001), size and age (Lange et al. 1994; Bidone et al. 1997; Burger et al. 2001; Pinho et al. 2002; Green and Knutzen 2003), and habitat (Burger et al. 2002). In general, concentrations are higher in species that are larger, older, and at a higher trophic level. Sanchez-Cabeza and Molero (2000) found higher ^{137}Cs concentrations in pelagic fishes, compared to more sedentary demersal fishes. These differences may be partly due to some of the larger pelagic fishes being higher on the food chain. Trophic level relationships have been previously reported for ^{137}Cs (Pentreath 1973).

In this study, species that were higher on the trophic scale and were large, such as pollock, cod, and halibut, generally had higher concentrations than the smaller fishes and than birds, several of which consume small fish (Puffins, Guillemots) or invertebrates (Eiders). However, ^{137}Cs concentrations were highest in Dolly Varden, which is a smaller fish than most others examined in this study, and is short-lived (up to 8–16 y; ADFG 1994), although the differences were not great. Halibut range in age up to 55 y, and Pacific Cod up to 25 y (Merrell 1977; Munk 2001). As large predators within the marine ecosystem, both cod and halibut eat other medium-sized fishes. There was no relationship between size or weight of cod and ^{137}Cs concentrations, however, unlike the fishes examined by Kasamatsu and Tshikawa (1997). This lack of difference may be due either to small sample sizes, or to lower concentrations of ^{137}Cs in the Amchitka/Kiska fish. However, Kasamatsu and Tshikawa (1997) also found no relationship of ^{137}Cs with size for 12 of the 16 species of fish they examined. The percent of composites above the MDA for $^{239,240}\text{Pu}$ was similar for birds and fish, and they were very low.

There were no inter-island differences in this study for fishes, and the concentrations were relatively low for all radionuclides. One potential source of radionuclides could have been seepage from the underground nuclear test cavities at Amchitka, but we found no evidence that this has occurred.

Temporal patterns for ^{137}Cs

Radiological analyses immediately after the *Cannikin* detonation (5 megatons in 1971) found no contamination in marine fishes (Held et al. 1973). The concentrations of ^{137}Cs in fishes in 2004 could be compared to those found immediately after the nuclear tests (Table 6). For all fishes there was a decline in the concentrations of

Table 6. Temporal patterns of ¹³⁷Cs for fish from Amchitka, compared to 1967–1968 (Isakson and Seymour 1968), and 1965–1974 (Seymour and Nelson 1977). Given are the means in Bq kg⁻¹ (wet weight). Some have been calculated from dry weight data in the literature using the average percent moisture content for that species. The percent of samples above the MDA is given in parentheses.

Species	1967–1968	1965–1975	This study
Dolly Varden	not given	7.2 (2.4%)	0.74 (100%)
Rock Greenling	0.89 (100%)	0.523 (not given)	< MDA of 0.29 (0%)
Walleye Pollock	0.96 (100%)	not given	0.31 (50%)
Pacific Halibut	1.24 (50%)	0.58 (not given)	0.24 (75%)
Pacific Cod	1.14 (100%)	not given	0.29 (57%)

¹³⁷Cs from the time of the tests until the present. The decline ranged from 60% in pollock, to over a 75% decline for halibut and cod. The individual fishes examined in this study from 2004 were not present at the time of the last underground nuclear test (1971), since no very large halibut were collected, and the oldest cod (aged by otoliths) was less than 10 y old. Mainly, radioactive decay of ¹³⁷Cs from earlier atmospheric testing (radiologic half-life of 30 y; biologic half-life about 110 d) can account for the lower concentrations.

Worldwide, the concentrations of radionuclides in seawater and biota have been declining since the period of intense above-ground nuclear testing in the 1950's and 1960's; this includes fishes (Waldichuk 1989; Noshkin et al. 1997; Duran et al. 2004). In the Marshall Islands, several radionuclides decreased significantly in fishes between 1958 (the end of above-ground nuclear testing there) and 1994, due to both radioactive decay and other natural processes (recycling or environmental decay; Noshkin et al. 1997). Similar declines have occurred in the Irish Sea (Kanisch et al. 2000) where there are multiple sources.

Geographical comparisons

One of the objectives of this study was to compare the concentrations of radionuclides found in the fishes and birds at Amchitka and Kiska with those from other regions in the Northern Hemisphere, both uncontaminated sites and contaminated sites such as the Irish Sea. Part of the difficulty with comparisons of results from this study with other studies reported in the literature is that the suite of radionuclides and associated detection limits examined varies by site and, of course, the objectives of the study reported.

Actinides. There are fewer data for actinides in fishes and birds from the Northern Hemisphere than there are for ¹³⁷Cs. However, Hunt and Smith (1999) noted that actinides released from Sellafield constitute a

major pathway to seafoods consumed by humans. Information on actinides may be less available in the literature because of inconsistency in the suite of radionuclides examined. This inconsistency is partly due to the great expense of radionuclide analysis, an emphasis on the radionuclides of high health concern, such as ¹³⁷Cs and ⁹⁰Sr, and because of local efforts to analyze only for the most likely radionuclides released from local nuclear activities, dumping, or accidents.

The concentrations of actinides from Amchitka and Kiska for fishes were an order of magnitude lower for ²⁴¹Am, higher for ²³⁸U, similar for ²³⁸Pu, and higher for ^{239,240}Pu, compared to other Northern Hemisphere sites (Table 7). From the Japanese coast, Yamada et al. (1999) reported ^{239,240}Pu concentrations of 0.0004 Bq kg⁻¹ in fishes, indicating that the fishes were not currently affected by nuclear waste dumping by the Former Soviet Union. Some studies report ²³⁹Pu alone (Marzano et al. 2000), making comparison difficult.

Rollo et al. (1992) examined mainly naturally-occurring radionuclides in the marine environment around the United Kingdom (UK), and found the following maximum concentration for Atlantic Cod: ²³⁴U = 0.011 Bq kg⁻¹ (compared to 0.29 Bq kg⁻¹ for Pacific Cod at Amchitka) and ²³⁸U = 0.009 Bq kg⁻¹ (compared to 0.258 Bq kg⁻¹ at Amchitka). Thus the concentrations of the naturally-occurring radionuclides were higher at Amchitka/Kiska than in the marine environment around the UK. In some places, such as the UK, radioactivity from natural sources is by far the most significant source of exposure to communities remote from nuclear sites (CEFAS 2004). Similarly, the anthropogenic ²³⁵U of 0.0007 Bq kg⁻¹ in cod around the United Kingdom (Rollo et al. 1992) was lower than the values for Amchitka. Around Amchitka all values of ²³⁵U

Table 7. Geographical comparisons of some actinides (Bq kg⁻¹, wet weight) for birds and fish from the Irish Sea and other Northern Hemisphere locations.^a Given are means or ranges of means when multiple data are available. Some results were originally reported in pCi or in dry weight and have been converted.

Group	Irish Sea	Other sites	Amchitka/Kiska (2004) ^b
Birds			
²⁴¹ Am			< MDA
²³⁸ U			< 0.45
²³⁸ Pu			< MDA
^{239,240} Pu			0.31
Fish			
²⁴¹ Am	0.0001–0.23	0.0012	0.029
²³⁸ U	0.003–.005	0.008–0.015	0.94
²³⁸ Pu	< MDA–0.02	< MDA	< MDA
^{239,240} Pu	< MDA–0.08	< MDA–0.07	0.02

^a Sources: Ryan et al. (2003), RPII (2003, 2004), CEFAS (2003, 2004).

^b The maximum value is given because the concentrations were so low and close to the MDA.

for cod were below the MDA, but for Walleye Pollock the high value was 0.053 Bq kg⁻¹.

There are even fewer data on actinides in birds from the Northern Hemisphere.

Radiocesium. Table 8 lists the mean concentrations for ¹³⁷Cs for some representative fishes and birds from the Northern Hemisphere. Several conclusions can be drawn from these data for ¹³⁷Cs. The ¹³⁷Cs mean for fishes from Amchitka (mean of 0.04 to 0.74 Bq kg⁻¹, depending upon species) was similar to concentrations for the Northern Hemisphere generally (mean of 0.22 Bq kg⁻¹, range up to 0.33 Bq kg⁻¹), but lower than the concentrations reported in fishes from the Irish Sea (mean of 4.64 Bq kg⁻¹, range up to 13 Bq kg⁻¹). More recently, Duran et al. (2004) reported median ¹³⁷Cs values of 0.20 Bq kg⁻¹ in fish from the Asian-Pacific and Yamada et al. (1999) reported ¹³⁷Cs concentrations of 0.30 Bq kg⁻¹ from the Japanese coast. Concentrations are similar from the Southern Hemisphere: Godoy et al. (2003) found ¹³⁷Cs concentrations to be 0.19 Bq kg⁻¹ in Brazil. Concentrations can be much higher in fishes living near nuclear waste dump sites; fishes from the Farallon Islands nuclear waste dump had mean muscle concentrations of 1.1 Bq kg⁻¹ (Suchanek et al. 1996).

There are a number of studies that report values for cod (Table 9), and the means range from 0.2 Bq kg⁻¹ for the Arctic and the English Channel, to 0.3 Bq kg⁻¹ for the Barents Sea, Norway, and North Atlantic, to 6.44 Bq kg⁻¹ in the Irish Sea and 8.86 Bq kg⁻¹ for the Baltic Sea. Concentrations in cod in the Barents and Kara Seas can

Table 8. Geographical comparisons of ¹³⁷Cs (Bq kg⁻¹, wet weight) for birds and fish. Concentrations or ranges of mean concentrations are compared from the contaminated Irish Sea with marine birds and fish from other Northern Hemisphere^a locations. Data from other locations are primarily from 1999 to the present. Some results were originally reported in pCi or in dry weight and have been converted.

Group	Irish Sea	Other sites	Amchitka/Kiska (2004)
Birds			
Mean level	124.8	1.62	< MDA
Range	9–613	< MDA–5.6	0.08–0.94
Number of analyses	15	15	12
Fish			
Mean level	4.64	0.22	0.04–0.74 ^b
Range	0.31–13	0.04–0.33	< MDA–0.78
Number of analyses	15	718	44

^a The Northern Hemisphere data comes from CEFAS (2003, 2004), RPII (2003, 2004), NRPA (2003, 2004), JCAC (2003, 2004), Hong Kong Observatory (2000, 2003, 2004), and Matishov and Matishov (2004). The Irish Sea data were extracted from RPII (2003, 2004), CEFAS (2003, 2004), and BNG (2004).

^b For different fish species.

also range as high as 4 Bq kg⁻¹ ¹³⁷Cs (Matishov et al. 1995, 2001). At Amchitka, Pacific Cod were at the low end of this range (mean of 0.29 Bq kg⁻¹).

The only value above the MDA for birds from Amchitka (0.094 Bq kg⁻¹) was below the average concentration for other Northern Hemisphere sites (mean of 1.62 Bq kg⁻¹, range up to 5.6 Bq kg⁻¹), as well as being considerably below the mean for birds in the Irish Sea (mean of 124.8 Bq kg⁻¹, range up to 613 Bq kg⁻¹). Dietz et al. (2000) reported lower concentrations of ¹³⁷Cs in birds from Greenland (means of 0.2 and 0.5 Bq kg⁻¹).

Overall, the concentrations of cesium in fishes and birds from Amchitka were similar to those of other uncontaminated sites in the Northern Hemisphere and were well below those from the contaminated Irish Sea. In any case, all of the concentrations of ¹³⁷Cs in all the organisms from the Amchitka study were well below the allowable concentrations in foods as set by the European Economic Community (600 Bq kg⁻¹; EEC 1986).

CONCLUSION

The only radionuclides above the minimum detectable activity (MDA) were ¹³⁷Cs, ²⁴¹Am, ^{239,240}Pu, ²³⁴U, ²³⁵U, and ²³⁸U for a wide range of fishes and birds. There were significant differences in ¹³⁷Cs as a function of species, but not location for top predatory fish. Most of the fishes (8 of 10 species) had ¹³⁷Cs concentrations above the MDA. However, Glaucous-winged Gull was the only bird species that had a value above the MDA. The highest concentrations of ¹³⁷Cs were in Dolly Varden and Pacific Cod. ¹³⁷Cs concentrations for all fishes and birds were low and close to the MDA, providing no evidence of any seepage from the Amchitka test shots. In aggregate, fish had 73 of 234 (31%) actinide analyses above the MDA, while birds had only 3 of 98 (3%) actinide composite analyses above the MDA, suggesting that fishes are better accumulators, and are thus more useful bioindicators to provide any early warning.

²³⁴U and ²³⁸U, nuclides that are primarily natural in origin, had the highest detection rates, and there were no significant differences in mean concentrations between Amchitka and Kiska. Thus we did not document evidence of higher levels or leakage at Amchitka. The concentrations of all radionuclides examined at Amchitka are similar to those of other uncontaminated Northern Hemisphere sites, and are lower than those reported for fishes and birds from the Irish Sea. The values for all samples in this study fell below the European Economic Community allowable health guidance concentrations of 600 Bq ¹³⁷Cs kg⁻¹ fresh weight (EEC 1986). The data from this study provide reassurance that the concentrations of radionuclides in fishes

Table 9. Geographical comparison for ¹³⁷Cs for representative marine fishes in the Irish Sea and other Northern Hemisphere sites, with Amchitka data shown for comparison. All values have been converted where necessary to Bq kg⁻¹ wet weight. Values below the MDA were converted to half the MDA for computing the mean value. Data are primarily from 1999 to the present.

Location/Sea	Species	Concentration	# (pooled)	Reference
Japan	Tilefish	0.12	2	Japan Chemical Analysis Center (2003)
	Greenling	0.12	2	
	Flounder	0.07	12	
	Rockfish	0.09	4	
	Mackerel (various)	0.12	18	
Arctic	Sculpin	0.3	10	Jensson et al. (2004)
	Flounder	0.3	6	Matishov and Matishov (2004)
	Pacific Cod	0.2	394	
	Haddock	0.3	65	
Hong Kong	Melon Coat	0.07	11	Li and Yeung (2004)
	Hair Tail	0.09	19	Hong Kong Observatory (2003)
	Bartail Flathead	0.06	11	
Barents Sea	Atlantic Cod	0.29	53	Gafvert et al. (2003)
	Haddock	0.2	10	CEFAS (2003 and 2004)
North Sea	Atlantic Cod	0.38	21	Ryan et al. (2001)
	Haddock	0.2	10	CEFAS (2003 and 2004)
	Plaice	0.21	19	Gafvert et al. (2003)
Norwegian	Atlantic Cod	0.32	20	Gafvert et al. (2003)
	Saithe	0.27 to 0.64	4	CEFAS (2003 and 2004)
	Mackerel	0.14	4	Ryan et al. (2001)
N. Atlantic	Atlantic Cod	0.28	3	CEFAS (2003 and 2004)
	Plaice	0.36	3	Gafvert et al. (2003)
	Haddock	0.47	3	
	Mackerel	0.09	5	
Channel	Atlantic Cod	0.2	8	CEFAS (2003 and 2004)
	Plaice	0.06	16	
	Mackerel	0.19	8	
Irish	Atlantic Cod	6.44	75	Ryan et al. (2001)
	Plaice	3.77	60	CEFAS (2003 and 2004)
	Mackerel	0.31	39	
	Flounder	11	19	
Baltic	Haddock	1.1	10	
	Atlantic Cod	8.86	7	CEFAS (2003 and 2004)
Amchitka	Dolly Varden	0.74	2	Powers et al. (2005, 2006)
	Pacific Cod	0.29	14	(1,000 g samples)
	Pacific Halibut	0.24	4	
	Black Rockfish	0.14	3	

and birds, all of which are important commercial or subsistence species, are currently below levels established as safe for human consumption (see above and Powers et al. 2005). The database can be used for bioindicator selection as part of a long-term biomonitoring plan for the region. These data are fundamental to establishing a baseline for the Bering Sea ecosystem.

Finally, transparency, trust, and sustainability, as well as the public's participation in decision-making, helped shape the Amchitka investigation. These will be needed to shape the public policy agenda with respect to nuclear wastes in the future (Omenn 2001; Florig 2001). Trust is particularly an issue with chemical and nuclear wastes (Slovic 1987), and some people feel that the government and experts downplay issues of nuclear safety and risk (Ahearne 2001; Thomas 2001). The CRESPP study benefited from stakeholder input at several levels. Transparency encouraged stakeholders to participate in the planning,

participation, interpretation, and acceptance of the results, improving both the quality and usefulness of the study.

Acknowledgments—We thank the many people who contributed to the development and execution of CRESPP's Amchitka Geophysical and Biological Project, especially L. Bliss, B. Goldstein, H. Mayer, and V. Vyas, and the following for help throughout the project, D. Barnes, L. Duffy, A. Morkill, R. Patrick, D. Rogers, D. Dasher, J. Halverson, P. Sanders, J. Alchowiak and the people of the villages of Unalaska, Nikolski, Atka, and Adak in the Aleutians. Technical help was provided by S. Burke, M. Donio, C. Dixon, M. Gray, G. Elias, V. Vyas, and H. Mayer. We thank the entire crew of the *Ocean Explorer*, Captain Ray Haddon, mate Glenn Jahnke, cook Don Dela Cruz, and Bill Dixon, Joao Do Mar, and Walter Pestka, for making our field work possible and pleasant, and for bringing us safely back to port. We also thank the Captain of the *Gladiator* trawler and his crew for aiding our collecting, and M. E. Wilkins for allowing us to participate on their cruise. An independent peer review panel of M. W. Carter, C. Fairhurst, M. Lippmann, A. C. Upton (chair), and B. Walker, Jr., vetted the study's science plan and reports. This research was funded by the Consortium for Risk Evaluation with Stakeholder Participation (CRESPP) through the Department of Energy (DE-FG 26-00NT 40938) and by NIEHS ESO 5022. The results, conclusions, and interpretations reported

herein are the sole responsibility of the authors, and should not in any way be interpreted as representing the views of the funding agencies.

REFERENCES

- Ahearne JF. Scientists, policy makers, and the public: a needed dialogue. *Health Phys* 80:384–387; 2001.
- Alaska Department of Fish and Game. ADF&G Wildlife Notebook Series: Dolly Varden. Juneau AK; ADFG; 1994. Available at http://www.adfg.state.ak.us/pubs/notebook/fish/dolly_v.php. Accessed 3 January 2007.
- AQ:M Alaska Fisheries Science Center. Walleye Pollock research. Juneau, AK. AFSC; 2003. Available at <http://www.afsc.noaa.gov/species/pollock.php>. Accessed 3 January 2007.
- AQ:N Amundsen I, Iosjpe M, Reistad O, Lind B, Gussgaard K, Strand P, Borghuis S, Sickel M, Dowdall M. The accidental sinking of the nuclear submarine, the Kursk: monitoring of the radioactivity and the preliminary assessment of the potential impact of radioactive releases. *Mar Poll Bull* 44:459–468; 2002.
- Aumento F, LeDonne K, Eroo K. Transuranium radionuclide pollution in the waters of the La Maddalena National Marine Park. *J Environ Radioact* 82:81–93; 2005.
- Baeza A, Miro C, Paniagua JM, Navarro E, Rodriguez MJ, Sanchez F. Natural and artificial radioactivity levels in Livingston Island (Antarctic regions). *Bull Environm Contam Toxicol* 52:117–124; 1994.
- Bidone ED, Castilhos ZC, Santos TJS, Souza TMC, Lacerda LD. Fish contamination and human exposure to mercury in Tartarugalzinho River, Northern Amazon, Brazil. A screening approach. *Water Air Soil Poll* 97:9–15; 1997.
- Bologa AS. Radioactivity assessment of the Black Sea with special emphasis on the Romanian sector. *Radiolog Impact Assess SE Mediterranean* 2:61–74; 2000.
- British Nuclear Group. Monitoring our environment: discharges and monitoring of the environment in the UK. Annual Report 2004. Berkeley, UK: BNG; 2004. Available at <http://www.britishnucleargroup.com/content.php?pageID=318>. Accessed 3 January 2007.
- Buesseler KO, Halverson J. The mass spectrometric analysis of fallout ^{239}Pu and ^{240}Pu in marine samples. *J Environ Radioact* 5:425–444; 1987.
- Burger J, Gaines KF, Boring CS, Stephens Jr WL, Snodgrass J, Gochfeld M. Mercury and selenium in fish from the Savannah River: species, trophic level, and locational differences. *Environ Res* 87:108–118; 2001.
- AQ:Q Burger J, Gaines KF, Boring CS, Stephens WL, Snodgrass J, Dixon C, McMahon M, Shukla S, Shukla T, Gochfeld M. Metal levels in fish from the Savannah River: potential hazards to fish and other receptors. *Environ Res* 89:85–87; 2002.
- Burger J, Gochfeld M, Kosson D, Powers CW, Friedlander B, Eichelberger J, Barnes D, Duffy LK, Jewett SC, Volz CD. Science, policy, and stakeholders: developing a consensus science plan for Amchitka Island, Aleutians, Alaska. *Environ Manage* 35:557–568; 2005.
- Burger J, Gochfeld M, Kosson DS, Powers CW. Biomonitoring for ecosystem and human health protection at Amchitka Island. Piscataway, New Jersey: Consortium for Risk Evaluation with Stakeholder Participation; 2006a.
- Burger J, Jewett S, Gochfeld M, Hoberg M, Harper S, Chenelot H, Jeitner C, Burke S. The use of biota sampling for environmental contaminant analysis for characterization of benthic communities in the Aleutians. *Sci Total Environ* 369:393–402; 2006b.
- AQ:R Burger J, Gochfeld M, Jewett SC. Selecting species for marine assessment of radionuclides around Amchitka: planning for diverse goals and interests. *Environ Monit Assess* 123:371–391; 2006c. AQ: S
- Burger J, Gochfeld M, Kosson DS, Jewett S, Friedlander B, Chenelot H, Volz CD, Jeitner C. Radionuclides in marine macroalgae from Amchitka and Kiska Islands in the Aleutians: establishing a baseline for future biomonitoring. *J Environ Radioact* 91:27–40; 2006d. AQ: T
- Center for Environment, Fisheries, and Aquaculture Science. Radioactivity in food and the environment. Lowestoft, Suffolk, UK: Environmental Agency, Environment and Heritage Service; RIFE 8; 2003. AQ: U
- Center for Environment, Fisheries, and Aquaculture Science. Radioactivity in food and the environment. Lowestoft, Suffolk, UK: Environmental Agency, Environment and Heritage Service; RIFE 9; 2004. AQ: V
- Consortium for Risk Evaluation with Stakeholder Participation. Amchitka independent assessment science plan. Piscataway, NJ: Amchitka; 2003. Available at <http://www.cresp.org/Amchitka/plan/ApprovedAmchitkaSciencePlan.pdf>. Accessed 3 January 2007. AQ: W
- Cooper LW, Beasley TM, Zhao XL, Doto C, Vinogradova KL, Duntion KH. Iodine-129 and plutonium isotopes in Arctic kelp as historical indicators of transport of nuclear fuel-reprocessing wastes from mid-to-high latitudes in the Atlantic Ocean. *Mar Biol* 131:391–399; 1998.
- Currie LA. Limits for qualitative detection and quantitative determination: application to radiochemistry. *Analytic Chem* 40:586–593; 1968.
- Dasher D, Hanson W, Read S, Faller S, Farmer D, Efurud W, Kelley J, Patrick R. An assessment of the reported leakage of anthropogenic radionuclides from the underground nuclear test sites at Amchitka Island, Alaska, USA to the surface environment. *J Environ Radioact* 60:165–187; 2002.
- Denton GRW, Burdon-Jones C. Trace metals in fish from the Great Barrier Reef. *Mar Poll Bull* 17:201–209; 1986.
- Dietz R, Riget F, Cleemann M, Aarkrog A, Johansen P, Hansen JC. Comparison of contaminants from different trophic levels and ecosystems. *Sci Total Environ* 245:221–231; 2000.
- Duran EB, Povinec PP, Fowler SW, Airey PL, Hong GH. ^{137}Cs and $^{239,240}\text{Pu}$ levels in the Asia-Pacific regional seas. *J Environ Radioact* 76:139–160; 2004.
- Eichelberger JC, Freymueller J, Hill G, Patrick M. Nuclear stewardship: lessons from a not-so-remote island. *Geotimes* 47:20–23; 2002.
- European Economic Community. Derived reference level as a basis for the control of foodstuffs following a nuclear accident: a recommendation from the group of experts set up under Article 31 of the Euratom Treaty (EEC Regulation 170/86). Brussels, Belgium: Commission of the EEC Printing Office; 1986.
- Fisher NS, Fowler SW, Boisson F, Carroll J, Rissanen K, Salbu B, Sazykina TG, Sjoebloom KL. Radionuclide bioconcentration factors and sediment partition coefficients in Arctic Seas subject to contamination from dumped nuclear wastes. *Environ Sci Technol* 33:1979–1982; 1999.
- Florig HK. Alternative goals and policy mechanisms for radiation protection. *Health Phys* 80:397–400; 2001.
- Gafvert T, Foyn L, Brungot AL, Lind B, Christensen GC, Stralberg E, Drefvelin J, Rudjord AL. Radioactivity in the marine environment 2000 and 2001 (RAME). Osteras, Norway: Norwegian National Monitoring Programme; Stralvern Rapport 8; 2003.

- AQ: Y
- Gochfeld M, Burger J, Vyas V. Statistical analysis of data sets with values below detection limits. Appendix 11D to CRESP report; 2005. Available at http://www.cresp.org/Amchitka/Amchitka_Final_Report/finalreport/11Append_radionuclides/11F_Statisticalanalysis.pdf. Accessed 3 January 2007.
- Godoy JM, Carvalho AL, Fernandes FC, Danelon OM, Ferreira ACM, Alfredo L. ¹³⁷Cs in marine samples from the Brazilian southeastern coastal region. *J Environ Radioact* 70:193–198; 2003.
- Green NW, Knutzen J. Organohalogenes and metals in marine fish and mussels and some relationships to biological variables at reference localities in Norway. *Mar Poll Bull* 46:362–377; 2003.
- Greenpeace. Nuclear flashback: the return to Amchitka. Anchorage, AK: Greenpeace; 1996.
- Hakanson L. A new general dynamic model predicting radionuclide concentrations and fluxes in coastal areas from readily accessible driving variables. *J Environ Radioact* 78:217–245; 2005.
- Hamrick K, Smith J. Subsistence food use in Unalaska and Nikolski. Anchorage, AL: Aleutian Pribilof Island Association; 2003.
- Held EE, Nelson VA, Schell WR, Seymour AH. Amchitka radiobiological program progress report for March 1972 to December 1972. Las Vegas, NV: DOE; Report NVO-269-19; 1973.
- Helsel DR. Non-detects and data analysis: statistics for censored environmental data. New York: Wiley & Sons; 2005.
- Hong Kong Observatory. Environmental radiation monitoring in Hong Kong. Annual Report 1999. Hong Kong: Hong Kong Special Administrative Region Government; Tech Rep 19; 2000.
- Hong Kong Observatory. Environmental radiation monitoring in Hong Kong. Hong Kong: Hong Kong Special Administrative Region Government; Tech Rep 22; 2003.
- Hong Kong Observatory. Summary of environmental radiation monitoring in Hong Kong. Hong Kong: Hong Kong Special Administrative Region Government; Tech Rep 25; 2004.
- Hung TC, Huang CC, Shao KT. Ecological survey of coastal water adjacent to nuclear power plants in Taiwan. *Chem Ecol* 15:129–142; 1998.
- Hunt GJ, Smith BD. The radiological impact of actinides discharged to the Irish Sea. *J Environ Radioact* 44:389–403; 1999.
- INEEL. Determination of selected actinide nuclides and strontium-90 in filters and solids. INEEL Analytic Method ACM 3816 (2001) included as Appendix 8F. 1 INL Methods Manual for Amchitka Environmental Sample Analysis. Idaho Falls: INEEL; 2001. Available at http://www.cresp.org/Amchitka/Amchitka_Final_Report/finalreport/08Append_Bio/8F_INL/Appendix8F.htm. Accessed 3 January 2007
- INEEL. Method manual and quality assurance project plan for the Amchitka environmental sample analysis by INL Department of Chemistry. Appendix 8F to CRESP report. Idaho Falls: INEEL; 2005. Available at http://www.cresp.org/Amchitka/Amchitka_Final_Report/finalreport/08Append_Bio/8F_INL/Appendix8F.htm. Accessed 3 January 2007.
- AQ: Z
- International Atomic Energy Agency. Inventory of radioactive waste disposal at sea. IAEA Techdoc Series 1105:1–121; 1999.
- Isakson JS, Seymour AH. Amchitka Bioenvironmental Program: Annual progress report July 1, 1967–June 30, 1968. Radiometric and elemental analyses on marine organisms from Amchitka, Alaska. Columbus, OH: Battelle Memorial Institute; 1968.
- Jackson TA. Biological and environmental control of mercury accumulation by fish in lakes and reservoirs of Northern Manitoba, Canada. *Can J Fish Aquat Sci* 48:2449–2470; 1991.
- Japan Chemical Analysis Center. Radioactivity survey data in Japan: environmental and dietary materials. Chiba, Japan: JCAC; Rep 138; 2003.
- Japan Chemical Analysis Center. Radioactivity survey data in Japan: environmental and dietary materials. Chiba, Japan: JCAC; Rep 139; 2004.
- Jensson H, Strand P, Tsaturov Y, Reiersen L. AMAP assessment 2002: radioactivity in the Arctic. Oslo, Norway; Arctic Monitoring and Assessment Programme (AMAP); 2004.
- Jewett SC, Hoberg M, Chenelot H, Harper S, Burger J, Gochfeld M. Scuba techniques used in risk assessment of possible nuclear leakage around Amchitka Island, Alaska. In: Shumway S, Godfrey J, eds. Diving for science. In: Proceedings of the American Acad Underwater Science 24th Annual Diving Symposium. Storrs, CT: University of Connecticut; 2006.
- AQ: BB
- Kanisch G, Nagel G, Krueger A, Kellermann JJ. Radioactivity in fish and other marine animals from the North Sea. *Inf Fischwirtsch Fischereiforsch* 47:131–139; 2000.
- Kasamatsu F, Tshikawa Y. Natural variation of radionuclide ¹³⁷Cs concentration in marine organisms with special reference to the effect of food habits and trophic level. *Mar Ecol Progr Ser* 160:109–120; 1997.
- Kohlhoff DW. Amchitka and the bomb: nuclear testing in Alaska. Seattle, WA: University of Washington Press; 2002.
- Krey PW, Hardy EP, Pachucki C, Rourke F, Coluzza J, Benson WL. Mass isotopic composition of global fall-out plutonium in soil. In: Transuranium nuclides in the environment. Vienna: International Atomic Energy Agency; IAEA-SM-199/39; 1976: 671–678.
- Kryshev AI, Sazykina TG, Kryshev II, Strand P, Brown JE. Radioecology modelling and the computer codes for calculations of doses to marine biota and man in the Arctic. *Environ Model Software Environ Data News* 16:697–709; 2001.
- Lange TR, Royals HE, Connor LL. Mercury accumulation in largemouth bass (*Micropterus salmoides*) in a Florida Lake. *Arch Environ Contam Toxicol* 27:466–471; 1994.
- Li SW, Yeung KC. Summary of environmental monitoring in Hong Kong, 2003. Hong Kong: Hong Kong Special Administrative Region Government; Hong Kong Observatory Technical Rep 23; 2004.
- Livingston HD, Povinec PP. Anthropogenic marine radioactivity. *Ocean Coast Manage* 43:689–712; 2000.
- Marzano FC, Flori F, Jia G, Chiantore M. Anthropogenic radionuclides bioaccumulation in Antarctic marine fauna and its ecological relevance. *Polar Biol* 23:753–758; 2000.
- Matishov DG, Matishov GG. Radioecology in Northern European seas. Berlin: Springer; 2004.
- Matishov GG, Matishov DG, Rissanen H. Accumulation of radionuclides in benthic organisms and fish of the Barents and Kara Seas. *Dokl Ran* 342:134–135; 1995.
- Matishov GG, Matishov DG, Anisimova NA, Dzhenyuk SL, Zuev AN. Radiation conditions of the environment and biota on the Murmansk Bank in the area of the sunken Kursk nuclear submarine. *Oecol* 41:853–860; 2001.
- Merrell TR Jr. Fishery resources of the Western Aleutians. In: Merritt ML, Fuller RG, eds. The environment of Amchitka

- Island, Alaska. Washington, DC; Energy Research and Development Administration; 1977: 315–330.
- Merritt ML, Fuller RG. The environment of Amchitka Island, Alaska, U.S. Washington, DC: Technical Information Center, Energy Research and Development Administration; Report NVO-79; 1977.
- Moscato AF, Erdmann RC. Possible effects of ionizing radiation upon marine life and some implications of postulated accidental releases of radioactivity. *Nuclear Technol* 22:184–190; 1974.
- Munk KM. Maximum ages of groundfishes in waters off Alaska and British Columbia and considerations of age determination. *Alaska Fish Res Bull* 8:12–21; 2001.
- National Oceanic and Atmospheric Administration. Dutch Harbor—Unalaska, in Alaska, Top U.S Port for landings in 2003. NOAA Report 04-096; 2004 [on line]. Available at www.nmfs.noaa.gov/docs/04-096_top_ports.pdf. Accessed 26 May 2006.
- Norwegian Radiation Protection Authority. Radioactivity in the marine environment 2000 and 2001. Results from the Norwegian National Monitoring Programme (RAME). Østerås, Norway: NRPA; StrålevernRapport 2003:8; 2003. Available at http://www.nrpa.no/archive/Internett/Publikasjoner/Stralevenrapport/2003/StralevenRapport_8_2003.pdf. Accessed 3 January 2007.
- Norwegian Radiation Protection Authority. Radioactivity in the marine environment, 2002. Results from the Norwegian National Monitoring Programme (RAME). Østerås, Norway: NRPA; StrålevernRapport 2004:10; 2004. Available at http://www.nrpa.no/archive/Internett/Publikasjoner/Stralevenrapport/2004/StralevenRapport_10_2004.pdf. Accessed 3 January 2007.
- Noshkin VE, Robison WL, Wong KM, Brunk JL, Eagle RJ, Jones HE. Past and present levels of some radionuclides in fish from Bikini and Enewetak Atolls. *Health Phys* 73:49–65; 1997.
- Omenn GS. The new millennium: values, perceptions of risk, and the key roles of science and technology. *Health Phys* 80:328–332; 2001.
- Pentreath RJ. The roles of food and water in the accumulation of radionuclides by marine teleost and elasmobranch fish. In: *Symposium on the Interactions of Radioactive Contaminants with the Constituents of the Marine Environment*, Seattle, WA (USA), 10 July 1972. Vienna: International Atomic Energy Agency; 1973: 421–436.
- Pinho AP, Guimaraes JRD, Marins AS, Costa PAS, Olavo G, Valentin J. Total mercury in muscle tissue of five shark species from Brazilian offshore waters: effects of feeding habit, sex, and length. *J Environ Res* 89:250–258; 2002.
- Poon CB, Au SM. Modelling the ¹³⁷Cs ingestion dose from consumption of marine fish in Hong Kong. *Radiat Prot Dosim* 98:199–209; 2002.
- Powers CW, Burger J, Kosson D, Gochfeld M, Barnes D. Amchitka independent science assessment: biological and geophysical aspects of potential radionuclide exposure in the Amchitka marine environment. Piscataway NJ: Consortium for Risk Evaluation with Stakeholder Participation; 2005.
- Powers CW, Burger J, Kosson D, Gochfeld M. Additional radiological data for bioindicator selection. Piscataway NJ: Consortium for Risk Evaluation with Stakeholder Participation; 2006.
- Radiological Protection Institute of Ireland. Radioactivity monitoring of the Irish marine environment 2000 and 2001. Dublin: The Radiological Protection Institute of Ireland; RPI-03/3; 2003.
- Radiological Protection Institute of Ireland. Radioactivity monitoring of the Irish marine environment 2002. Dublin: The Radiological Protection Institute of Ireland; RPI-03/3; 2004. Available at <http://www.rpii.ie/download/2002MarineReport161205.pdf>. Accessed 3 January 2007.
- Rollo SFN, Camplin WC, Allington DJ, Young AK. Natural radionuclides in the UK marine environment. *Radiat Protect Dosim* 45:203–209; 1992.
- Ryan TP, McMahon CA, Dowdall A, Fegan M, Sequeria S, Murray M, McKittrick L, Hayden E, Wong J, Colgan PA. Radioactivity monitoring of the Irish marine environment, 2000 and 2001. Dublin: Radiological Protection Institute of Ireland (RPII); 2000, 2001, 2003.
- Sanchez-Cabeza JA, Molero J. Plutonium, americium and radiocesium in the marine environment close to the Vandellós I nuclear power plant before decommissioning. *J Environ Radioact* 51:211–228; 2000.
- Sazykina TG. Long-distance radionuclide transfer in the Arctic seas related to fish migration. *Radiat Prot Dosim* 75:219–222; 1998.
- Seymour AH, Nelson VA. Radionuclides in air, water, and biota. In: Merritt ML, Fuller RG, eds. *The environment of Amchitka Island, Alaska*. Washington DC: TIC, Energy Research and Development Administration; 1977: 579–613.
- Shinohara K. Assessment of radiological effects on the regional environment due to the operation of the Tokai Reprocessing Plant. *J Environ Radioact* 72:299–322; 2004.
- Simenstad CA, Isakson JS, Nakatani RE. Marine fish communities. In: Merritt ML, Fuller RG, eds. *The environment of Amchitka Island, Alaska*. Washington, DC: TIC, Energy Research and Development Administration; 1977: 451–492.
- Skwarzec B. Polonium, uranium and plutonium in the Southern Baltic Sea. *Ambio* 26:113–117; 1997.
- Slovic P. Perception of risk. *Sci* 236:280–285; 1987.
- Suchanek TH, Lagunas-Solar MC, Raabe OG, Helm RG, Gielow F, Peek N, Carvacho O. Radionuclides in fishes and mussels from the Farallon Islands Nuclear Waste Dump Site, California. *Health Phys* 71:167–178; 1996.
- Thomas JP. Rebuilding trust in established institutions. *Health Phys* 80:379–383; 2001.
- Togawa O, Povinec PP, Pettersson HBL. Collective dose estimates by the marine food pathway from liquid radioactive wastes dumped in the Sea of Japan. *Sci Total Environ* 237–238; 241–248; 1999.
- UNSCEAR. Sources and effects of ionizing radiation. New York: United Nations Scientific Committee on the Effects of Atomic Radiation; Report to the General Assembly; 2000.
- U.S. Department of Energy. Regional groundwater flow and tritium transport modeling and risk assessment of the underground test area, Nevada Test Site, Nevada. Las Vegas, NV: Nevada Operations Office; DOE/NV-477; 1997.
- U.S. Department of Energy. United States Nuclear Tests July 1945 through September 1992. Las Vegas, NV: Nevada Operations Office; DOE/NV-209; 2000.
- U.S. Department of Energy. Modeling groundwater flow and transport of radionuclides at Amchitka Island's underground nuclear tests: Milrow, Long Shot, and Cannikin. Las Vegas, NV: Nevada Operations Office; DOE/NV-11508-51; 2002a.

- U.S. Department of Energy. Screening risk assessment for possible radionuclides in the Amchitka marine environment. Las Vegas, NV: Nevada Operations Office; DOE/NV-857; 2002b.
- Vanderbilt University. Quality assurance manual for the Vanderbilt Sample Analysis Program in the Amchitka independent assessment. Nashville, TN: Vanderbilt University Dept of Civil & Environmental Engineering; Appendix 8E to the CRESP Report; 2005. Available at http://www.cresp.org/Amchitka/Amchitka_Final_Report/finalreport/08Append_Bio/8E_VandyProcedures_QA_%20Manual_5_10_05.pdf. Accessed 3 January 2007.
- Waldichuk M. State of pollution in the marine environment. *Mar Poll Bull* 20:598–602; 1989.
- Watras CJ, Back RC, Halvorsen S, Hudson RJM, Morrison KA, Wentz SP. Bioaccumulation of mercury in pelagic freshwater food webs. *Sci Total Environ* 219:183–208; 1998.
- White CM, Williamson FSL, Emison WB. Avifaunal investigations. In: Merritt ML, Fuller RG, eds. *The environment of Amchitka Island, Alaska*. Washington, DC: Energy Research and Development Administration; 1977: 227–260.
- Wiener JG, Spry DJ. Toxicological significance of mercury in freshwater fish. In: Beyer MN, Heins GH, Redmon-Norwood AW, eds. *Environmental contaminants in wildlife*. Boca Raton, FL: Lewis Publications; 1996: 297–339.
- Wiener JG, Krabbenhoft DP, Heinz GH, Scheuhammer M. Ecotoxicology of mercury. In: Hoffman DJ, Rattner BA, Burton GA, Cairns J Jr, eds. *Handbook of ecotoxicology*. Boca Raton, FL: Lewis Publications; 2003: 409–463.
- Yamada M, Aono T, Hirano S. $^{239,240}\text{Pu}$ and ^{137}Cs concentrations in fish, cephalopods, crustaceans, shellfish, and algae collected around the Japanese coast in the early 1990s. *Sci Total Environ* 239:131–142; 1999.

