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Radionuclides in Air, Water, and Biota

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Air, water, and biological samples collected before and after the 1965, 1969, and 1971 underground nuclear detonations at Amchitka Island were analyzed for natural and fallout radionuclides by gamma spectrometry. Selected samples were also analyzed for tritium, ^{55}Fe, and ^{90}Sr. The objectives were to search for and identify radionuclides of Amchitka origin in the samples and to contribute to the general knowledge of the distribution of radionuclides in the environment. The collection of seafoods and the analyses of samples for radionuclides potentially available to man through the food web were emphasized, but other organisms were also analyzed in the search for radionuclide indicator species. The identification of the origin of the fallout radionuclides in the samples required accurate measurement of the radionuclides in both the preevent and postevent samples since some fallout radionuclides were present at Amchitka before the 1965 event and other fallout radionuclides arrived during the 11-year period of study.

The samples were principally collected in areas likely to be contaminated if any seepage of radionuclides from the site of the underground detonations occurred. Of the 81 types of organisms analyzed, 37 were vertebrates (2 mammals, 22 fish, and 13 birds), 20 were invertebrates, 11 were marine algae, 4 were freshwater plants, and 9 were land plants; several thousand were analyzed. The results have been published in several reports, including a series of six progress reports for the years 1970 to 1975.

The studies showed that there has been no escape of radionuclides from the underground sites of the three nuclear detonations at Amchitka Island except for trace quantities of radionuclides, principally tritium, in water and soil gas samples from the immediate vicinity of the surface ground zero for the 1965 event. Two naturally occurring radionuclides, ^{40}K and ^{7}Be, were the most abundant radionuclides in the samples, usually by a factor of 10 or more, except for ^{137}Cs in lichen samples. All levels were well below applicable Radiation Protection Guides, often being near the statistical limit of detection.

The underground nuclear detonations at each of three locations on Amchitka Island were designed to retain in the immediate vicinity of the detonation all the radionuclides that were produced. Air, water, and biological samples collected before and after each of the detonations were analyzed for their radionuclide content to determine if this goal was achieved. Some naturally occurring and worldwide fallout radionuclides were present on Amchitka Island before the first Amchitka nuclear detonation, and some fallout of radionuclides from nuclear detonations elsewhere occurred during the period of study. Therefore the objectives of the program were to search for radionuclides of Amchitka origin in the environment and to advance general knowledge about the environmental distribution of radionuclides. The collection of seafoods and the analyses for radionuclides potentially available to man through the food web were emphasized, but other organisms were collected and analyzed to obtain clues about the origin of radionuclides at Amchitka and to identify indicator species, species that significantly concentrate one or more of the radionuclides present at Amchitka.

Radioecological surveys were made for each of the three underground nuclear detonations on Amchitka, Long Shot (1965), Milrow (1969), and Cannikin (1971). Information about the three events and references to event-related radioecological surveys are given in Table 1.

The program in 1965 included observation and radiometric analyses of samples collected during the period from 2 weeks before until 4 days after the Long Shot detonation. In a series of nuclear detonations, a postevent survey for one detonation is a preevent survey for the following detonation. In this sense the limited post-Long Shot observations were a part of the pre-Milrow survey, but more intensive surveys for Milrow began in 1967. Likewise, the immediate post-Milrow survey data supplemented the information obtained from the pre-Cannikin surveys that began in July 1970. The post-Cannikin surveys began immediately after the November 1971 detonation and have continued periodically since. At present (1976) the program

Table 1—Schedule of Amchitka Underground Nuclear Detonations and References to Reports of Event-Related Radioecological Surveys

Event	Date	Yield, kt	Depth, m	References
Long Shot	Oct. 29, 1965	80	710	Seymour and Nakatani, 1967 Koranda et al., 1967
Milrow	Oct. 2, 1969	~1000	1219	Isakson and Seymour, 1968 Vogt et al., 1968 Koranda et al., 1969 Merritt, 1970
Cannikin	Nov. 6, 1971	~5000	1791	Held, 1971 Held, 1972 Held et al., 1973 Merritt, 1973 Nelson and Seymour, 1974 Nelson and Seymour, 1975 Nelson, 1975 Nelson and Seymour, 1976

has been reduced to a single field survey and collection per year.

In addition, the U. S. Environmental Protection Agency (EPA) conducted an extensive offsite monitoring program throughout the Aleutian Island chain and in mainland Alaska. Also, there has been a program since 1965 for the collection and analysis of groundwater and surface-water samples for tritium (^3H) by the U. S. Geological Survey, Teledyne Isotopes, Inc., EPA's National Environmental Research Center (NERC), Las Vegas, and the Lawrence Radiation Laboratory (now Lawrence Livermore Laboratory). The reports by Ballance (1974), Essington (1971), Fort and Wruble (1972), and Koranda, Martin, and Wikkerink (1967) are representative of the work performed by these groups. The collection and analysis of samples for ^3H by the Laboratory of Radiation Ecology began in 1970.

The program for the collection and analyses of samples was designed on the expectation that the amounts of radionuclides in the samples would be only slightly greater than the existing low levels of background radiation from natural and man-made sources. Hence large samples and sensitive radiation detection and measurement systems were required. The two categories of radionuclides that contribute to background radiation are (1) natural and (2) artificial.

The natural radionuclides are either of terrestrial or atmospheric origin. Those of terrestrial origin are residual radionuclides from the time of the earth's formation and hence are of long half-life, whereas those of atmospheric origin are constantly being produced by the interaction of cosmic radiation with nuclei of gases in the atmosphere. Potassium-40 is the most abundant radionuclide of terrestrial origin in biological samples, and, generally, it is present in amounts that range from a few to many times greater than all other radionuclides, natural or artificial. As examples of the distribution of ^{40}K, levels in muscle of marine fish from Amchitka ranged from 9 to 20 pCi/g of dry tissue; levels in a sample of *Alaria*, a marine algae, were 80 pCi/g of dry weight. In seawater there are about 0.32 pCi/g, and in the whole body of an 80-kg man, about 140,000 pCi, which is equivalent to 1.75 pCi/g of wet weight. Other radionuclides of terrestrial origin that may or may not be present in detectable quantities are ^{87}Rb and isotopes of thorium and uranium and their daughter nuclides.

The most common natural radionuclides of atmospheric origin are ^3H, ^{14}C, and ^7Be. These radionuclides are produced by the interaction of cosmic-ray particles with nuclei of nitrogen atoms in the atmosphere. However, not all the ^3H and ^{14}C in the environment is of natural origin since these two radionuclides are also produced in significant amounts by nuclear detonations. After the 1961 and 1962 atmospheric test series by the Union of Soviet Socialist Republics and the United States of America, the earth's reservoir of ^3H was increased by nearly 500% and of ^{14}C by 10 to 15% (Schell, Sauzay, and Payne, 1974). The present level of ^3H in rainwater ranges from about 0.1 to 1 pCi/g of water (Schell et al., 1974). Without input from nuclear detonations, the reservoir of ^3H will decrease relatively rapidly since its radiological half-life is 12.3 years.

Carbon-14 produced in the atmosphere combines with oxygen to form a CO_2 molecule that becomes immediately available to terrestrial plants and somewhat later, owing to holdup at the

air–water interface, to aquatic plants. The concentration of ^{14}C in contemporary terrestrial plants is 6.11 pCi (13.56 dpm) per gram of carbon (Karlen et al., 1964). Any changes in the reservoir of environmental ^{14}C, such as those which occurred in 1961 and 1962 from nuclear testing, will persist for a long period of time because of the long radiological half-life of ^{14}C, 5730 years.

The third radionuclide produced in the atmosphere that is detectable in some samples, especially lichens and freshwater plants, is ^{7}Be. Maximum values for this radionuclide in Amchitka organisms are less than 5 pCi/g of wet sample and 0.3 pCi/g for water (Nelson and Seymour, 1975). (On a dry-weight basis, a maximum value of 37 pCi/g for *Ranunculus*, a freshwater plant, was observed.)

The other sources of background radiation are the fallout radionuclides—fission products, induced radionuclides, and unused parent materials from the nuclear devices. Fallout radionuclides in the troposphere reach the earth's surface in a few days to a few months, but a few months to a few years are required for radionuclides that are injected into the stratosphere to return to the earth's surface. Amchitka, at 51°N 179°E, is at a latitude where fallout would be expected to be at a maximum both for tropospheric fallout from detonations at the Lop Nor test site in China and for stratospheric fallout that reaches the earth through the break in the tropopause in the northern hemisphere. No tropospheric and little, if any, stratospheric fallout from the French nuclear detonations in the South Pacific, 22°S, would be expected at Amchitka Island. The rate of fallout on Amchitka, although small, may have varied severalfold within a year during the period of study because of fresh tropospheric fallout from nuclear detonations at Lop Nor and the usual seasonal changes in stratospheric fallout. This accounts for much of the variability in radionuclide values that has been observed for samples of the same species collected at different seasons of the year. However, some of the variability in radionuclide values is also due to ecological and biological factors that affect the metabolic rate of organisms.

Any new contributions of small quantities of fresh-fallout radionuclides to Amchitka would be difficult to detect. A large increase in environmental radioactivity at Amchitka only would obviously point to a local source of contamination, but a small increase could be attributed either to a local source of radioactivity or to worldwide fallout. Since the radionuclides in fallout are the same as those produced by the Amchitka detonations, there is no direct means of identifying the origin of the radionuclides by the presence of specific radionuclides in the samples. One indirect means of identifying their origin would be to compare the amounts and kinds of radionuclides in Amchitka samples with radionuclides in samples from distant areas. A second means would be to compare a calculated date of origin of the radionuclides in the samples with the dates of the Amchitka detonations. The date of origin can be readily calculated from the ratio of a radioactive parent to a radioactive daughter in the sample if the half-lives of the two radionuclides are significantly different and relatively short and if no fractionation of parent and daughter by either physical or biological processes has occurred.

SAMPLE COLLECTION

The number of samples collected was a compromise between the need to know about the kinds and amounts of radionuclides in as many types of samples as possible and recognition that only a finite number of samples could be analyzed. For this reason the highest priority was given to the collection of samples that would provide information on the transfer of radionuclides from the ocean to man. Organisms of special interest were fish and crabs from Amchitka and salmon from Alaska canneries as well as organisms in trophic levels immediately below seafoods. Other organisms were also collected and analyzed in a search for indicator species, species which significantly concentrate one or more radionuclides and which are readily available in quantities sufficient to provide adequate amounts of samples without significantly affecting the population of the species in the collection area.

Samples were collected from offshore and intertidal areas, freshwater streams and ponds, and terrestrial areas. At the offshore stations on both the Pacific Ocean and Bering Sea sides of Amchitka Island, fish and water samples were collected by the M. V. *Commander*, and in situ measurements of radioactivity in seawater were made with a gamma probe operated from the M. V. *Pacific Apollo* (Held, 1972). The sample collection stations, both offshore and intertidal, where appropriate, were the same stations that were selected by the Fisheries Research Institute, University of Washington, for their ecological studies. Stations on the island proper were selected either as sites that were most likely to be contaminated if radionuclides escaped from the undergound detonations or sites that were unlikely to be contaminated, i.e., control areas; hence the sample collection stations were either near or some distance from the ground zero areas. The three detonations

were within 8 km of each other and in the southeastern part of the island, as shown on the Geological Survey map in the pocket at the back of this volume. Landmarks and the locations of collection stations near the ground zero areas are shown in Figs. 1 (Long Shot), 2 (Milrow and Long Shot), and 3 (Cannikin).

fish muscle, 4.3; king crab muscle, 6.6; plankton, 21; noncoralline marine algae, 6.3; freshwater plants, 7.4; and lichens, 3.8.

In addition to the biological samples, air and water samples were collected and analyzed to determine the amounts and kinds of radionuclides available to the biota and to signal the arrival of

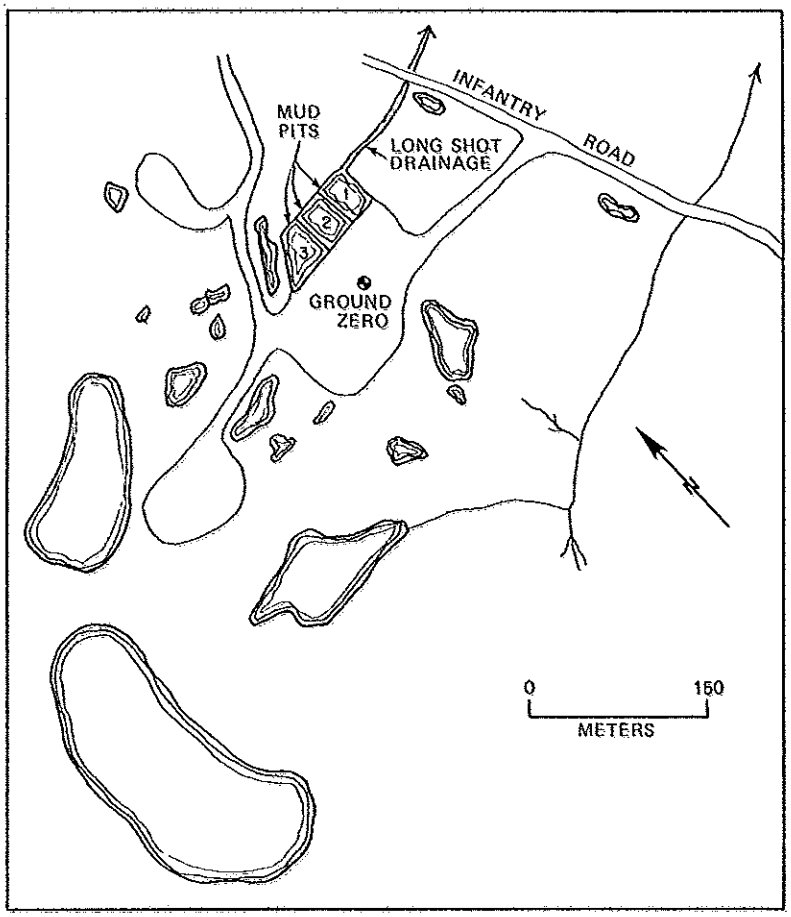

Fig. 1—Collection sites and other prominent features in the vicinity of Long Shot ground zero.

Of the 81 types of biological samples collected for analyses, 37 were vertebrates (2 mammals, 22 fish, and 13 birds), 20 were invertebrates, 11 were marine algae, 4 were freshwater plants, and 9 were land plants. Their scientific and common names are given in Table 2.

The radioactivity values have been reported most frequently in terms of dry weight because accurate wet weights are difficult to determine routinely for some organisms, such as mussels, algae, aufwuchs, and plankton. Held (1971) prepared a table of approximately 100 wet–dry weight ratios based on a limited number of carefully determined wet and dry weights. Representative values from this list are as follows:

radionuclides at Amchitka from other areas. The presence of fresh or unexpected radionuclides in air or water samples could herald the arrival of either tropospheric or stratospheric fallout from nuclear detonations elsewhere in the northern hemisphere.

Most of the samples were collected with conventional instruments, but the water sampler, the air sampler, and the in situ detector for measurement of radioactivity in seawater have unique features that need description for proper interpretation of results. The measurement of trace amounts of radionuclides or chemical elements in water frequently depends on the collection and transport of large quantities of water in toto from

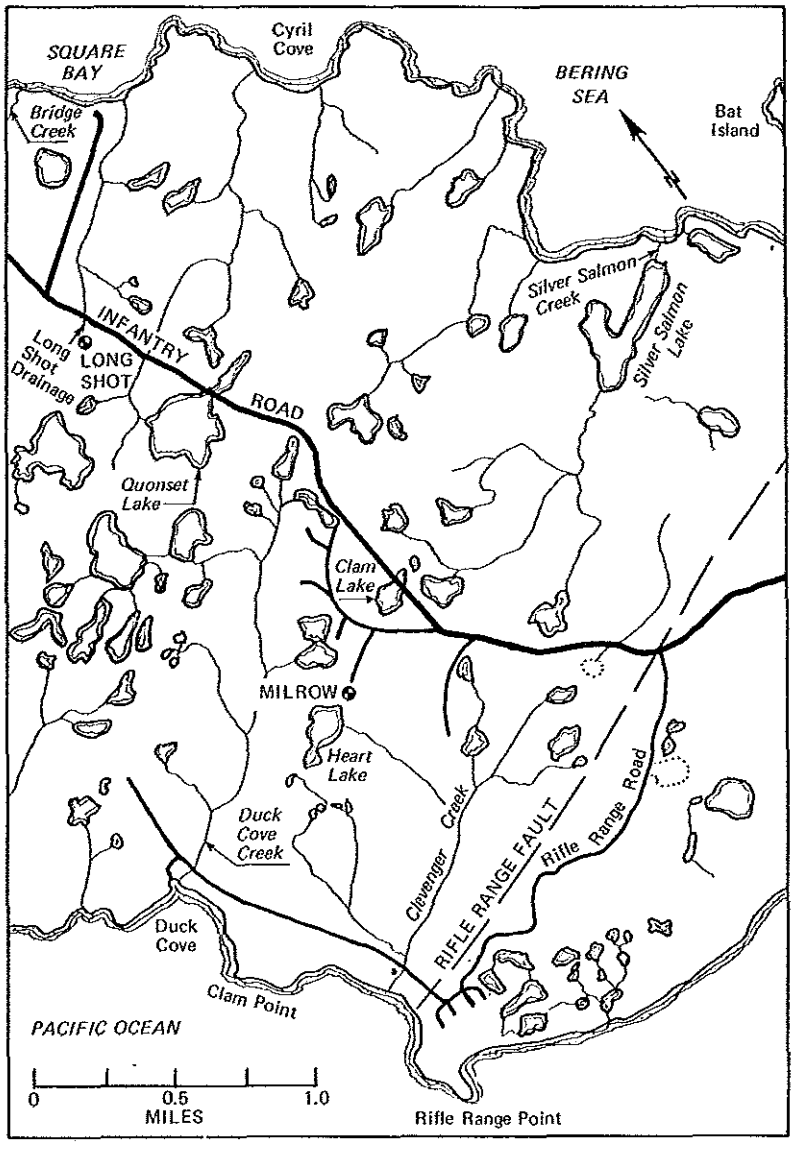

Fig. 2—Collection sites and other prominent features in the Long Shot and Milrow areas.

the field to the home laboratory for analysis. To simplify the problems of collection and transport, Battelle Northwest Laboratories developed a water sampler that permits the collection of particulates on a filter and of charged ions on a sorption bed. This sampler can process a large volume of water in the field in a relatively short period of time, and only the filter papers and the sorption beds need to be returned to the laboratory for analyses. The essential components of the sampler are a pump, six to eight 0.3-μm Millipore filters arranged in parallel, and one to three aluminum oxide (Al_2O_3) sorption beds arranged in series. The Al_2O_3 bed sorbs both anions and cations but has a limited holding capacity for some ions; this bed also is an efficient collector of colloids.

The air samplers used by the Laboratory of Radiation Ecology (LRE) in the late post-Cannikin period were the same samplers used by Eberline Instrument Company during the pre-Cannikin and immediate post-Cannikin surveys. The essential components of the sampler are a Gast positive displacement pump, calibrated at 10 ft^3/min, and a 15-cm filter head lined with No. 41 Whatman filter paper. For the late post-Cannikin period, three units were operated continuously from Feb. 23, 1972, to Aug. 28, 1973, in a shed near the main camp but away from potential sources of contamination. Air particulates were collected on No. 41 Whatman filter paper, but the charcoal filter was not used. Since closure of the camp in September 1973, only an 8-day sample in August–September 1974 has been collected.

The in situ probe for measurement of gamma-emitting radionuclides in seawater is essentially a 5- by 5-in. sodium iodide detector with a photomulti-

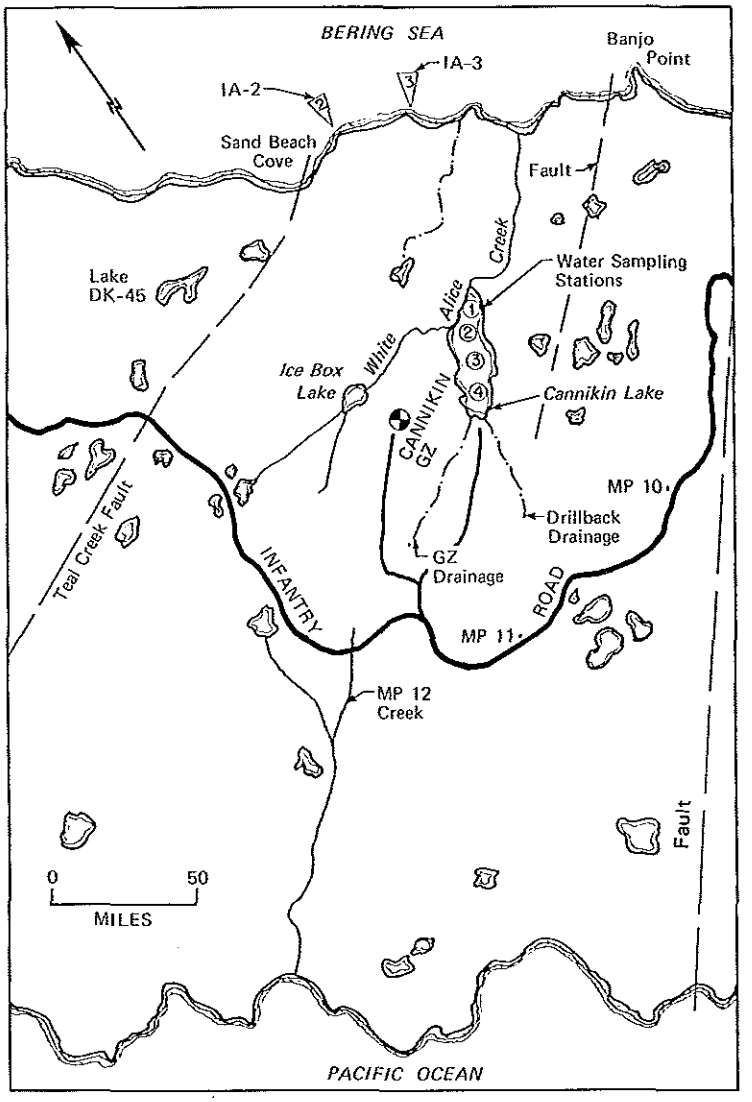

Fig. 3—Collection sites and other prominent features in the Cannikin area.

plier tube and a preamplifier and a linear amplifier enclosed in a pressure-resistant case for use in deep water (Riel, 1966). The probe was tested and calibrated aboard the M.V. *Pacific Apollo* at Amchitka in August 1971 and later used at four locations in the Bering Sea near C Site on the day after the Cannikin event. No gamma radionuclides were detected other than naturally occurring ^{40}K. The limit of detection for a 1-hr counting period was approximately 1 pCi of ^{95}Zr per liter of seawater.

SAMPLE ANALYSES

The samples were analyzed for gamma-emitting radionuclides, ^{3}H, ^{55}Fe, ^{90}Sr, and plutonium, with most of the effort at LRE being spent on the analyses for gamma-emitting radionuclides by gamma-ray spectrometry. Two systems were used. The principal components for one were a 3- by 3-in. sodium iodide crystal detector (NaI) and a 200-channel pulse-height analyzer and for the other a germanium lithium-drifted diode detector [Ge(Li)] and a 4096-channel pulse-height analyzer. If the radionuclides in the samples were not satisfactorily identified by the NaI system, the samples were then analyzed by the Ge(Li) system, which has a higher degree of resolution for gamma energies than the NaI system. For example, the three gamma photons emitted by ^{95}Zr–^{95}Nb (724, 756, and 765 keV) appear as a single peak on the NaI spectrum but as three peaks on the Ge(Li) spectrum.

Analysis for tritium in water requires distillation of either free or extracted water and measurement of ^{3}H in the distilled water by liquid scintillation detection methods (Held et al., 1973). Since a system for measuring tritium in tissue-

Table 2—Common and Scientific Names of Organisms Collected for Radiological Analyses

	Common name	Scientific name
	Vertebrates	
Mammals	Otter, sea	*Enhydra lutris*
	Rat	*Rattus norvegicus*
Fish	Cod, Pacific	*Gadus macrocephalus*
	Dolly Varden	*Salvelinus malma*
	Flounder, arrowtooth	*Atheresthes stomias*
	Greenling, rock	*Hexagrammos lagocephalus*
	Halibut, Pacific	*Hippoglossus stenolepis*
	Lampfish, northern	*Stenobrachius leucopsarus*
	Lantern fish	
	Mackerel, Atka	*Pleurogrammus monopterygius*
	Perch, Pacific ocean	*Sebastes alutus*
	Pollock, walleye: whiting; Alaska	*Theragra chalcogramma*
	Rattail	*Coryphaenoides acrolepis*
	Red Irish lord	*Hemilepidotus hemilepidotus*
	Rockfish, dusky	*Sebastes ciliatus*
	Salmon	
	Chinook; king	*Oncorhynchus tshawytscha*
	Chum	*Oncorhynchus keta*
	Coho; silver	*Oncorhynchus kisutch*
	Pink	*Oncorhynchus gorbuscha*
	Sockeye	*Oncorhynchus nerka*
	Sculpin	Cottidae
	Smelt, deep sea; California smoothtongue	*Bathylagus stilbius*
	Sole, rock	*Lepidopsetta bilineata*
	Stickleback, threespine	*Gasterosteus aculeatus*
Birds	Auklet	
	Least	*Aethia pusilla*
	Parakeet	*Cyclorrhynchus psittacula*
	Goose, Emperor	*Philacte canagica*
	Guillemot, Pigeon	*Cepphus columba*
	Gull, Glaucous-winged	*Larus glaucescens*
	Murre, Thick-billed	*Uria lomvia*
	Oystercatcher, Black	*Haematopus bachmani*
	Ptarmigan, Rock	*Lagopus mutus*
	Puffin, Tufted	*Lunda cirrhata*
	Sandpiper, Rock	*Calidris ptilocnemis*
	Teal, Green-winged	*Anas crecca*
	Tern, Arctic	*Sterna paradisaea*
	Wren, Winter	*Troglodytes troglodytes*
	Invertebrates	
	Amphipod, sand flea	*Gammarus* sp.
	Basket star	*Gorgonocephalus caryi*
	Invertebrates (Continued)	
	Crab	
	False king	*Lithodes aequispina*
	Horse	*Erimacrus isenbeckii*
	King	*Paralithodes camtschatica*
	Tanner	*Chionoecetes tanneri*
	Isopod	*Idotea wosnesenskii*
	Krill	Euphausids
	Medusa	*Cyanea* sp.
	Medusa	*Aurellia* sp.
	Mussel	*Mytilus edulis*
	Mysids	*Acanthomysis* sp.
	Octopus	*Octopus* sp.
	Plankton	spp.
	Scallop	*Pecten hericeus*
	Snail	*Littorina* sp.
	Snail	*Thais lima*
	Sponge	*Halichondria* sp.
	Squid, pelagic	*Gonatus* sp.
	Urchin, green sea	*Strongylocentrotus polyacanthus*
	Marine Algae	
	Algae, coralline	*Corallina* sp.
	Seaweed	*Alaria crispa*
	Seaweed	*Constantinea rosa-marina*
	Seaweed	*Fucus distichus*
	Seaweed	*Hedophyllum sessile*
	Seaweed	*Halosaccion glandiforme*
	Seaweed	*Hypophyllum dentatum* or *ruprechtianum*
	Seaweed	*Laminaria longipes*
	Seaweed	*Porphyra* spp.
	Seaweed	*Thalassophyllum clathrus*
	Seaweed	*Ulva lactuca*
	Freshwater Plants	
	Algae, filamentous	*Cladophora* sp.
	Aufwuchs, periphyton, and other organisms	
	Moss	*Fontinalis neomexicana*
	Ranunculus, crowfoot	*Ranunculus* sp.
	Land Plants	
	Crowberry	*Empetrum nigrum*
	Clover, white	*Trifolium repens*
	Grass	*Agrostis* sp.
	Grass	*Calamagrostis nutkaënsis*
	Lichen	*Cladonia* sp.
	Lupine	*Lupinus nootkatensis*
	Moss	
	Rye, wild	*Elymus arenarius mollis*
	Sedge	*Carex* sp.

bound hydrogen (TBH) of plants and animals has just been completed and tested, only preliminary results are available at this time. The system makes use of a combustion chamber to extract the tissue-bound water and an azeotropic distillation process to purify the extracted water (Nelson and Seymour, 1975).

Iron-55 decays by electron capture and is detected by the X ray that is produced indirectly in the decay process. The measurement of ^{55}Fe requires chemical separation and deposition of the extracted iron on a planchette and the use of a thin crystal for spectrometric detection of the X ray.

Strontium-90 decays entirely by beta emission and can be measured most reliably by the measurement of its radioactive daughter, ^{90}Y. The procedure is to chemically extract strontium from the sample, set the extracted sample aside for 2 weeks

to allow the radioactive decay of ^{90}Sr and ^{90}Y to reach equilibrium, and then separate and beta count the ^{90}Y.

Plutonium is extracted from the samples by ion exchange, electroplated on platinum disks, and analyzed by an alpha spectrometry system that includes surface-barrier detectors and a pulse-height analyzer. For the determination of the chemical yield, ^{242}Pu is used as a tracer.

The limits of detection of the gamma systems for each of the radionuclides were an important factor in the consideration of the error terms for the values of the radionuclides because the amounts of radionuclides in the samples were often near the limit of detection. Many factors influence the limit of detection, including the type of detector and analyzer, the presence of other radionuclides, the duration of the counting period, the size and density of the sample, and the geometry relationship of the sample and detector. Hence the limits of detection varied considerably for various radionuclides and types of samples but can be summarized by stating that the detection limits were approximately as follows:

By gamma detection	
^{40}K	2.1 pCi/g or less
^{7}Be, ^{103}Ru, ^{144}Ce ^{228}Th, ^{238}U	0.41 pCi/g or less
^{95}Nb, ^{95}Zr, ^{125}Sb, ^{137}Cs, ^{155}Eu, ^{226}Ra	0.12 pCi/g or less
By beta detection	
^{3}H	<48 pCi/liter
^{90}Sr	<0.04 pCi/g
By X-ray detection	
^{55}Fe	<0.04 pCi/g
By alpha detection	
$^{239,240}Pu$	<0.005 pCi/g

RESULTS

Detailed results of radiometric analyses of Amchitka samples are given in the LRE Long Shot, Milrow, and Cannikin progress reports (Table 1). The effort expended on the radiobiological programs has been much greater for Cannikin than for the other two programs, and, since each Cannikin progress report summarizes data from previous reports as well as presents the results of current analyses, the most recent progress report (1976) is the best single source of radiobiological information. For this reason tables from recent progress reports (Nelson and Seymour, 1975; 1976) are included in this report as Tables A.1 to A.20 of the appendix.

The long-term trends of the radionuclide values for various sample types for the period 1965 to

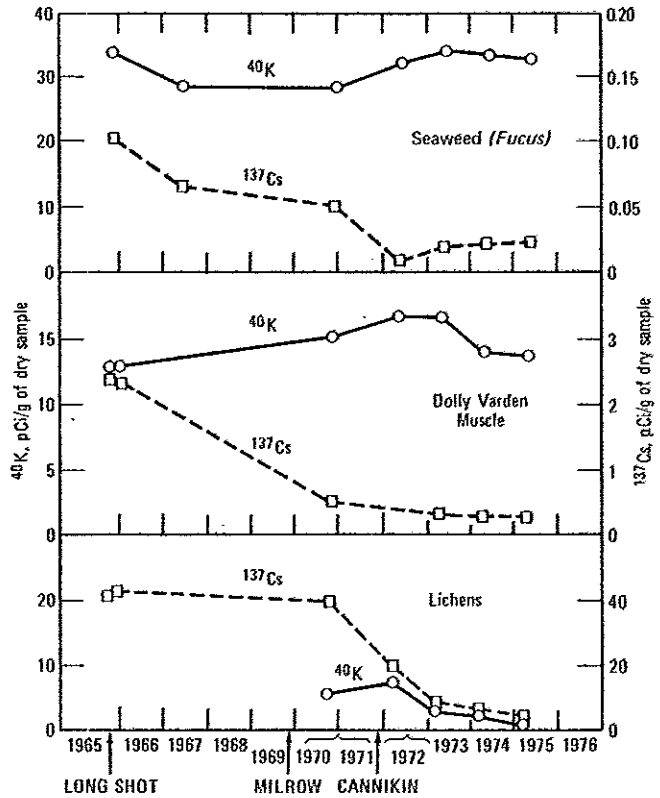

Fig. 4—Cesium-137 and ^{40}K in seaweed, Dolly Varden muscle, and lichens for the period 1965 to 1975.

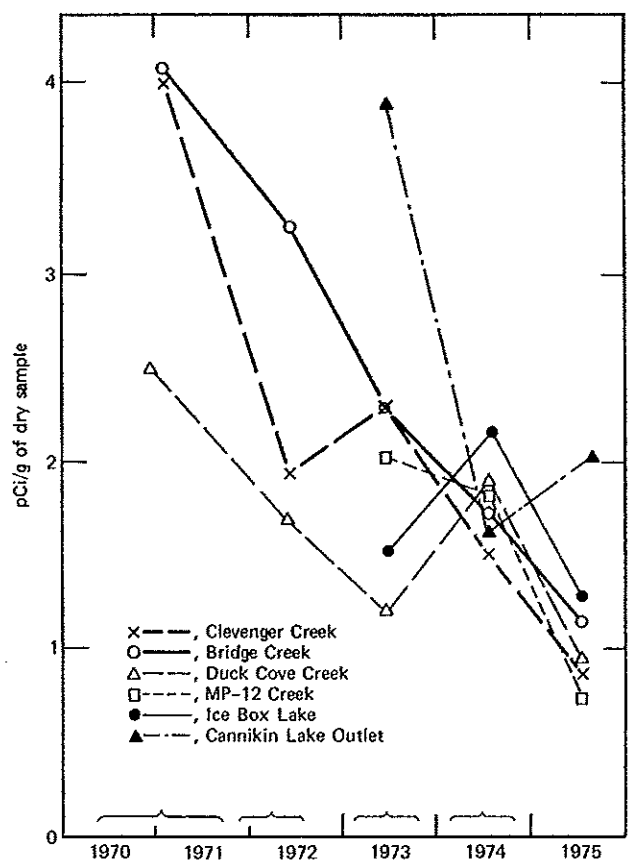

Fig. 5—Cesium-137 in the freshwater moss, *Fontinalis* sp., from six locations, 1970 to 1975.

1975 are given in Figs. 4 to 7 and Table 3. In these figures and tables, data have been averaged for selected time periods, usually 1 year. Figure 4 shows the relationship between a naturally occurring radionuclide (^{40}K) and a long-lived fallout radionuclide (^{137}Cs) for a biological indicator species from each of three environments. The data in Fig. 5 for one radionuclide (^{137}Cs) and one sample type (freshwater moss) from each of six areas demonstrate area effect. In Fig. 6 the four

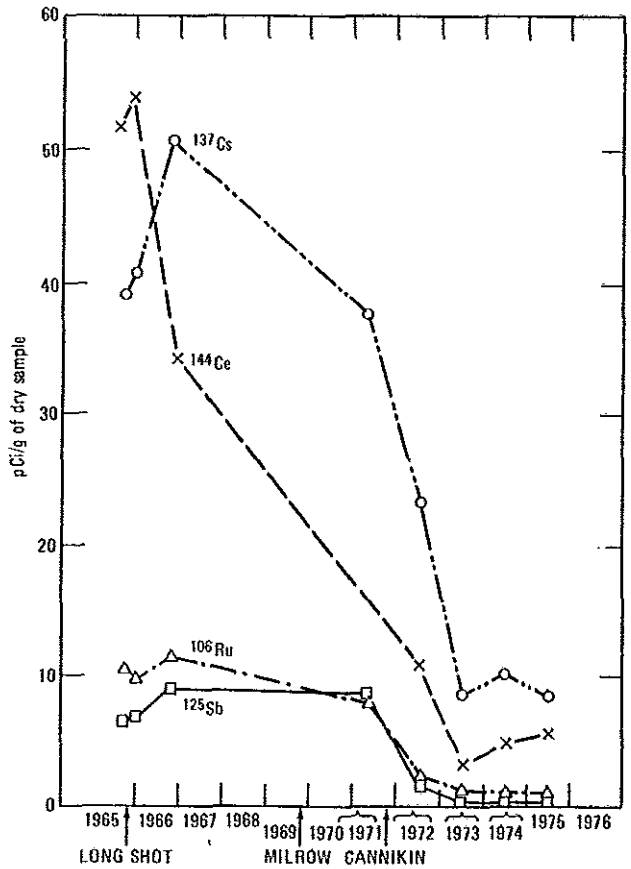

Fig. 6—Selected fallout radionuclides in lichens for the period 1965 to 1975.

most abundant fallout radionuclides (^{137}Cs, ^{144}Ce, ^{106}Ru, and ^{125}Sb) are quantitatively related to the sample type (lichens) in which they occur in greatest concentrations. The values for the amount of ^{3}H in samples of water from Long Shot Mud Pit No. 1, other freshwater sources, and the ocean are given in Fig. 7. For an evaluation of the amount of radioactivity in the most likely pathways for the transfer of radionuclides from the Amchitka environment to man, the results of analyses of fish, crab, and a game bird for the most abundant naturally occurring and fallout radionuclides are given in Table 3.

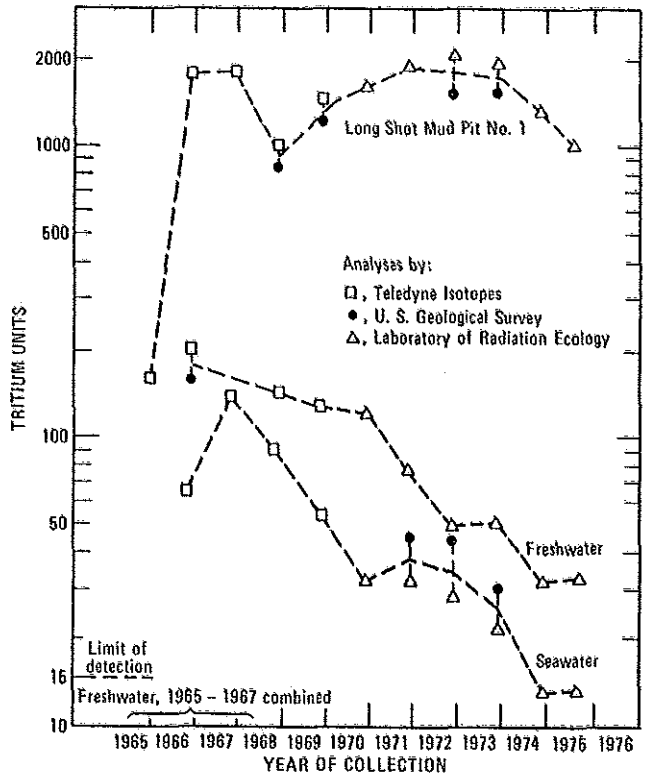

Fig. 7—Mean tritium concentrations in water samples from Long Shot Mud Pit No. 1, other freshwater sources, and the ocean, 1965 to 1975.

DISCUSSION

Introduction

The values for the fallout radionuclides were often near or below the limits of detection, and the error terms for the values were large. Often the coefficient of variation (standard deviation ÷ mean) exceeded 100%. The small values and relatively large error terms for the fallout radionuclides did not obscure the answer to the question about the presence or absence of radionuclides of Amchitka origin in the samples, the primary objective of the program; however, the Amchitka radiobiological data did not contribute significant new information about the cycling, concentration, and transfer of fallout radionuclides in the environment, which was the secondary objective.

A concise interpretation of the results of radiometric analyses of many hundreds of Amchitka samples collected over an 11-year period requires some screening of the data and, ultimately, limiting the principal discussion to a few significant sample types for a few radionuclides. Two variables considered in the process of selecting and reducing data were the time and the area of collection.

Table 3—Potassium-40, ^{55}Fe, and ^{137}Cs Concentration in Muscle of Fish, Crab, and Ptarmigan Collected at Amchitka Island from 1965 to 1975

		^{40}K, pCi/g of dry weight			^{55}Fe, pCi/g of dry weight			^{137}Cs, pCi/g of dry weight		
Sample type	Year	Range	x̄ ± SD	n*	Range	x̄ ± SD	n*	Range	x̄ ± SD	n*
Salmon	1965		11.6	1/5		Na†			0.13	1/5
	1967	12–13	13 ± 0.6	2/22		Na		Ns†–0.11	0.06 ± 0.08	2/22
	1969	10–15	12 ± 1.7	14/14	0.6–9.7	2.2 ± 2.3	15/30	Ns–0.14	0.06 ± 0.03	14/14
	1971	8–15	12 ± 1.9	29/29		Na		Ns–0.12	0.04 ± 0.03	29/29
	1972	11–21	14 ± 2.9	10/10	0.39–1.1	0.58 ± 0.24	6/6	Ns	Ns	10/10
	1973		Na			Na			Na	
	1974	15–15	15 ± 0.1	2/2	0.36–0.42	0.39 ± 0.4	2/2	Ns–0.09	0.05 ± 0.06	2/2
Dolly Varden	1965	13–13	13 ± 0.3	2/41		Na		2.2–2.3	2.3 ± 0.11	2/41
	1969	3–13	12 ± 3.7	9/9	Ns–0.65	0.19 ± 0.19	11/11	Ns–1.8	0.50 ± 0.70	9/9
	1970	13–14	14 ± 0.7	2/22	1.6–1.6	1.6 ± 0.1	2/22	0.29–0.34	0.32 ± 0.04	2/22
	1971		15 ± 0.8	1/1		Na			0.35 ± 0.05	1/1
	1972	15–17	16 ± 1.0	3/8	0.23–0.49	0.36 ± 0.18	2/2	1.1–8.2	5.7 ± 3.9	3/8
	1973	15–16	16 ± 0.6	3/7		0.05 ± 0.01	1/4	0.13–0.28	0.18 ± 0.09	3/7
	1974	13–17	14 ± 1.6	6/28	Ns–0.09	0.06 ± 0.03	4/19	0.17–0.35	0.24 ± 0.08	6/28
	1975	4–16	12 ± 4.4	5/19		Na		0.05–0.33	0.17 ± 0.12	5/19
Halibut	1967	15–16	15 ± 0.6	2/2		Na		Ns–0.12	0.06 ± 0.08	2/2
	1969	11–18	14 ± 2.9	4/4		0.31	1/1	Ns–0.11	0.03 ± 0.06	4/4
	1970		20 ± 0.7	1/26		0.12	1/26		0.10 ± 0.05	1/26
	1971	16–20	19 ± 1.3	7/7		Na		Ns–0.19	0.07 ± 0.08	7/7
	1972	15–20	16 ± 1.4	7/7	0.35–0.36	0.36 ± 0.01	2/2	Ns–0.06	0.01 ± 0.02	7/7
	1973	17–20	18 ± 1.1	5/5	0.01–0.16	0.09 ± 0.10	2/2	0.08–0.14	0.11 ± 0.02	5/5
	1975	18–19	19 ± 0.7	2/3		Na		0.05–0.06	0.06 ± 0.01	2/3
Crab, king	1965	12	12	1/1		Na		Ns	Ns	1/1
Lithodes	1967	12–13	13 ± 0.9	2/37		Na		Ns	Ns	2/37
Lithodes	1971		Na			Na		Ns–2.4	0.43 ± 0.88	7/7
Ptarmigan	1970		11 ± 1.2	1/1		Na			0.25 ± 0.08	1/1
	1971	11–12	11 ± 0.6	3/3		Na		1.0–1.7	1.3 ± 0.4	3/3
	1972	11–13	12 ± 1.4	2/2		Na		0.72–0.73	0.73 ± 0.01	2/2
	1973	10–12	11 ± 0.8	5/5		Na		0.18–0.76	0.43 ± 0.25	5/5
	1974	10–13	11 ± 1.3	5/6		Na		0.39–1.1	0.80 ± 0.36	5/6
	1975	11–14	12 ± 1.5	3/8		Na		1.4–3.4	2.2 ± 1.1	3/8

*N, number of pooled samples/total number of organisms in all samples.
†Na, not analyzed; Ns, not significantly greater than background.

So that the variation with time of radionuclide concentration in the biological samples could be determined, the data for the results of analyses were segregated by year of collection and sample type for the natural and the long-lived fallout radionuclides in greatest concentration in the samples. The sample types selected were *Fucus distichus*, a brown alga from the marine environment; Dolly Varden, a char that lives in freshwater but often migrates to the sea and returns; and lichens, terrestrial cryptogamic plants. The radionuclides selected were ^{137}Cs, which has a half-life of 30 years, and ^{40}K. These data are given in Fig. 4 and indicate a decline with time for ^{137}Cs but not for ^{40}K. The decrease in the ^{137}Cs concentration suggests that the principal source of this radionuclide was fallout in the early 1960s, and the constant values for ^{40}K reflect a constant source of this radionuclide, as would be expected.

For the determination of the effect of area of collection, the best source of information appeared to be the data for ^{137}Cs in the freshwater moss (*Fontinalis*) collected at six areas on Amchitka Island in the period from 1970 to 1975. These data are given in Fig. 5 and indicate that there are some, but not consistent, differences between areas. Therefore the area of collection has been removed as a variable in the interpretation of the data, and, generally, the results of analyses of collections from all areas of Amchitka have been transposed to a mean value for a single year.

Sample Types

Most of the remaining discussion of the interpretation of the radiometric data relates to sample type and radionuclide species. Since the two subjects are interrelated and cannot be clearly separated, they will be discussed separately at the expense of some redundancy.

Biological Samples. *Indicator Species.* About 90 sample types were analyzed, including whole samples for, or selected tissue samples from, 81 organisms; the remainder were soil, water, or air

samples. A review of the data for the 81 organisms indicated that little, if any, information would be lost by limiting the discussion to a few indicator species. An ideal indicator species is defined as a sessile species which significantly concentrates one or more radionuclides from the environment and which is readily available throughout the year to the collector in quantities sufficient to provide repeated samples of adequate size for analysis without a significant effect on the population of the organism in the collection area. On the basis of this definition, the following organisms have been selected as the principal indicator species for Amchitka Island:

Indicator species	Environment
Fucus distichus, a brown alga	Marine
Fontinalis neomexicana, a moss	Freshwater
Ranunculus sp., crowfoot	Freshwater
Lichens, cryptogamic plants	Terrestrial

The concentrations of fallout radionuclides by *Fucus* and by other marine algae were not greatly different, but *Fucus* was selected as the indicator species because of its accessibility and abundance at Amchitka and its use as an indicator species in Great Britain and other geographical areas. The sample collection areas for *Fucus* were Constantine Harbor, Duck Cove, Square Bay, and Sand Beach Cove. The most abundant fallout radionuclides in these samples were ^{95}Zr, ^{95}Nb, ^{137}Cs, and ^{144}Ce, and the greatest value for any of the four radionuclides was 1.5 pCi/g of dry weight (see Table A.1). The values for naturally occurring ^{40}K ranged from 23 to 46 pCi/g of dry weight for the same samples.

The radionuclides detected in the freshwater indicator species were the naturally occurring radionuclides ^{7}Be and ^{40}K and the fallout radionuclides ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{155}Eu (Tables A.2 and A.3). Of these radionuclides, ^{7}Be and ^{40}K were present in the greatest concentration (1 to 29 pCi/g of dry weight), whereas the concentrations of ^{95}Nb, ^{106}Ru, ^{137}Cs, and ^{144}Ce did not exceed 6.4 pCi/g of dry weight. Radionuclides commonly detected in aquatic vegetation samples collected prior to 1973 but only sporadically since 1973 include ^{54}Mn and ^{60}Co. The concentrations of radionuclides in *Fontinalis* and *Ranunculus* samples in 1974 were similar to those in aufwuchs and filamentous algae (Table A.4) and lichens (Table A.5) except that ^{155}Eu was not detected in the aufwuchs and greater concentrations of ^{137}Cs and ^{144}Ce were present in some 1974 aufwuchs and lichen samples than in the freshwater indicator species. Samples were collected from Clevenger Creek, Bridge Creek, Duck Cove Creek, Mile Post 12 Creek, Ice Box Lake Inlet, and the outlets of Clevenger and Cannikin Lakes.

The indicator species selected for the terrestrial environment were lichens because of their well-established capability for accumulation of fallout radionuclides. The lichen samples were collected near Clam Lake, Ice Box Lake, and Cannikin Lake and were not sorted for species. *Cladonia rangifera* was the principal species reported by Koranda et al. (1969), but other species and mosses were also present in the samples used for analyses. A large array of fallout radionuclides, which included ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{155}Eu, was present in the lichen samples (see Table A.5). Of these, ^{137}Cs was the most abundant, and it was also more abundant than the naturally occurring radionuclides. The ranges of mean yearly values in terms of pCi/g of dry weight were 6 to 47 for ^{137}Cs, 5 to 15 for ^{7}Be (a naturally occurring radionuclide), and 1 to 6 for ^{40}K.

Food-Chain Organisms. Many species of fish, of commercial importance and otherwise, were collected and analyzed. The species that best represented the potential transfer of radionuclides from the sea to man were selected.

Of special interest are seafoods and other organisms that may be eaten by man. Although there are no significant commercial fisheries in the immediate vicinity of Amchitka (Merrell, Chap. 15, this volume), radionuclide data were obtained for salmon and Dolly Varden (Table A.6), halibut (Table A.7), and crab. The amount of ^{55}Fe and ^{137}Cs (the principal or only fallout nuclides present) and ^{40}K in muscle samples of these species by year for all collection sites is listed in Table 3. Similar information for the ptarmigan, a game bird present on Amchitka, is also given in Table 3 and supplemental information for the ptarmigan samples in Table A.8.

The predominant radionuclide was ^{40}K for all species for all years, with mean yearly values ranging from 11 to 20 pCi/g of dry weight. The values for ^{55}Fe and ^{137}Cs were severalfold less; this difference increased with time since the ^{40}K values remained relatively constant and the values for ^{55}Fe and ^{137}Cs declined. The decline was more rapid for ^{55}Fe than for ^{137}Cs. Another observation of interest was that landlocked Dolly Varden concentrated more ^{137}Cs, perhaps ten times more, than anadromous Dolly Varden captured after their return to freshwater. The maximum value for ^{137}Cs in muscle tissue of all the Dolly Varden samples was 8.2 pCi/g of dry weight for fish caught in a landlocked lake.

Many other species of fish were collected and analyzed (Tables A.9 and A.10), including greenling, which were sampled because they are an abundant inshore resident species. However, these data did not bring forth any new information. The wide array of marine invertebrates sampled, in addition to crabs, included sponges, snails, scallops, urchins, octopus, mussel, and plankton. Data for the sponge are given in Table A.11. The other species were not readily available in the intertidal zone, and most of the samples were obtained in 1971 and 1972 from otter-trawl catches by the M. V. *Commander*. Results of gamma-spectrum analyses of 40 samples are given in Table 7 of the 1973 Progress Report (Nelson and Seymour, 1974) and indicate no unusual kinds or amounts of radionuclides. The fallout radionuclides included ^{60}Co, ^{65}Zn, ^{95}Zr, ^{95}Nb, and ^{144}Ce. Their concentrations, with only a few exceptions, were less than 1 pCi/g of dry weight, whereas the ^{40}K values were usually greater by a factor of 10 or more.

Environmental Samples. The results of radiometric analyses of air and water samples indicate the kinds and amounts of radionuclides that are potentially available for accumulation by plants and animals. Also, significant changes in the amounts or kinds of radionuclides in air samples can herald the arrival of new airborne radionuclides to an area.

Air. The air-sampling program was not continuous. Biweekly samples were collected from Oct. 2, 1970, to Nov. 12, 1971, weekly samples from Feb. 23, 1972, to Aug. 28, 1973, and a single 8-day sample in August–September 1974. This program was designed to detect fallout radionuclides in air particulates and did not include the use of a charcoal filter for the collection of radioactive gases.

Three air samplers, operated simultaneously, were used to collect air particulates; in August–September 1974, however, only one sampler was used. The airflow rate through a 15-cm filter head lined with Whatman No. 41 filter paper was about 500 m^3/day. This paper has a retention index of 100 and retains particles of 5 μm and larger in diameter. The results of analyses are reported in Table A.12.

The most abundant radionuclides in the air samples were naturally occurring ^{7}Be and fallout radionuclides ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{137}Cs, and ^{144}Ce. Because of their relatively short half-lives and large fission yield, a significant increase in the occurrence of ^{95}Zr, ^{95}Nb, and ^{103}Ru in the samples would indicate the arrival of fresh fallout. All the fallout radionuclide values for air samples were less than 10 fCi/m^3 of air and often less than 1 fCi; however, the values for ^{7}Be ranged from 3 to 47 fCi/m^3. A review of the radioactivity values for the short-lived fallout radionuclides indicates changes in values from time to time, but no strong correlation of radioactivity in Amchitka air samples with nuclear detonations at Lop Nor, China, was established.

The average yearly values for fallout radionuclides commonly detected in the samples (^{95}Zr, ^{95}Nb, ^{103}Ru, and ^{137}Cs) generally decreased during the period from 1970 to 1973. Niobium-95, for example, decreased from 5.9 to 0.04 fCi/m^3 of air filtered. The average yearly value of naturally occurring ^{7}Be, however, remained between 16 and 20 fCi/m^3 for the same period.

Air data obtained during 1974 from other sources (United States Environmental Protection Agency, 1973; 1974; LRE, Annual Report to Ebasco Services Inc., 1975, unpublished) indicated slightly greater amounts of radionuclides in airborne particulates and in precipitation in 1974 than 1973 from most stations in Alaska, Canada, and contiguous United States. This trend also would be expected at Amchitka, although the single 8-day sample taken in August–September 1974 did not contain detectable amounts of any radionuclide, including ^{7}Be. This may be explained by the relatively small volume of air sampled and the time of sampling, which was after the spring peak of stratospheric fallout.

Seawater. Both seawater and freshwater were sampled with a system of filters and sorption beds in a modified Battelle–Northwest Laboratories large-volume water sampler. The system consists of eight Millipore filters of 0.3-μm porosity which are 29 cm in diameter and which are arranged in parallel so that the water passes through the filters and then through one or more aluminum oxide beds arranged in series. An accurate analyses can be made of the filter papers for radionuclides 0.3 μm in diameter or larger retained on the filter paper, but the estimate of the fraction of the radionuclide in soluble form, as determined by analyses of the aluminum oxide beds, is less accurate because bed efficiency has not been precisely established for all radionuclides. The problem of determining bed efficiency is complicated by changes in the physical and chemical form of the nuclide which may occur naturally during efficiency calibration of the sampler. Also, ^{3}H and ^{40}K and perhaps some other radionuclides in ionic form are not captured by aluminum oxide. The results of seawater analyses for gamma-emitting radionuclides are reported in Table A.13.

Pre-Cannikin samples of offshore seawater were obtained in September 1970 and August 1971.

After the Cannikin detonation in November 1971, the collection of seawater samples was limited to intertidal areas. Cobalt-60, ^{65}Zn, and ^{110m}Ag were present in all seawater samples collected in September 1970; also present in some samples were ^{46}Sc, ^{54}Mn, and ^{108m}Ag. The presence of ^{108m}Ag was unexpected, but it was identified qualitatively in the sample taken from the station farthest offshore on the Pacific Ocean side of Amchitka Island. The average concentrations of radionuclides in particulate form were 69, 120, and 44 pCi/m^3 for ^{60}Co, ^{65}Zn, and ^{110m}Ag, respectively; the fraction of each of these radionuclides in particulate form is about one-eighth for ^{60}Co and ^{65}Zn and two-thirds for ^{110m}Ag. From these data the concentration of ^{60}Co, ^{65}Zn, and ^{110m}Ag in seawater was calculated to be 550, 1000, and 70 pCi/m^3 of seawater, respectively. Fewer species of radionuclides were present in the seawater samples collected the following year, 1971.

Seawater samples collected after Cannikin were limited to the intertidal areas of Constantine Harbor, Duck Cove, and Sand Beach Cove, and the radionuclides detected were ^{7}Be, ^{95}Zr, ^{95}Nb, and ^{137}Cs. Beryllium-7 was present in the soluble fraction of the 1971–1972 samples from Constantine Harbor and Sand Beach Cove in amounts that averaged from 0.072 to 0.14 pCi/liter. Beryllium-7 was not detected in the soluble fraction of the 1971–1972 samples from Duck Cove but was slightly above the limit of detection in the particulate fraction. The fallout radionuclides were present in the 1971–1972 and 1974 particulate fraction and the 1971–1972 soluble fraction in amounts that averaged from nonsignificant to 0.046 pCi/liter. No radionuclides were detected in the six samples collected in 1973, but trace amounts of ^{95}Zr and ^{95}Nb were detected in the particulate fraction of some 1974 seawater samples. The significance of this observation is not obvious in light of the range of values for similar samples in other years, although both air and biological samples also indicated a slight increase in fallout radionuclides in 1974.

Freshwater. Samples for gamma-spectrum analyses were collected in August 1971, prior to Cannikin, and in each of the following years. The results of analyses of these samples are given in Table A.14.

Samples were obtained from Jones, Heart, DK-45, and Cannikin Lakes and Long Shot Mud Pit No. 1. The radionuclides detected included ^{7}Be, ^{95}Zr, ^{95}Nb, ^{137}Cs, and ^{144}Ce, but not all the radionuclides were present in all samples. For the lake samples, the values for ^{7}Be ranged from nondetectable to 4 pCi/liter, but for the fallout radionuclides the annual values were less than 0.5 pCi/liter. The radionuclide values, except ^{137}Cs, for the Long Shot Mud Pit No. 1 samples were five times or more greater than comparable values for the lake-water samples. One possible explanation of this difference is that the mud-pit samples contained more particulate material than the lake-water samples. Like the seawater samples, the values for gamma-emitting radionuclides in freshwater declined to near zero in 1973 but increased slightly in 1974.

Both seawater and freshwater samples were also analyzed for tritium, and these analyses are discussed in the tritium section.

Soils and Sands

In 1975 surface soils and beach sands were added to the sample collection list. Samples of soils from the surface to a depth of 2.5 cm were collected from the main camp and in the vicinity of Cannikin surface ground zero. Beach sand samples of the same size were also collected at Constantine Harbor and Sand Beach Cove. The results of gamma-spectrum analyses are listed in Table A.15. The fallout radionuclides detected in the soil samples were ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{106}Ru, ^{137}Cs, ^{141}Ce, and ^{144}Ce, but all the values for these radionuclides were less than 1 pCi/g of dry weight. The natural radionuclides ^{226}Ra, ^{228}Th, and ^{40}K were present in both soil and sand samples, and, in addition, trace quantities of ^{238}U were present in the beach sand samples. The amounts and species of fallout radionuclides in Amchitka soil samples were similar to those in soil samples collected in the western region of Washington State in 1973–1975 (Laboratory of Radiation Ecology, Annual Report to Ebasco Services, 1975, unpublished).

Background Radiation. The results of background-radiation measurements made in August 1974 and 1975 with a survey instrument are given in Table A.16. A survey meter with a thin end-window detector less than 2 mg/cm^2 was used without the beta shield. The detector was sensitive to beta-particle energies as low as 40 keV, and its efficiency for the detection of ^{60}Co gamma photons, measured in terms of dose rates, was about 5000 cpm/(mr/hr). Tritium cannot be detected by this survey meter since the maximum energy of the beta particles emitted by ^{3}H is 19 keV. The locations surveyed included the surface ground zero and adjacent areas for Long Shot, Milrow, and Cannikin. Maximum values recorded while holding the survey instrument 1 m above the ground ranged from 0.03 to 0.05 mr/hr. Average values at all sites were about 0.01 mr/hr or less.

These values are similar to those for values obtained from comparable surveys in other areas of the United States.

Radionuclide Species

Natural. The source of natural radionuclides in the environment of either terrestrial or atmospheric origin is constant, whereas the amounts and kinds of fallout radionuclides change with time and season in accordance with the input into the troposphere of fresh radionuclides from nuclear detonations and of older radionuclides from the stratosphere. Hence the amounts of natural radionuclides in one type of sample would be expected to be relatively constant from year to year, and a review of the radionuclide values in the appendix tables indicates that this is true. The variation for any one sample for any one year appears to be no greater than the sample variation between years. This also indicates year-to-year consistency in analytical procedures.

The natural gamma-emitting radionuclides in greatest concentrations were ^{7}Be and ^{40}K, but lesser concentrations of ^{226}Ra, ^{228}Th, and ^{238}U were detected in some samples. If the samples had been analyzed for alpha-emitting radionuclides, other natural radionuclides, such as radium and radon, would have been expected in amounts at or near the limit of detection.

In the samples the natural radionuclides were more abundant than the fallout radionuclides, usually by a factor of 10 or greater, and ^{40}K was more abundant than ^{7}Be except in lichen, aufwuchs, and water samples. Both lichens and aufwuchs have a great capacity to accumulate radionuclides by adsorption, and this may explain the greater values for ^{7}Be than for ^{40}K in these samples. For the water samples, the amount of ^{40}K was greatly underestimated. Potassium-40, which is principally in solution in seawater, is very poorly removed by the aluminum oxide beds of our water sampler; hence little or no ^{40}K was reported to be present in our samples, although the actual amount, which can be accurately calculated from the salinity, was about 300 pCi/liter.

Fallout

Gamma-Emitting Radionuclides. The gamma-emitting radionuclides detected most commonly by gamma-spectrum analyses were ^{95}Zr, ^{95}Nb, ^{137}Cs, and ^{144}Ce. Radionuclides detected less frequently include ^{46}Sc, ^{54}Mn, ^{60}Co, ^{65}Zn, ^{103}Ru, ^{106}Ru, ^{108m}Ag, ^{125}Sb, and ^{155}Eu.

Four other radionuclides, ^{3}H, ^{55}Fe, ^{90}Sr, and ^{239,240}Pu, have been given special attention, each for a different reason. Tritium is an excellent "tag" for water and should be an excellent indicator of any movement of water away from the underground sites of the nuclear detonations. Iron-55 was found in relatively large quantities after the atmospheric detonations in the mid-Pacific and U.S.S.R. in 1961 and 1962, and, although its half-life is only 2.5 years, this radionuclide was the most abundant fallout radionuclide in the fishes of the world's oceans for many years after 1962. Strontium-90 has always been a fallout radionuclide of interest because it is chemically similar to calcium, is a relatively abundant fission product, and has a long half-life (28 years).

Tritium. The analysis of seawater and freshwater for tritium was a two-step process: (1) The purification of the sample by either a vacuum or an azeotropic distillation process and (2) the measurement of ^{3}H in the distillate with a liquid scintillation system (Held et al., 1973). The analyses of biological samples for ^{3}H in tissue-water hydrogen (TWH) and tissue-bound hydrogen (TBH) were similar except that the first step for the analysis of TBH was preceded by a water-extraction procedure (Nelson and Seymour, 1975) that has recently been modified (Nelson and Seymour, 1976).

Tritium is produced naturally and by nuclear detonations. Natural tritium production by cosmic-ray interactions with atmospheric gases results in a ^{3}H concentration of a few tens of tritium units (TU)* in rainwater (Grosse et al., 1951; Perkins and Nielsen, 1965). After the advent of the nuclear age, the ^{3}H content of precipitation increased to a maximum of several thousand TU in 1963 owing to the release of tritium from nuclear explosions and, to a very small extent, from reactors and fuel-processing plants (Castagnola, 1969a). At Adak Island, which is only 300 km east of Amchitka, the monthly values in 1963 ranged from 550 to 3900 TU and the mean value was 1860 TU (International Atomic Energy Agency, 1971). Since the peak values in 1963, tritium levels in precipitation have decreased to present values of less than 100 TU.

The results of analyses of seawater and freshwater samples for ^{3}H by Teledyne Isotopes, the U. S. Geological Survey, and the Laboratory of Radiation Ecology for the years 1965 to 1975 are shown in Fig. 7 as mean yearly concentrations. Also in Fig. 7 are values for a special freshwater area, Long Shot Mud Pit No. 1. The results of ^{3}H analyses for single samples of seawater and freshwater for the period 1970 to 1975 are given in Table A.17.

*A tritium unit (TU) is one tritium atom per 10^{18} hydrogen atoms, or 3.23 pCi of ^{3}H per liter of water.

The seawater values for ^3H were less than the freshwater values, presumably because of the greater dilution in the ocean than in the small lakes of Amchitka Island of the ^3H that comes to the earth's surface in precipitation. The monthly mean value for ^3H in Amchitka seawater reached a maximum of 138 TU in 1967 (Essington, Forslow, and Castagnola, 1970) and has decreased since that time to 15 TU in 1975 (Table A.17). The latter number compares favorably with a predicted value of 15 to 30 TU that can be obtained by extrapolation of the data of Dockins et al. (1967) and by recognizing that only a few atmospheric detonations of nuclear devices have occurred since 1962.

The ^3H values for freshwater ponds, lakes, and streams shown in Fig. 7 are based on the results of analyses of 268 samples. [Excluded from the calculation of the yearly mean values were several hundred samples collected and analyzed by the U. S. Geological Survey for which the results of analyses were reported as less than 200 TU (pre-1973) or 150 TU (1973).] The maximum annual value recorded was 175 TU in 1966, the first year freshwater samples were collected. The yearly mean values steadily declined from 1966 to a value of 32 TU in 1974 and 34 TU in 1975. The amount of ^3H to be expected in freshwater at Amchitka can be estimated from the long-time continuous records of the amount of ^3H in precipitation at Valentia, a marine station in Ireland that is approximately the same latitude as Amchitka (Schell et al., 1974). Comparison of the Valentia and Amchitka data indicates that the amount of ^3H in surface waters at Amchitka and in rainfall at Valentia is of the same order of magnitude and is decreasing in a similar manner at the two stations. From this and the known values for ^3H in rainfall at Adak, Schell (personal communication, 1975) predicts that the amount of ^3H in Amchitka surface water now ranges from about 15 TU in winter to 140 TU in early summer.

The data for ^3H in water from the Long Shot ponds were not included with the data for the other freshwater samples since it was established soon after the Long Shot detonation that the radionuclide values for some water samples from this area were significantly greater than those from samples from other sites on Amchitka Island. Some tritium moved away from the underground site of the detonation, and the main front of activity reached the surface in September 1966, about 11 months after Long Shot. Tritium values in surface waters at that time reached a peak of 5130 TU in the drainage ditch 60 m east of surface ground zero (Castagnola, 1969b). In addition to ^3H, traces of radioiodine were also detected in 4 of 78 water samples during the initial breakthrough of activity, and ^{85}Kr was found in soil gas stripped from water draining the Long Shot pad area (Castagnola, 1969b). Tritium, ^{85}Kr, and ^{131}I could be detected only in the samples from the immediate area surrounding Long Shot surface ground zero, and only tritium was detectable one year after Long Shot.

So that the amount of ^3H in groundwater could be further investigated, shallow wells were dug in the Long Shot area in late 1971. Analyses of water from these wells indicated that the maximum ^3H concentrations were in samples from a depth between 200 and 300 ft (60 and 90 m) below the surface and that the concentration of ^3H decreased at greater depths. Tritium also decreased with distance away from the Long Shot placement hole. Thus "these observations indicate that gaseous activity, mostly tritium and krypton, moved at an early time to the top of the chimney (which at Long Shot did not reach the surface). As the chimney filled with water, these gases were pushed ahead upwards, passing through uncompacted material in the upper portion of the stemming, out into the spall zone, where they went into solution" (Merritt, 1973).

Figure 7 indicates that the mean yearly values for Long Shot Mud Pit No. 1 approached a maximum of 1800 TU in 1966 and 1967, decreased to 850 TU in 1968, increased again to 1750 TU in 1971, and declined to 900 TU in 1975. Because heavy rainfall is believed to have significantly diluted the sample collected in 1975, the value for the sample collected 3 m downstream from Long Shot Mud Pit No. 1 was used (Nelson and Seymour, 1976). Although some single sample values for Long Shot Mud Pit No. 1 exceeded 5000 TU, all the values are well below the Maximum Permissible Concentration for ^3H in water (MPC_w) for occupational exposure. This value is 3×10^{-2} μCi of ^3H per milliliter of water, equivalent to 9×10^6 TU, and was established by the International Commission on Radiological Protection (ICRP) (1959) and the U. S. National Committee on Radiation Protection (NCRP) (1959). For an individual member of the population in an uncontrolled area, the Radiation Protection Guide (RPG) value is one-tenth the MPC for occupational exposure, or 3×10^{-3} μCi of ^3H per milliliter of water, which is equivalent to 9×10^5 TU (Energy Research and Development Administration, 1975a). The average value for the general population is less than that for the individual, and, for isotopes that concentrate in organs other than the gonads, a value of one-thirtieth the MPC value for continuous occupational exposure, or 10^{-3} μCi of ^3H (3×10^5 TU), has been established by the International Commission on Radiological Protec-

tion (1964). Another perspective on the significance of ^3H in the Amchitka samples is obtained by a comparison of the maximum values of 5000+ TU at Amchitka (Long Shot Mud Pit No. 1) with values for ^3H in rainfall at other areas. At nearby Adak in the Aleutian Islands, where the concentration of ^3H in precipitation can be assumed to be about the same as that at Amchitka, monthly samples have been collected, and in 1963 the mean value was 1860 TU and the maximum 3900 TU (International Atomic Energy Agency, 1971). Although the tritium concentration in Long Shot Mud Pit No. 1 at Amchitka was somewhat greater than in precipitation at Adak in 1963, it was comparable to the tritium concentration in precipitation in the Central United States (Stewart and Farnsworth, 1968), a continental location where the concentration of ^3H in precipitation is expected to be significantly greater than at a coastal location, such as Adak or Amchitka. Also, in 1963 the tritium concentration in precipitation at another continental site, Vienna, Austria, ranged from 800 TU to almost 6000 TU (Schell et al., 1974).

No tritiated water has been observed in the samples collected for the Milrow or Cannikin events, probably because the rubble chimneys reached the surface, and, if the tritium or krypton came to the surface with the rising water in the chimney, it dissipated at undetectable levels. Also, the emplacement holes contained plugs of epoxy cement, which prevented the stemming from being an escape route (Merritt, 1973).

In addition to the measurement of the ^3H concentrations in seawater and freshwater, measurements of ^3H in seafoods from two sources were also made. Samples of canned salmon, crab, scallops, and shrimp caught in Alaska and Washington waters before and after Cannikin were provided by the National Canners Association for analysis by the Environmental Protection Agency's National Environmental Research Center in Las Vegas, Nev. A second set of samples was collected near Amchitka by the Fisheries Research Institute, University of Washington, and also forwarded to the EPA laboratory for analysis. These samples included salmon caught before Cannikin and salmon, halibut, cod, and crab caught after Cannikin.

The results of analyses for total tritium, i.e., tritium in tissue-water hydrogen (TWH) plus tissue-bound hydrogen (TBH), are given in three EPA reports (Fort and Wruble, 1972; United States Environmental Protection Agency, 1972; United States Environmental Protection Agency, 1973). The values were less than the limit of detection, 200 to 300 TU, for most samples, and the maximum value was 540 ± 240 TU. For all samples, including those collected before and after Cannikin and from areas near and at a distance from Amchitka, the tritium values were essentially the same, and hence no relationship of Cannikin to the concentration of ^3H in seafoods was observed.

Another set of samples was collected in August 1975 and analyzed by the Laboratory of Radiation Ecology for ^3H in TWH and in TBH. The species sampled were *Fucus*, greenling, Dolly Varden, and *Fontinalis*, and the results of the analyses are given in Table A.18. The ^3H values for TWH and for ambient water (Table A.17) were essentially the same for organisms from freshwater, saltwater, and the Long Shot Mud Pit drainage area. Hence there appears to be a free exchange of ambient and tissue water without any apparent change in ^3H concentration. Others (Bruner, 1973; Robertson, 1973; and Feinendegen, 1967) have made similar observations and have also reported that the half-life for TWH for a variety of animal species ranges from 1 to 20 days.

Although the ^3H concentrations in ambient water and TWH were the same, ^3H concentration in TBH was two to five times greater than that in TWH for the same sample. The greater ^3H values for TBH are not unexpected if the turnover rate for ^3H in TBH is relatively long and if the ^3H concentration in ambient water was greater in the spring of 1975 than in August 1975; both of these suppositions are believed to be true for the following reasons. Whereas the half-life for TWH, as noted above, is 1 to 20 days, the half-life for TBH has been reported to range from 110 to 300 days for animals (Robertson, 1973; Harrison, Koranda, and Tucker, 1973) and up to 2.7 years for plants (Stewart, Rosenthal, and Kline, 1973). In regard to the spring and summer 1975 values for ^3H in ambient water, Schell et al. (1974) have shown that the ^3H content of rainfall consistently varies within a single year by a factor of 5 or more with the maximum value occurring in the spring and the minimum value in the winter. Also, ^3H values for freshwater samples collected at Amchitka in May 1974 were found to be twice as great as those for similar samples collected 3 months later (August 1974). Therefore the comparison of ^3H values in TWH and TBH for samples collected in August 1975 is essentially a comparison of ^3H in ambient water of August 1975 (TWH) and spring 1975 (TBH); greater values for ^3H in TBH were expected.

Iron-55. This radionuclide is produced in nuclear detonations by neutron activation and was relatively abundant in the fishes of the world's oceans after the 1961–1962 series of atmospheric

nuclear detonations. So that the current background values for ^{55}Fe in seafoods could be established, samples of canned salmon and of fresh fish were analyzed for ^{55}Fe as a part of the Amchitka program. The results of analyses for canned salmon for the years 1971 and 1972 are reported by Nelson and Seymour (1974), and the results for fresh fish are given in Tables 3 and A.10.

The canned salmon sampled included sockeye, Chinook, and chum species obtained by EPA's Environmental Research Center, Las Vegas, from five canneries in Bristol Bay, Alaska. Values for single samples ranged from 0.45 to 3.68 pCi of ^{55}Fe per gram of dry weight. These values are ascribed, totally, to worldwide fallout, probably of 1961–1962 origin.

The species of fresh fish sampled at Amchitka from 1969 to 1974 for ^{55}Fe analysis included pink salmon, Dolly Varden, halibut, and greenling. The amount of ^{55}Fe in muscle samples for all species ranged from 0.05 to 6.7 pCi/g of dry sample. Values for liver and viscera samples were greater than those for muscle, and the maximum value was 57 pCi of ^{55}Fe per gram of dry weight in a liver sample. In 1969 the amount of naturally occurring ^{40}K in the muscle samples was several times greater than the amount of ^{55}Fe, and this difference has steadily increased in recent years as the amount of ^{55}Fe in marine fish has continued to decline.

Strontium-90. Only a few samples (plants, grasses, the exoskeleton of crabs, and the bones of rats, ptarmigan, fish, and seals) have been analyzed for ^{90}Sr. Results of analyses of ^{90}Sr in rat and ptarmigan bone are reported in Table A.19. Results of the analyses of the other samples are reported in Seymour and Nakatani (1967) and in Isakson and Seymour (1968).

The sample with the greatest ^{90}Sr content was the bone of a Dolly Varden collected in 1965; the value was 71 pCi/g of dry weight. Values for ptarmigan (1971 to 1975) ranged from 11 to 35 pCi/g of dry weight and for rats (1965 to 1975) 0.5 to 10 pCi/g of dry weight. The values for seal bone, greenling bone, and king crab exoskeleton were near or below the limits of detection. The amount of ^{90}Sr in plants and grasses (crowberry, wild rye, grass, and moss) collected only in 1965 ranged from 1 (wild rye) to 15 (moss) pCi/g of dry weight. The data for ptarmigan indicate a decrease in ^{90}Sr concentration from 1971 to 1974, but there was no significant change in the values for the rat samples (Table A.19); however, the small number of samples analyzed precludes any definitive statement about the significance of any observed changes in ^{90}Sr concentration. The concentration of ^{90}Sr in plants and animals would be expected to be slowly decreasing since the peak of ^{90}Sr fallout at Adak, 300 km from Amchitka, was reported to have occurred in 1963 (Energy Research and Development Administration, 1975b).

Plutonium-239, 240. In 1975 selected samples (soil, sand, *Fucus,* and greenlings) were also analyzed for $^{239,240}Pu$; results of the analyses are listed in Table A.20. In terms of dry sample weight, the values ranged from 0.015 to <0.002 pCi/g. The values for Amchitka soils were similar to values for September 1974 soil samples from the western region of Washington State, 0.005 to 0.012 pCi of $^{239,240}Pu$ per gram of dry weight (Laboratory of Radiation Ecology, Annual Report to Ebasco Services, Inc., 1975, unpublished). The values for brown alga, *Fucus distichus,* from Amchitka were somewhat less than $^{239,240}Pu$ values for the alga, *Sargassum* sp., collected in 1970 from the Atlantic Ocean but somewhat greater than values for *Fucus vessaculosa* collected at Woods Hole in 1971 (Noshkin et al., 1973) and for *Pelagophycus porra* collected from the California Coast in 1971 (Wong, Hodge, and Folsom, 1972). From this evidence the source of $^{239,240}Pu$ for the samples from Amchitka and other areas is assumed to be the same, worldwide fallout.

CONCLUSION

There has been essentially no escape of radionuclides from the sites of the Long Shot, Milrow, and Cannikin underground nuclear detonations. Radionuclide values for Amchitka samples were similar to those for comparable samples from other geographical areas. The only radioactivity of Amchitka nuclear test origin that was detected consisted of trace quantities of radionuclides, principally tritium, in water and soil gas samples in the immediate vicinity of surface ground zero for the Long Shot detonation.

The naturally occurring radionuclides ^{40}K and ^{7}Be were the most abundant radionuclides in the samples except for ^{137}Cs in lichen samples. Potassium-40 was the most abundant natural radionuclide except for water samples, air particulates, and freshwater moss, aufwuchs, and filamentous algae, where ^{7}Be was the predominant radionuclide. (The system used for the collection of water samples did not effectively retain ^{40}K in ionic form.) The principal fallout radionuclides present were ^{95}Zr, ^{95}Nb, ^{137}Cs, and ^{144}Ce. The indicator species used for fallout radionuclides at Amchitka Island were lichens for the terrestrial environment, *Ranunculus* sp., *Fontinalis* sp., or aufwuchs for the

freshwater environment, and *Fucus distichus* for the marine environment. Plankton was not collected regularly but would be expected to be another good indicator of fallout radionuclides. The most likely pathway to man for radionuclides produced at Amchitka would be via seafoods (halibut, salmon, and king crab), although there is virtually no commercial fishery in the immediate vicinity of Amchitka Island. Values for the fallout radionuclides were often near or below the limits of detection with attendant large error terms.

ACKNOWLEDGMENTS

Many persons and organizations have assisted in the collection of samples and with other aspects of the field program. In 1965, R. E. Nakatani was the field party leader and M. B. Dell, K. W. Kenyon, E. J. Huizer, A. Peden, D. L. Spencer, and N. J. Wilimovsky were the other field party members, all from outside the Laboratory. In 1967 and 1968, samples were collected by J. S. Isakson and other members of the Fisheries Research Institute, University of Washington.

The field program that began in 1970 and has continued since that date was originally directed by E. E. Held and later by V. A. Nelson. Other Laboratory members who assisted with the program include K. Buchanan, R. Eagle, A. Johnson, T. Jokela, R. Lusk, A. Seymour, and C. Vick. Also, the field operation was strongly supported by the Nevada Operations Office of Energy Research and Development Administration (formerly U. S. Atomic Energy Commission), Holmes and Narver, and Battelle Columbus Laboratories, and assistance with field collections was provided by the Fisheries Research Institute (University of Washington), the U. S. Fish and Wildlife Service (Anchorage), EPA's National Environmental Research Center (Las Vegas), the Center for Ecology (Utah State University), University of Tennessee, and the Smithsonian Institute.

Financial support was provided by research contract E (26-1)-269 from the Nevada Operations Office of the Energy Research and Development Administration.

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APPENDIX

AMCHITKA RADIOBIOLOGICAL DATA (NELSON AND SEYMOUR, 1975;1976)

Table A.1—Gamma-Emitting Radionuclides in the Marine Alga *Fucus* Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight					
		^{7}Be	^{40}K	^{95}Zr	^{95}Nb	^{137}Cs	^{144}Ce
Composite from several sites							
1965†	1	Na	34‡	Ns	Ns	0.10‡	Ns
Cyril Cove							
1967†	2	Na	24 ± 0.3	Na	Na	0.06 ± 0.01	Ns
Makarius Bay							
1967†	2	Na	25 ± 1.8	Ns	Ns	0.06 ± 0.0	Ns
1968†	2	Na	46 ± 2.8	Na	Na	Ns	0.64 ± 0.42
Constantine Harbor							
1970–1971†	3	0.52 ± 0.18	25 ± 6	0.10 ± 0.08	0.21 ± 0.17	0.05 ± 0.02	Na
1972	4	2.5 ± 2.0	34 ± 2	0.04 ± 0.04	0.07 ± 0.08	Ns	Ns
1973	2		34 ± 0.7	Ns	Ns	0.03 ± 0.04	Ns
May 1974	1	1.0 ± 0.4	32 ± 2.0	0.36 ± 0.04	0.73 ± 0.09	0.05 ± 0.03	1.5 ± 0.2
August 1975	1	1.7 ± 1.3	32 ± 2.3	Ns	Ns	0.04 ± 0.04	Ns
Duck Cove							
1970–1971†	3	0.8 ± 0.3	23 ± 2	0.07 ± 0.04	0.15 ± 0.10	0.04 ± 0.02	Na
1971–1972	5	1.9 ± 1.5	35 ± 4.5	0.05 ± 0.03	0.10 ± 0.07	0.01 ± 0.03	
1973	3	0.47 ± 0.41	35 ± 9.9	Ns	Ns	0.03 ± 0.05	0.08 ± 0.14
May 1974	1	Ns	38 ± 1.2	0.08 ± 0.06	0.22 ± 0.05	0.07 ± 0.02	0.91 ± 0.10
August 1974	1	Ns	36 ± 2.3	Ns	Ns	0.07 ± 0.04	0.35 ± 0.21
August 1975	1	Ns	33 ± 2.3	Ns	Ns	Ns	Ns
Square Bay							
August 1975	1	Ns	38 ± 2.4	Ns	Ns	Ns	Ns
Sand Beach Cove							
1970–1971†	5	0.09 ± 0.09	26 ± 6	0.08 ± 0.06	0.17 ± 0.14	0.06 ± 0.03	Na
1971–1972	6	3.8 ± 3.2	26 ± 4.6	0.22 ± 0.20	0.45 ± 0.43	0.01 ± 0.02	Ns
1973	2	Ns	35 ± 2.1	Ns	Ns	Ns	0.16 ± 0.23
May 1974	1	0.61 ± 0.45	39 ± 2.3	0.23 ± 0.09	0.34 ± 0.08	Ns	0.92 ± 0.19
August 1974	1	Ns	27 ± 1.4	Ns	Ns	Ns	0.25 ± 0.19
August 1975	1	Ns	34 ± 2.2	Ns	0.16 ± 0.12	0.04 ± 0.04	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Pre-Cannikin.

‡Counting errors were not given in the original reference (Seymour and Nakatani, 1967).

Table A.2—Gamma-Emitting Radionuclides in the Freshwater Moss *Fontinalis neomexicana* Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight									
		^{7}Be	^{40}K	^{95}Zr	^{95}Nb	^{103}Ru	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce	^{155}Eu
Clevenger Creek											
1970–1971†	4	8 ± 4	5.8 ± 3.0	1.4 ± 1.0	2.9 ± 2.3	0.28 ± 0.54	3.2 ± 1.2	1.4 ± 0.6	4.0 ± 1.5	Na	Na
1971–1972	5	2.7 ± 4.3	6.2 ± 2.1	0.6 ± 0.3	2.0 ± 2.0	0.67 ± 0.87	0.54 ± 0.75	0.18 ± 0.4	1.9 ± 1.2	1.1 ± 1.6	Ns
1973	2	4.5 ± 1.1	5.4 ± 0.2	Ns	0.15 ± 0.21	0.07 ± 0.10	0.74 ± 0.18	0.23 ± 0.03	2.3 ± 1.1	0.84 ± 0.37	0.22 ± 0.01
May 1974	1	17 ± 11	3.9 ± 1.8	2.4 ± 1.2	3.4 ± 0.8	Ns	3.1 ± 0.9	0.55 ± 0.16	1.2 ± 0.1	2.8 ± 0.3	0.26 ± 0.10
August 1974	1	4.3 ± 1.9	5.7 ± 1.4	0.7 ± 0.3	1.5 ± 0.2	Ns	2.5 ± 0.5	0.31 ± 0.10	1.5 ± 0.1	3.9 ± 0.3	0.27 ± 0.06
August 1975	1	4.2 ± 2.0	6.3 ± 1.4	Ns	0.44 ± 0.18	Ns	0.88 ± 0.47	0.17 ± 0.09	0.7 ± 0.1	2.3 ± 0.3	0.08 ± 0.06
Bridge Creek											
1970–1971†	3	10 ± 5	7.3 ± 3.2	1.7 ± 1.4	3.9 ± 3.1	Ns	4.4 ± 2.5	1.2 ± 0.8	4.1 ± 3.0	Na	Na
1971–1972	5	6.2 ± 2.8	6.8 ± 1.0	1.0 ± 0.6	2.2 ± 1.5	0.6 ± 0.8	1.1 ± 1.3	0.4 ± 0.6	3.3 ± 1.3	0.52 ± 1.2	Ns
1973	2	5.1 ± 1.4	5.8 ± 0.4	Ns	0.08 ± 0.11	Ns	Ns	0.14 ± 0.19	2.3 ± 1.9	1.1 ± 0.5	0.11 ± 0.15
May 1974	1	5.2 ± 0.9	7.9 ± 1.6	2.1 ± 0.2	4.4 ± 0.2	0.24 ± 0.10	3.5 ± 0.6	0.33 ± 0.11	1.9 ± 0.1	4.5 ± 0.3	0.18 ± 0.06
August 1974	1	3.6 ± 2.5	5.2 ± 1.8	1.0 ± 0.3	2.1 ± 0.3	Ns	2.3 ± 0.7	0.20 ± 0.15	1.0 ± 0.1	4.6 ± 0.4	0.23 ± 0.09
August 1975	1	3.3 ± 2.2	5.8 ± 1.7	0.3 ± 0.3	0.6 ± 0.23	Ns	1.7 ± 0.7	0.25 ± 0.14	1.1 ± 0.1	3.1 ± 0.4	0.10 ± 0.08
Duck Cove Creek											
1970–1971†	3	8 ± 3	6.6 ± 2.6	1.3 ± 1.1	2.7 ± 2.3	0.5 ± 0.6	2.8 ± 1.5	1.4 ± 0.5	2.6 ± 1.1	Na	Na
1971–1972	5	6.4 ± 5.4	6.1 ± 0.8	0.5 ± 0.2	1.3 ± 0.8	0.9 ± 1.2	1.2 ± 1.0	1.1 ± 0.5	1.7 ± 0.9	0.32 ± 0.72	Ns
1973	2	7.1 ± 7.0	6.4 ± 0.4	Ns	Ns	Ns	0.65 ± 0.92	0.32 ± 0.23	1.2 ± 0.5	0.9 ± 1.3	0.09 ± 0.13
May 1974	1	7.4 ± 1.0	5.4 ± 1.2	1.6 ± 0.2	3.5 ± 0.2	0.36 ± 0.11	3.4 ± 0.6	0.53 ± 0.13	2.2 ± 0.1	5.7 ± 0.3	1.16 ± 0.05
August 1974	1	1.4 ± 0.8	<6	Ns	0.21 ± 0.08	Ns	0.29 ± 0.19	Ns	0.8 ± 0.1	0.34 ± 0.1	Ns
August 1975	1	1.9 ± 1.2	5.4 ± 1.1	0.2 ± 0.2	0.65 ± 0.15	Ns	0.69 ± 0.44	0.26 ± 0.09	0.8 ± 0.1	2.4 ± 0.26	0.09 ± 0.05
Long Shot drainage											
August 1975	1	4.4 ± 1.2	4.0 ± 1.3	0.2 ± 0.1	0.61 ± 0.13	Ns	2.3 ± 0.4	0.27 ± 0.01	1.2 ± 0.1	3.2 ± 0.2	0.2 ± 0.08
Mile Post 12 Creek											
1973	2	9.0 ± 8.6	4.7 ± 2.0	Ns	0.17 ± 0.23	Ns	0.7 ± 0.9	0.12 ± 0.17	2.0 ± 1.2	1.4 ± 0.8	0.09 ± 0.12
May 1974	1	13 ± 1.0	6.0 ± 1.1	1.4 ± 0.13	3.4 ± 0.18	0.20 ± 0.05	4.1 ± 0.6	0.23 ± 0.10	2.1 ± 0.1	6.0 ± 0.3	0.16 ± 0.04
August 1974	1	4.5 ± 2.0	5.8 ± 1.2	0.8 ± 0.3	1.3 ± 0.3	Ns	1.9 ± 0.6	Ns	0.7 ± 0.1	3.9 ± 0.3	0.13 ± 0.06
August 1975	1	6.5 ± 1.8	4.5 ± 1.7	0.3 ± 0.2	0.67 ± 0.18	Ns	2.7 ± 0.7	Ns	0.5 ± 0.1	5.2 ± 0.3	0.21 ± 0.11
Ice Box Lake inlet											
1973	2	4.1 ± 0.8	5.7 ± 1.0	Ns	0.08 ± 0.11	Ns	0.5 ± 0.0	0.28 ± 0.06	1.5 ± 0.6	0.87 ± 0.12	0.17 ± 0.08
May 1974	1	3.7 ± 0.6	5.0 ± 1.0	0.70 ± 0.09	1.2 ± 0.11	Ns	1.0 ± 0.4	0.20 ± 0.09	3.1 ± 0.1	2.4 ± 0.21	0.13 ± 0.04
August 1974	1	2.3 ± 0.8	5.9 ± 0.5	0.17 ± 0.14	0.6 ± 0.1	Ns	0.9 ± 0.3	0.23 ± 0.08	1.0 ± 0.1	1.6 ± 0.2	Ns
August 1975	1	Ns	4.7 ± 1.3	Ns	0.27 ± 0.16	Ns	0.7 ± 0.5	0.20 ± 0.11	1.3 ± 0.1	1.8 ± 0.3	0.09 ± 0.07
Cannikin Lake outlet											
1973	2	7.3 ± 0.5	6.2 ± 0.7	0.09 ± 0.12	0.16 ± 0.23	0.07 ± 0.09	0.6 ± 0.8	0.30 ± 0.18	3.9 ± 4.6	1.1 ± 0.4	0.15 ± 0.21
May 1974	1	10 ± 1.0	2.4 ± 0.6	1.2 ± 0.12	2.7 ± 0.15	0.24 ± 0.13	2.2 ± 0.3	0.29 ± 0.05	1.1 ± 0.1	6.3 ± 0.2	0.13 ± 0.03
August 1974	1	Ns	4.2 ± 0.6	1.2 ± 0.15	2.3 ± 0.17	0.21 ± 0.11	2.6 ± 0.5	0.33 ± 0.12	1.6 ± 0.1	6.4 ± 0.3	Ns
August 1975	1	7.9 ± 1.9	5.1 ± 1.1	Ns	0.52 ± 0.16	Ns	1.8 ± 0.5	0.24 ± 0.09	2.0 ± 0.1	2.1 ± 0.3	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Pre-Cannikin.

Table A.3—Gamma-Emitting Radionuclides in the Freshwater Plant *Ranunculus* sp. Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight									
		^{7}Be	^{40}K	^{95}Zr	^{95}Nb	^{103}Ru	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce	^{155}Eu
Clevenger Creek											
1970–1971†	4	4.1 ± 4.7	21 ± 4	0.6 ± 0.8	1.3 ± 1.6	Ns	1.9 ± 1.8	0.3 ± 0.6	1.7 ± 1.1	Na	Na
1971–1972	5	5.0 ± 8.7	16 ± 1.6	0.36 ± 0.49	0.99 ± 0.96	0.54 ± 0.53	0.6 ± 0.8	0.5 ± 0.54	1.6 ± 0.7	Na	Na
1973	2	1.9 ± 2.7	22 ± 3.5	Ns	Ns	Ns	Ns	Ns	0.8 ± 0.5	0.3 ± 0.4	Ns
May 1974	1	3.1 ± 0.6	24 ± 1.6	0.80 ± 0.10	1.8 ± 0.1	0.12 ± 0.08	1.0 ± 0.4	0.14 ± 0.09	0.87 ± 0.07	2.3 ± 0.2	Ns
August 1974	1	1.4 ± 1.4	15 ± 1.3	Ns	Ns	Ns	Ns	Ns	0.24 ± 0.07	0.5 ± 0.3	Ns
August 1975	1	Ns	19 ± 2.3	Ns	Ns	Ns	Ns	Ns	0.52 ± 0.09	0.34 ± 0.3	Ns
Bridge Creek											
1970–1971†	3	8.4 ± 5.8	17 ± 3	1.0 ± 0.4	2.3 ± 1.0	Ns	2.1 ± 0.5	0.5 ± 0.5	3.2 ± 0.2	Na	Na
1971–1972	5	3.6 ± 5.0	21 ± 7.6	0.36 ± 0.22	0.78 ± 0.48	0.19 ± 0.30	0.62 ± 0.91	0.3 ± 0.4	2.2 ± 1.4	Na	Na
1973	1	4.7 ± 1.5	29 ± 2.3	Ns	Ns	Ns	Ns	Ns	1.2 ± 0.1	0.7 ± 0.2	0.15 ± 0.10
May 1974	1	3.8 ± 0.8	19 ± 2.5	1.1 ± 0.2	2.4 ± 0.2	0.15 ± 0.09	1.5 ± 0.6	0.23 ± 0.12	1.6 ± 0.1	3.4 ± 0.3	Ns
August 1974	1	2.0 ± 0.8	19 ± 0.8	0.4 ± 0.1	0.7 ± 0.1	Ns	0.94 ± 0.32	0.16 ± 0.08	0.85 ± 0.06	1.7 ± 0.2	Ns
August 1975	1	2.5 ± 1.2	21 ± 2.2	Ns	0.35 ± 0.13	Ns	0.67 ± 0.46	Ns	1.2 ± 0.1	1.0 ± 0.23	Ns
Duck Cove Creek											
1970–1971†	2	4.0 ± 3.5	15 ± 8	0.41 ± 0.15	0.86 ± 0.32	Ns	1.0 ± 1.0	0.7 ± 0.5	1.3 ± 0.4	Na	Na
1971–1972	5	6.2 ± 8.9	20 ± 5	0.42 ± 0.24	0.94 ± 0.57	0.52 ± 0.66	0.87 ± 0.80	0.6 ± 0.4	1.6 ± 0.9	Na	Na
1973	1	6.0 ± 1.5	20 ± 1.5	Ns	Ns	Ns	Ns	0.26 ± 0.09	2.9 ± 0.1	0.9 ± 0.2	0.14 ± 0.08
May 1974	1	3.1 ± 0.7	14 ± 1.5	0.46 ± 0.09	1.2 ± 0.1	0.16 ± 0.08	0.81 ± 0.36	Ns	4.0 ± 0.2	1.8 ± 0.2	Ns
August 1974	1	Ns	21 ± 2	Ns	0.47 ± 0.19	Ns	Ns	Ns	0.67 ± 0.08	0.78 ± 0.22	Ns
August 1975	1	Ns	13 ± 1.8	Ns	Ns	Ns	0.63 ± 0.43	Ns	1.6 ± 0.13	0.85 ± 0.24	Ns
Clevenger Creek outlet											
1970–1971†	2	2.5 ± 2.2	5.3 ± 3.5	0.39 ± 0.07	0.81 ± 0.16	0.4 ± 0.5	0.5 ± 0.6	0.6 ± 0.1	0.6 ± 0.8	Na	Na
1971–1972	5	12 ± 14	10 ± 9	0.78 ± 0.86	2.5 ± 2.4	0.9 ± 1.3	1.2 ± 0.4	0.1 ± 0.2	1.1 ± 0.1	Na	Na
1973	1	3.4 ± 1.0	20 ± 2.1	Ns	Ns	Ns	Ns	Ns	0.3 ± 0.1	Ns	Ns
August 1974	1	Ns	24 ± 1.1	0.45 ± 0.20	0.80 ± 0.19	Ns	Ns	Ns	0.7 ± 0.1	1.4 ± 0.3	Ns
August 1975	1	1.9 ± 0.7	18 ± 1.5	Ns	0.07 ± 0.07	Ns	0.5 ± 0.3	Ns	0.8 ± 0.1	0.6 ± 0.2	Ns
Long Shot drainage											
August 1975	1	5.3 ± 2.4	19 ± 3.0	Ns	0.42 ± 0.26	Ns	1.3 ± 0.8	Ns	1.0 ± 0.1	1.4 ± 0.4	Ns
Cannikin Lake outlet											
May 1974	1	13 ± 1.2	17 ± 1.8	1.6 ± 0.2	3.9 ± 0.2	0.45 ± 0.13	3.4 ± 0.6	Ns	1.3 ± 0.1	6.4 ± 0.3	0.20 ± 0.06
August 1974	1	3.5 ± 1.3	28 ± 3.3	0.31 ± 0.19	0.60 ± 0.16	Ns	1.2 ± 0.8	Ns	1.4 ± 0.1	2.0 ± 0.3	Ns
August 1975	1	2.3 ± 0.9	10 ± 1.5	Ns	0.18 ± 0.09	Ns	Ns	0.22 ± 0.1	2.9 ± 0.2	1.5 ± 0.2	0.14 ± 0.06

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean.
Na, not analyzed; Ns, not significant.
†Pre-Cannikin.

Table A.4—Gamma-Emitting Radionuclides in Freshwater Aufwuchs and Filamentous Algae Collected at Amchitka Island*

Location and date	No.	Gamma-emitting radionuclides,† pCi/g of dry weight								
		^{7}Be	^{40}K	^{95}Zr	^{95}Nb	^{103}Ru	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce
Long Shot Pond										
1970–1971‡	7	15 ± 12	9 ± 4	3.1 ± 1.9	6.7 ± 3.9	2.1 ± 2.7	5.8 ± 4.1	1.5 ± 0.9	1.8 ± 0.9	Na
1971–1972	5	3.2 ± 3.4	10 ± 1.4	0.8 ± 1.0	2.2 ± 2.9	0.39 ± 0.56	0.2 ± 0.4	0.4 ± 0.3	0.5 ± 0.1	1.1 ± 1.6
1973	2	3.7 ± 2.1	9.8 ± 0.4	Ns	0.09 ± 0.12	Ns	Ns	Ns	0.27 ± 0.02	0.42 ± 0.26
May 1974	1	26 ± 9	4.9 ± 1.4	Ns	4.6 ± 1.0	Ns	2.5 ± 0.8	0.39 ± 0.13	0.40 ± 0.07	7.7 ± 0.6
August 1974	1	3.4 ± 1.0	9.4 ± 0.8	0.55 ± 0.15	0.92 ± 0.14	Ns	1.3 ± 0.4	0.24 ± 0.09	0.34 ± 0.05	1.2 ± 0.2
August 1975	1	2.8 ± 1.8	9.8 ± 1.6	Ns	0.28 ± 0.19	Ns	Ns	0.21 ± 0.09	0.19 ± 0.05	1.4 ± 0.3
Mile Post 12 Creek										
July 1972	1	7.8 ± 1.7	5.2 ± 0.5	3.5 ± 0.4	6.4 ± 0.5	1.7 ± 0.3	0.76 ± 0.28	Ns	2.0 ± 0.2	3.8 ± 0.4
August 1973	1	8.3 ± 0.9	9.6 ± 1.6	0.29 ± 0.11	0.34 ± 0.08	0.24 ± 0.09	Ns	Ns	2.7 ± 0.1	0.36 ± 0.17
May 1974	1	9.1 ± 1.1	8.9 ± 1.6	4.0 ± 0.2	7.6 ± 0.3	0.28 ± 0.13	2.9 ± 0.7	0.79 ± 0.13	2.5 ± 0.2	12 ± 0.5
August 1975	1	13 ± 1.2	6.2 ± 1.5	0.36 ± 0.11	0.97 ± 0.12	Ns	2.3 ± 0.5	0.26 ± 0.10	2.3 ± 0.1	3.2 ± 0.2
White Alice Inlet to Cannikin Lake										
August 1973	1	23 ± 1.5	6.1 ± 1.4	0.59 ± 0.13	1.1 ± 0.14	0.91 ± 0.15	Ns	Ns	0.72 ± 0.09	1.4 ± 0.2
August 1974	1	12 ± 1.2	9.8 ± 0.6	0.99 ± 0.14	2.0 ± 0.15	0.43 ± 0.08	1.7 ± 0.4	Ns	1.1 ± 0.08	4.3 ± 0.2
August 1975	1	3.8 ± 0.9	5.1 ± 1.3	Ns	0.2 ± 0.08	Ns	0.89 ± 0.4	0.16 ± 0.09	0.75 ± 0.09	2.0 ± 0.3

*Aufwuchs samples were collected from Long Shot Pond and Mile Post 12 Creek, whereas the algae samples were collected from White Alice Inlet to Cannikin Lake.

†Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

‡Pre-Cannikin.

Table A.5—Gamma-Emitting Radionuclides in Lichens Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight									
		^{7}Be	^{40}K	^{95}Zr	^{95}Nb	^{103}Ru	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce	^{155}Eu
Composite from several sites (pre-Cannikin)											
1965	2	Na	Na	Na	Na	Na	11 ± 1.5	6.6 ± 0.1	38 ± 7	54 ± 7	Na
1966	2	Na	Na	Na	Na	Na	11 ± 2.5	7.8 ± 1.3	47 ± 7	54 ± 26	Na
1967†	4	Na	Na	Na	Na	Na	Na	Na	26 ± 3	Na	Na
1968†	4	Na	2.8 ± 0.6	Na	Na	Na	Na	1.5 ± 1.8	20 ± 9.6	4.5 ± 5.7	1.2 ± 0.8
1970†	9	Na	Na	1.4 ± 0.5	Na	Na	3.9 ± 1.7	0.88 ± 0.59	16 ± 7.3	11 ± 4	0.83 ± 0.48
Clam Lake											
1970–1971‡	7	15 ± 6.1	4.5 ± 6.4	1.0 ± 1.0	2.1 ± 1.9	1.5 ± 3.1	5.4 ± 3.2	5.6 ± 7.2	37 ± 39	Na	Na
1971–1972	5§	9.7 ± 8.2	6.2 ± 5.5	0.7 ± 0.7	1.7 ± 1.4	0.5 ± 0.7	3.6 ± 3.8	3.4 ± 3.5	27 ± 23	9 ± 0.4	1.5 ± 0.14
1973	3	5.3 ± 0.5	3.5 ± 0.3	0.03 ± 0.05	0.1 ± 0.1	0.03 ± 0.06	1.1 ± 0.2	0.60 ± 0.12	7 ± 6.9	3.7 ± 1.3	0.56 ± 0.32
May 1974	1	4.5 ± 0.9	2.4 ± 0.9	0.48 ± 0.09	1.2 ± 0.1	Ns	1.4 ± 0.5	0.56 ± 0.11	12 ± 0.3	4.0 ± 0.3	0.38 ± 0.05
August 1974	1	5.2 ± 1.2	3.7 ± 0.4	0.23 ± 0.18	0.9 ± 0.1	Ns	1.3 ± 0.4	0.33 ± 0.09	9 ± 0.2	4.1 ± 0.2	0.33 ± 0.09
August 1975	1	4.6 ± 1.7	2.5 ± 1.1	Ns	0.5 ± 0.1	Ns	1.0 ± 0.6	0.28 ± 0.14	6 ± 0.2	5.5 ± 0.4	0.23 ± 0.08
Ice Box Lake											
October 1972	1	Ns	2.8 ± 1.1	0.7 ± 0.1	1.4 ± 0.3	3.8 ± 2.0	Ns	2.6 ± 0.7	14 ± 0.2	Na	Na
1973	2	5.7 ± 0.3	0.6 ± 0.8	Ns	Ns	Ns	1.3 ± 0.1	0.86 ± 0.12	16 ± 0.7	4.3 ± 1.1	0.63 ± 0.18
May 1974	1	8.6 ± 1.1	1.4 ± 0.9	0.80 ± 0.12	2.1 ± 0.2	Ns	2.1 ± 0.5	0.59 ± 0.13	13 ± 0.3	8.1 ± 0.4	0.40 ± 0.06
August 1974	1	5.7 ± 1.5	1.3 ± 0.5	0.49 ± 0.19	0.8 ± 0.1	Ns	2.2 ± 0.5	0.64 ± 0.13	9 ± 0.2	6.0 ± 0.3	0.43 ± 0.07
August 1975	1	5.2 ± 1.5	1.9 ± 1.6	Ns	0.4 ± 0.1	Ns	1.5 ± 0.6	0.48 ± 0.14	11 ± 0.3	5.4 ± 0.3	0.38 ± 0.13
Cannikin Lake											
July 1972	1	5.3 ± 1.7	2.0 ± 0.7	0.7 ± 0.1	1.6 ± 0.1	0.6 ± 0.3	Ns	0.2 ± 0.4	21 ± 0.2	Na	Na
1973	2	5.3 ± 1.3	2.3 ± 0.1	Ns	Ns	0.07 ± 0.09	1.3 ± 0.1	0.90 ± 0.06	16 ± 0.7	4.1 ± 1.6	0.73 ± 0.17
May 1974	1	6.7 ± 0.6	1.6 ± 0.6	0.62 ± 0.07	1.6 ± 0.1	0.09 ± 0.06	1.6 ± 0.3	0.65 ± 0.08	11 ± 0.2	5.8 ± 0.2	0.39 ± 0.03
August 1974	1	5.1 ± 1.3	2.5 ± 0.6	0.30 ± 0.15	0.7 ± 0.1	Ns	1.7 ± 0.5	0.34 ± 0.12	8 ± 0.2	4.3 ± 0.3	0.30 ± 0.06
August 1975	1	6.1 ± 2.1	Ns	Ns	0.4 ± 0.2	Ns	1.4 ± 0.5	0.40 ± 0.10	7 ± 0.2	4.6 ± 0.3	0.26 ± 0.11

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Data from J. J. Koranda and J. R. Martin, 1973, Gamma-Emitting Radionuclides in Alaskan Environments, 1967–1970, in Proceedings of the Third National Symposium on Radioecology, Oak Ridge, Tenn., May 10–12, 1971, D. J. Nelson (Ed.), USAEC Report CONF-710501, pp. 81-107.

‡Pre-Cannikin.

§n equals 1 for ^{144}Ce and ^{155}Eu.

Table A.6—Potassium-40 and ^{137}Cs in Dolly Varden and Pink Salmon Collected at Amchitka Island

Collection date	Collection location	Tissue	No.†	Gamma-emitting radionuclides,* pCi/g of dry weight	
				^{40}K	^{137}Cs
Pink Salmon					
1971‡	Bering Sea	Muscle	1/1	15 ± 0.8	0.10 ± 0.05
1972	Bering Sea	Muscle	8/8	14 ± 3.1	Ns
August 1974	Chapel Cove stream	Muscle	1/1	15 ± 0.9	Ns
August 1974	Signal Cove stream	Muscle	1/1	15 ± 0.5	0.09 ± 0.03
Dolly Varden					
1965	Composite, several sites	Muscle	1/23	13§	2.3§
1966	Composite, several sites	Muscle	1/18	13§	2.2§
1971	Jones Lake	Muscle	1/1	15 ± 0.8	0.35 ± 0.05
1972	DK-45 Lake	Muscle	3/8	16 ± 1.0	5.7 ± 3.9
1973	Jones Lake	Muscle	1/2	16 ± 0.5	0.28 ± 0.03
1973	Bridge Creek	Muscle	1/1	15 ± 0.9	0.13 ± 0.06
1973	Silver Salmon outlet	Muscle	1/4	16 ± 0.4	0.13 ± 0.02
May 1974	Jones Lake	Muscle	1/5	14 ± 1.7	0.28 ± 0.05
August 1974	Cannikin Lake	Muscle	1/9	14 ± 0.5	0.31 ± 0.03
August 1974	Jones Lake	Muscle	3/10	13 ± 0.9	0.17 ± 0.10
August 1974	Duck Cove	Muscle	1/4	17 ± 0.5	0.35 ± 0.03
August 1975	Jones Lake	Muscle	1/5	4.4 ± 0.9	0.10 ± 0.03
August 1975	Cannikin Lake	Muscle	1/6	12 ± 1.6	0.25 ± 0.05
August 1975	Bridge Creek	Muscle	1/1	16 ± 2.2	0.33 ± 0.07
August 1975	Duck Cove Creek¶	Muscle	1/3	14 ± 1.7	0.10 ± 0.04
August 1975	Clevenger Creek¶	Muscle	1/4	13 ± 1.7	0.05 ± 0.04

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Ns, not significant.

†Number of pooled samples/total number of fish in all samples.

‡Pre-Cannikin.

§No counting error given in original publication (Seymour and Nakatani, 1967).

¶Collected from the intertidal area at the mouths of these streams.

Table A.7—Potassium-40 and ^{137}Cs in Halibut Collected off Amchitka Island

Location and date	Tissue	No.†	Gamma-emitting radionuclides,* pCi/g of dry weight	
			^{40}K	^{137}Cs
Bering Sea				
off C Site				
1971‡	Muscle	4/4	18 ± 1.7	0.06 ± 0.08
1971–1972	Muscle	9/9	17 ± 1.7	0.02 ± 0.03
1973	Muscle	5/5	18 ± 1.1	0.11 ± 0.02
August 1975	Muscle	1/1	18 ± 1.6	0.06 ± 0.04
1971‡	Liver	4/4	13 ± 5.9	0.27 ± 0.28
1971–1972	Liver	8/8	6.7 ± 2.1	Ns
1973	Liver	5/5	6.9 ± 1.3	0.04 ± 0.05
August 1975	Liver	1/8	11 ± 1.5	0.05 ± 0.03
Constantine Harbor				
August 1967‡	Muscle	2/2	15 ± 0.6	0.06 ± 0.08
August 1974§	Liver	5/5	7.5 ± 2.6	0.06 ± 0.07
Midden Cove				
August 1975	Muscle	2/2	19 ± 1.9	0.05 ± 0.04
August 1975	Liver	4/4	10 ± 1.5	Ns

*Values are given as the mean ± one standard deviation. Ns, not significant; i.e., all the net sample counts in that group were less than their two-sigma, propagated, counting errors.

†Number of pooled samples/total number of fish in all samples.

‡Pre-Cannikin.

§Cobalt-60 was present (0.03 ± 0.02 pCi/g of dry weight) in one liver sample.

Table A.8—Potassium-40 and ^{137}Cs in Rock Ptarmigan and Sea Otters Collected at Amchitka Island

Collection date	Collection location	Tissue	No.	Radionuclides,* pCi/g of dry weight	
				^{40}K	^{137}Cs
Ptarmigan					
1970–1971†	South Bight	Muscle	4	11 ± 0.5	1.0 ± 0.6
1971–1972	C Site	Muscle	3	11 ± 1.6	0.70 ± 0.04
1973	‡	Muscle	5	11 ± 0.8	0.43 ± 0.25
May 1974	C Site	Muscle	2	11 ± 1.2	0.42 ± 0.05
August 1974	C Site	Muscle	4	11 ± 1.5	0.90 ± 0.35
August 1975	C Site	Muscle	4	14 ± 2	3.4 ± 0.2
August 1975	Mile 8	Muscle	2	11 ± 2	1.4 ± 0.1
August 1975	Milrow area	Muscle	2	12 ± 2	1.8 ± 0.6
1970–1971†	South Bight	Liver	1	Ns	Ns
August 1974	C Site	Viscera	4	13 ± 1.2	1.6 ± 0.8
Sea Otters					
February 1971		Liver	1	8.6 ± 1.1	0.27 ± 0.08
February 1971		Skin	1	1.1 ± 0.9	Ns
February 1971		Kidney	1	9.8 ± 1.0	Ns
February 1971		Muscle	1	10 ± 0.5	Ns
April 1973	Duck Cove	Muscle	1	6.8 ± 0.3	Ns
April 1973	Duck Cove	Liver	1	6.7 ± 0.5	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Ns, not significant.

†Pre-Cannikin.

‡One each from Mason Lake, C Site, and Mile Post 16; two from Mile Post 5.

Table A.9—Potassium-40 and ^{137}Cs in Greenling Collected off Amchitka Island

Location and date	Tissue	No.†	Gamma-emitting radionuclides,* pCi/g of dry weight	
			^{40}K	^{137}Cs
Composite, several sites				
1965	Muscle	1/13	11‡	0.13‡
1965	Viscera	1/13	3.8‡	Ns
Cyril Cove				
1967	Muscle	2/38	17 ± 0.9	0.13 ± 0.01
1967	Liver	1/38	8.5‡	Ns
Constantine Harbor				
1967	Entire (less viscera)	1/1	11‡	0.06‡
1971§	Muscle	2/19	16 ± 0.7	0.37 ± 0.42
1971–1972	Muscle	15/29	15 ± 1.3	0.04 ± 0.04
1973	Muscle	2/9	17 ± 2.8	0.05 ± 0.06
May 1974	Muscle	1/5	18 ± 1.5	0.06 ± 0.03
August 1974	Muscle	1/5	16 ± 0.8	0.07 ± 0.05
August 1975	Muscle	1/4	21 ± 2.5	0.49 ± 0.07
1971§	Viscera	2/19	13 ± 0.7	0.15 ± 0.05
December 1971	Liver	1/10	13 ± 1.6	0.21 ± 0.12
1973	Viscera	1/4	9.1 ± 0.6	Ns
May 1974	Viscera	1/5	15 ± 1.0	0.03 ± 0.02
August 1974	Viscera	1/5	9.2 ± 0.8	Ns
August 1975	Viscera	1/4	11 ± 2.2	0.06 ± 0.05
Sand Beach Cove				
1971§	Muscle	3/27	15 ± 1.2	0.07 ± 0.02
1971–1972	Muscle	15/26	15 ± 1.6	0.03 ± 0.05
1973	Muscle	2/12	17 ± 1.4	0.05 ± 0.06
May 1974	Muscle	1/5	21 ± 1.9	0.05 ± 0.04
August 1974¶	Muscle	1/4	15 ± 0.7	Ns
August 1975	Muscle	1/8	25 ± 2.7	0.08 ± 0.06
1971§	Viscera	3/27	13 ± 0.6	0.02 ± 0.02
1972	Liver	1/6	21 ± 2.9	Ns
1973	Viscera	1/6	11 ± 0.4	Ns
May 1974	Viscera	1/5	9.1 ± 1.1	Ns
August 1974	Viscera	1/4	8.1 ± 2.1	Ns
August 1975	Viscera	1/8	6.3 ± 1.4	0.06 ± 0.04
Square Bay				
August 1975	Muscle	1/5	16 ± 1.6	Ns
August 1975	Viscera	1/5	7.8 ± 1.4	0.07 ± 0.04
Duck Cove				
1972	Muscle	8/14	16 ± 1.1	0.06 ± 0.06
1973	Muscle	2/8	15 ± 2.8	0.08 ± 0.01
May 1974	Muscle	1/3	18 ± 1.6	0.06 ± 0.03
August 1974**	Muscle	2/6	15 ± 1.8	0.07 ± 0.02
August 1975	Muscle	1/6	17 ± 1.8	0.09 ± 0.04
1973	Viscera	1/4	12 ± 0.5	0.13 ± 0.03
May 1974	Viscera	1/3	7.7 ± 0.8	0.04 ± 0.02
August 1974	Viscera	2/6	9.5 ± 0.1	0.15 ± 0.05
August 1975	Viscera	1/6	9.5 ± 1.2	0.04 ± 0.03

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Ns, not significant.

†Number of pooled samples/total number of fish in all samples.

‡Counting errors were not given in the original publication (Seymour and Nakatani, 1967).

§Pre-Cannikin.

¶Cobalt-60 (0.07 ± 0.04 pCi/g of dry weight) was also detected in this sample.

**Cobalt-60 (0.03 ± 0.02 pCi/g of dry weight) was also detected in this sample.

Table A.10—Iron-55 in Fish Collected at Amchitka Island

Species and tissue	Collection year	No.*	pCi ^{55}Fe/g of dry weight†	pCi ^{55}Fe/mg Fe
Halibut				
Muscle	1969–1970	2/27	0.21 ± 0.14	11 ± 1.8
Muscle	1972	2/2	0.36 ± 0.11	8.7 ± 2.6
Muscle	1973	2/2	0.09 ± 0.10	2.7 ± 2.3
Liver	1970	2/27	2.5 ± 0.03	13 ± 0.7
Liver	1972	2/2	3.1 ± 0.08	26 ± 7.1
Liver	1973	2/2	0.54 ± 0.37	5.3 ± 2.1
Liver	1974	2/2	2.2 ± 0.33	6.7 ± 2.4
Greenling				
Muscle	1970	5/60	0.75 ± 0.74	12 ± 6.7
Muscle	1972	3/20	0.09 ± 0.07	1.1 ± 0.5
Muscle	1973	3/15	0.04 ± 0.02	1.8 ± 1.0
Muscle	1974	4/17	0.09 ± 0.07	4.5 ± 1.8
Liver	1970	5/60	8.3 ± 6.3	13 ± 11
Liver	1973	3/15	1.4 ± 1.5	0.7 ± 0.3
Viscera	1974	4/17	0.37 ± 0.18	0.2 ± 0.1
Pink Salmon				
Muscle	1969	2/2	6.7 ± 4.3	93 ± 6.6
Muscle	1972	4/4	0.61 ± 0.30	18 ± 2.8
Muscle	1974	2/2	0.39 ± 0.04	11 ± 1.5
Liver	1969–1970	3/3	57 ± 2.7	82 ± 24
Liver	1972	1/8	15 ± 0.1	21 ± 1.1
Viscera	1974	1/1	13 ± 0.1	13 ± 0.7
Dolly Varden				
Muscle	1969–1970	3/33	0.91 ± 1.0	50 ± 59
Muscle	1972	2/2	0.36 ± 0.18	9.1 ± 5.0
Muscle	1973	1/4	0.05 ± 0.01	1.6 ± 0.1
Muscle	1974	4/19	0.06 ± 0.03	2.3 ± 0.5
Liver	1969–1970	3/29	7.2 ± 5.0	47 ± 44‡
Liver	1973	1/4	2.1 ± 0.1	1.9 ± 0.1
Viscera	1974	4/19	0.35 ± 0.22	0.43 ± 0.23

*Number of pooled samples/total number of fish in all samples.

†Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean.

‡n equals 2/11 since there was no stable iron value for one group of 18 fish.

Table A.11—Some Gamma-Emitting Radionuclides in Green Sponge Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight				
		^{7}Be	^{40}K	^{95}Zr	^{95}Nb	^{144}Ce
Duck Cove						
1971–1972	4	2.7 ± 2.7	11 ± 3	0.05 ± 0.07	0.11 ± 0.14	Na
1973	2	1.5 ± 0.6	9.8 ± 0.1	Ns	Ns	0.42 ± 0.04
May 1974	1	1.0 ± 0.4	10 ± 1.5	0.16 ± 0.07	0.36 ± 0.07	1.1 ± 0.17
August 1974	1	Ns	7.2 ± 1.3	Ns	Ns	1.2 ± 0.23
August 1975	1	Ns	7.7 ± 1.4	Ns	Ns	0.73 ± 0.20
Sand Beach Cove						
June 1972	1	Ns	6.8 ± 1.7	0.24 ± 0.13	0.54 ± 0.28	Na
April 1973	1	Ns	12 ± 1.7	Ns	Ns	0.31 ± 0.17
May 1974	1	1.1 ± 0.4	9.0 ± 1.5	0.10 ± 0.07	0.26 ± 0.07	0.60 ± 0.16
August 1974	1	Ns	9.6 ± 1.4	Ns	Ns	1.2 ± 0.2
August 1975	1	Ns	10.0 ± 1.6	Ns	Ns	0.56 ± 0.2
Square Bay						
1973	2	0.7 ± 0.9	9.7 ± 0.5	Ns	Ns	0.35 ± 0.12
August 1975	1	1.2 ± 0.9	9.5 ± 1.7	Ns	0.11 ± 0.09	0.61 ± 0.20

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

Table A.12—Some Gamma-Emitting Radionuclides on Air Filters at Ground Level at the Amchitka Island Base Camp

Collection period	No.†	Mean volume, 10^3 m^3	Gamma-emitting radionuclides,* fCi/m^3					
			^{7}Be	^{95}Zr	^{95}Nb	^{103}Ru	^{137}Cs	^{144}Ce
Pre-Cannikin								
1970–1971	28	24.5 ± 3.7	20 ± 9	2.8 ± 2.1	5.9 ± 4.5	0.7 ± 1.1	0.7 ± 0.3	Na
Post-Cannikin								
1972	45	11.3 ± 1.6	17 ± 11	0.7 ± 1.2	1.3 ± 1.6	0.37 ± 0.59	0.24 ± 0.24	Na
1973	34	11.1 ± 1.4	16 ± 10	Ns	0.04 ± 0.09	0.04 ± 0.07	0.16 ± 0.13	0.42 ± 0.53
1974	1	~3	Ns	Ns	Ns	Ns	Ns	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Number of pooled samples.

Table A.13—Gamma-Emitting Radionuclides in Samples Collected with a Filter and Sorption Bed System from Intertidal Areas of Amchitka Island

Location and date	Liters sampled	Fraction	No.	Gamma-emitting radionuclides,* pCi/liter			
				^{7}Be	^{95}Zr	^{95}Nb	^{137}Cs
Constantine Harbor							
1970–1971†	2590 ± 1800	Particulate	6	0.009 ± 0.011	0.002 ± 0.008	0.006 ± 0.007	0.001 ± 0.001
1970–1971	2590 ± 1800	Soluble	6	0.38 ± 0.81	0.003 ± 0.017	0.012 ± 0.015	0.002 ± 0.035
1971–1972	730 ± 600	Particulate	5	Ns	0.001 ± 0.002	0.003 ± 0.006	0.02 ± 0.02
1971–1972	730 ± 600	Soluble	5	0.14 ± 0.21	0.002 ± 0.004	0.004 ± 0.009	0.02 ± 0.04
1973	1280 ± 770	Particulate	2	Ns	Ns	Ns	Ns
1973	1280 ± 770	Soluble	2	Ns	Ns	Ns	Ns
May 1974‡	534	Particulate	1	Ns	0.006 ± 0.005	0.009 ± 0.003	Ns
May 1974	534	Soluble	1	Ns	Ns	Ns	Ns
August 1974	1134	Particulate	1	Ns	Ns	Ns	Ns
August 1974	1134	Soluble	1	Ns	Ns	Ns	Ns
Duck Cove							
1971†	660 ± 380	Particulate	2	0.018 ± 0.025	0.004 ± 0.005	0.008 ± 0.011	Ns
1971†	660 ± 380	Soluble	2	Ns	0.002 ± 0.002	0.003 ± 0.004	Ns
1971–1972	305 ± 182	Particulate	6	0.032 ± 0.078	0.001 ± 0.002	0.002 ± 0.005	0.005 ± 0.008
1971–1972	305 ± 182	Soluble	6	Ns	0.002 ± 0.005	0.005 ± 0.011	Ns
1973	544 ± 557	Particulate	2	Ns	Ns	Ns	Ns
1973	544 ± 557	Soluble	2	Ns	Ns	Ns	Ns
May 1974§	98	Particulate	1	Ns	Ns	0.046 ± 0.025	0.016 ± 0.014
May 1974§	98	Soluble	1	Ns	Ns	Ns	Ns
August 1974	437	Particulate	1	Ns	Ns	0.036 ± 0.013	Ns
August 1974	437	Soluble	1	Ns	Ns	Ns	Ns
Sand Beach Cove							
1971–1972	494 ± 233	Particulate	6	Ns	0.004 ± 0.006	0.008 ± 0.013	0.003 ± 0.004
1971–1972	494 ± 233	Soluble	6	0.072 ± 0.18	Ns	Ns	0.003 ± 0.007
1973	462 ± 310	Particulate	2	Ns	Ns	Ns	Ns
1973	462 ± 310	Soluble	2	Ns	Ns	Ns	Ns
May 1974¶	314	Particulate	1	Ns	Ns	0.028 ± 0.010	Ns
May 1974	314	Soluble	1	Ns	Ns	Ns	Ns
August 1974	310	Particulate	1	Ns	Ns	Ns	Ns
August 1974	310	Soluble	1	Ns	Ns	Ns	Ns

*Single-sample error values are two-sigma, propagated, counting errors, whereas the value given for more than one sample is the mean ± one standard deviation. Ns, not significant.

†Pre-Cannikin.

‡Cerium-144 was also present, 0.014 ± 0.008 pCi/liter.

§Cerium-144 was also present, 0.13 ± 0.07 pCi/liter.

¶Cerium-144 was also present, 0.035 ± 0.024 pCi/liter.

Table A.14—Gamma-Emitting Radionuclides in Water Samples Collected from Lakes on Amchitka Island

Location and date	Liters sampled	Fraction	No.	Gamma-emitting radionuclides,* pCi/liter			
				^{7}Be	^{95}Zr	^{95}Nb	^{137}Cs
Jones Lake							
1971†	278 ± 240	Particulate	4	Ns	0.05 ± 0.04	0.11 ± 0.08	0.02 ± 0.04
1971	278 ± 240	Soluble	4	Ns	0.01 ± 0.01	0.02 ± 0.02	0.02 ± 0.02
1971–1972	154 ± 103	Particulate	5	0.2 ± 0.3	0.008 ± 0.011	0.02 ± 0.02	0.004 ± 0.009
1971–1972	154 ± 103	Soluble	5	1.3 ± 2.9	0.07 ± 0.15	0.16 ± 0.33	0.05 ± 0.10
1973	172 ± 30	Particulate	2	Ns	Ns	Ns	0.042 ± 0.015
1973	172 ± 30	Soluble	2	Ns	Ns	Ns	Ns
May 1974‡	53	Particulate	1	Ns	0.084 ± 0.062	0.19 ± 0.06	0.039 ± 0.029
May 1974‡	53	Soluble	1	Ns	Ns	Ns	Ns
August 1974	413	Particulate	1	Ns	Ns	Ns	Ns
August 1974	413	Soluble	1	Ns	Ns	Ns	Ns
August 1975	56	Entire	1	1.1 ± 0.3	Ns	0.05 ± 0.03	0.12 ± 0.03
Lake DK-45							
1971–1972	148 ± 133	Particulate	5	0.16 ± 0.22	0.07 ± 0.09	0.15 ± 0.20	0.07 ± 0.15
1971–1972	148 ± 133	Soluble	5	4 ± 9	Ns	Ns	Ns
1973	110 ± 57	Particulate	2	Ns	Ns	Ns	0.07 ± 0.05
1973	110 ± 57	Soluble	2	Ns	Ns	Ns	Ns
May 1974§	170	Particulate	1	0.33 ± 0.16	0.23 ± 0.04	0.47 ± 0.05	Ns
May 1974§	170	Soluble	1	Ns	0.20 ± 0.17	0.24 ± 0.13	Ns
August 1974	174	Particulate	1	Ns	Ns	Ns	Ns
August 1974	174	Soluble	1	Ns	Ns	Ns	Ns
Heart Lake							
August 1975	52	Entire	1	2.3 ± 0.4	0.09 ± 0.05	0.15 ± 0.04	0.25 ± 0.04
Cannikin Lake							
1972	9 ± 1.4	Particulate	2	Ns	0.17 ± 0.23	0.34 ± 0.48	Ns
1973	84 ± 16	Particulate	2	Ns	Ns	Ns	0.04 ± 0.057
1973	84 ± 16	Soluble	2	Ns	Ns	Ns	0.08 ± 0.11
May 1974¶	314	Particulate	1	Ns	0.20 ± 0.04	0.25 ± 0.03	0.019 ± 0.013
May 1974¶	314	Soluble	1	Ns	Ns	Ns	Ns
August 1974	99	Particulate	1	Ns	Ns	Ns	Ns
August 1974	99	Soluble	1	Ns	Ns	Ns	Ns
August 1975	53	Entire	1	Ns	Ns	Ns	0.21 ± 0.04
Long Shot Mud Pit No. 1							
1970–1971†	418 ± 398	Particulate	6	4.0 ± 4.7	0.4 ± 0.6	0.9 ± 1.2	0.02 ± 0.03
1970–1971	418 ± 398	Soluble	6	11 ± 18	0.002 ± 0.003	0.006 ± 0.009	0.08 ± 0.18
1971–1972	56 ± 41	Particulate	5	1.2 ± 1.3	0.25 ± 0.29	0.48 ± 0.55	0.03 ± 0.07
1971–1972	56 ± 41	Soluble	5	0.44 ± 0.98	Ns	Ns	Ns
1973	35 ± 5	Particulate	2	2.0 ± 1.0	Ns	Ns	0.04 ± 0.06
1973	35 ± 5	Soluble	2	Ns	Ns	Ns	Ns
May 1974**	48	Particulate	1	4.0 ± 0.7	1.3 ± 0.1	2.7 ± 0.2	0.034 ± 0.028
May 1974	48	Soluble	1	Ns	Ns	Ns	Ns
August 1974	189	Particulate	1	0.7 ± 0.2	0.06 ± 0.03	0.14 ± 0.02	Ns
August 1974	189	Soluble	1	Ns	Ns	0.21 ± 0.10	Ns
August 1975††	50	Entire	1	1.2 ± 0.3	Ns	Ns	0.08 ± 0.03

*Single-sample error values are two-sigma, propagated, counting errors, whereas the value given for more than one sample is the mean ± standard deviation. Ns, not significant.

†Pre-Cannikin.

‡Cerium-144 was also present, 0.44 ± 0.14 pCi/liter.

§Ruthenium-106 (0.45 ± 0.25 pCi/liter), ^{125}Sb (0.09 ± 0.06 pCi/liter), and ^{144}Ce (0.24 ± 0.11 pCi/liter) were also present in this sample.

¶Cerium-144 was also present, 0.41 ± 0.07 pCi/liter.

**Cerium-144 was also present 4.9 ± 0.3 pCi/liter.

††Barium-140 was also present, 0.43 ± 0.37 pCi/liter.

Table A.15—Gamma-Emitting Radionuclides in Sand and Soil Collected at Amchitka Island in August 1975

Sample type	Collection location	Gamma-emitting radionuclides,* pCi/g of dry weight				
		^{40}K	^{137}Cs	^{141}Ce	^{144}Ce	Other†
Soil	Main camp	8.0 ± 1.2	Ns	0.20 ± 0.13	0.14 ± 0.13	Ns
Soil	Cannikin area	11 ± 1.3	0.32 ± 0.05	0.22 ± 0.15	0.97 ± 0.18	‡
Sand	Constantine Harbor	13 ± 1.2	0.07 ± 0.03	Ns	Ns	Ns
Sand	Sand Beach Cove	9.8 ± 1.1	0.06 ± 0.03	Ns	0.2 ± 0.1	Ns

*Errors are two-sigma, propagated, counting errors for a single sample. Ns, not significant.

†Radium-226, ^{228}Th, and ^{238}U in the sand samples and ^{226}Ra and ^{228}Th in the soil samples were present in concentrations of less than 0.5 pCi/g of dry weight.

‡Zirconium-95 (0.16 ± 0.14 pCi/g of dry weight), ^{95}Nb (0.18 ± 0.07 pCi/g of dry weight) and ^{106}Ru (0.42 ± 0.30 pCi/g of dry weight) were also present in this sample.

Table A.16—Radiation Survey of Selected Sites on Amchitka Island

Location	Radiation level,* mR/hr			
	Average reading		Maximum reading	
	August 1974	August 1975	August 1974	August 1975
Decon Facility	0.01	0.01	0.05	0.04
Inside "D" barracks	0.01	<0.01	0.04	0.04
Hus-Key Camp	<0.01	0.01	0.04	0.05
Jones Creek effluence	<0.01	<0.01	0.04	0.04
Eberline Instrument Corp. Calibration Range	<0.01	0.01	0.04	0.04
Rifle Range target area	0.01	0.01	0.04	0.05
Duck Cove	<0.01	<0.01	0.03	0.04
Milrow surface ground zero and vicinity	<0.01	0.01	0.04	0.04
Long Shot surface ground zero and vicinity	0.01	0.01	0.05	0.05
Cannikin surface ground zero and vicinity	0.01	0.01	0.04	0.04
Cannikin drillback	0.01	0.01	0.05	0.04
Sand Beach Cove	<0.01	<0.01	0.04	0.04
D Site	0.01	<0.01	0.05	0.03
E Site	0.01	<0.01	0.03	0.04

*Geiger-Mueller detector, probe window thickness less than 2 mg/cm^2.

Table A.17—Tritium Concentration in Water Samples Collected at Amchitka Island, 1970–1975

Date	Collection site	Number of samples	Tritium units*	pCi/liter†
Seawater				
1970–1971‡	§	10	32 ± 19	103 ± 61
1972	§	16	28 ± 25	90 ± 81
1973	§	6	22 ± 13	71 ± 42
1974	§	6	<13	<42
1975	§	6	<15	<48
August 1975	Constantine Harbor	1	18 ± 12	57 ± 40
August 1975	Square Bay	1	17 ± 12	56 ± 40
August 1975	Sand Beach Cove	1	<13	<42
August 1975	Makarius Bay	1	<13	<42
August 1975	Rifle Range Point	1	<13	<42
August 1975	Duck Cove	1	<13	<42
Freshwater, except Long Shot Area				
1970–1971‡	§	12	92 ± 46	298 ± 149
1972	§	18	49 ± 14	158 ± 45
1973	§	46	50 ± 17	162 ± 55
1974	§	44	32 ± 18	103 ± 58
1975	§	29	34 ± 14	110 ± 45
August 1975	South Hangar (ppt)	1	33 ± 13	106 ± 43
August 1975	Constantine Spring	1	56 ± 13	182 ± 41
August 1975	Jones Lake outlet	1	28 ± 12	89 ± 40
August 1975	Clevenger Lake outlet	1	51 ± 13	165 ± 41
August 1975	Clevenger Creek (mouth)	1	30 ± 12	98 ± 40
August 1975	Clevenger Creek (headwaters)	1	26 ± 12	84 ± 40
August 1975	Heart Lake	1	<13	<42
August 1975	Clam Lake	1	24 ± 12	78 ± 38
August 1975	Duck Cove Creek (mouth)	1	41 ± 13	132 ± 38
August 1975	Seep at Duck Cove	1	47 ± 13	151 ± 41
August 1975	Quonset Creek (at road)	1	24 ± 13	78 ± 43
August 1975	Bridge Creek (at road)	1	55 ± 13	177 ± 41
August 1975	Mile Post 12 Creek	1	40 ± 12	129 ± 38
August 1975	Cannikin Lake inlet from ground zero	1	<13	<42
August 1975	Cannikin Lake inlet from drillback	1	53 ± 13	173 ± 41
August 1975	Cannikin Lake White Alice inlet	1	41 ± 13	133 ± 41
August 1975	Cannikin Lake Station No. 1 surface	1	21 ± 10	67 ± 33
August 1975	Cannikin Lake Station No. 1 bottom	1	27 ± 10	87 ± 34
August 1975	Cannikin Lake Station No. 2 surface	1	<13	<42
August 1975	Cannikin Lake Station No. 2 bottom	1	38 ± 12	124 ± 38
August 1975	Cannikin Lake Station No. 3 surface	1	47 ± 11	151 ± 34
August 1975	Cannikin Lake Station No. 3 bottom	1	36 ± 10	115 ± 34
August 1975	Cannikin Lake Station No. 4 surface	1	46 ± 11	148 ± 34
August 1975	Cannikin Lake Station No. 4 bottom	1	33 ± 10	108 ± 34
August 1975	Cannikin Lake outlet	1	19 ± 12	63 ± 40
August 1975	Ice Box Lake inlet¶	1	31 ± 12	102 ± 40
August 1975	Ice Box Lake outlet¶	1	57 ± 13	183 ± 41
August 1975	DK-45 Lake	1	<13	<42
August 1975	Seep-Sand Beach Cove	1	45 ± 13	144 ± 41
Long Shot Mud Pits				
1970–1971‡	Mud Pit No. 3	3	3500 ± 460	11300 ± 1500

(Table continues on page 612.)

Table A.17—(Continued)

Date	Collection site	Number of samples	Tritium units*	pCi/liter†
1974	Mud Pit No. 3	1	2900 ± 460	9400 ± 160
August 1975	Mud Pit No. 3	1	867 ± 19	2802 ± 61
1970–1971‡	Mud Pit No. 1	3	1800 ± 260	5800 ± 840
1972	Mud Pit No. 1	4	2050 ± 240	6600 ± 780
1973	Mud Pit No. 1	2	1900 ± 420	6100 ± 1400
1974	Mud Pit No. 1	2	1300 ± 250	4200 ± 810
August 1975	Mud Pit No. 1	1	122 ± 11	395 ± 36
Long Shot Mud Pit drainage				
August 1975	3 m below Mud Pit No. 1	1	872 ± 19	2817 ± 61
August 1975	Infantry Road	1	666 ± 16	2153 ± 52
August 1975	100 m below road	1	424 ± 15	1369 ± 47
August 1975	500 m below road	1	82 ± 13	264 ± 42
August 1975	200 m above Square Bay	1	121 ± 13	390 ± 44
August 1975	Mouth of creek	1	107 ± 13	347 ± 43

*The error shown for single samples is a one-sigma counting error, whereas the error for more than one sample is the one-standard deviation of the mean.

†One TU equals 3.23 pCi/liter.

‡Pre-Cannikin.

§Mean value for all collection sites.

¶A small lake formed in the north fork of White Alice Creek after surface subsidence occurred at the Cannikin site.

Table A.18—Tritium Concentration in Tissue-Water Hydrogen (TWH) and Tissue-Bound Hydrogen (TBH) from Biological Samples Collected at Amchitka Island in August 1975

Organism	Tissue	Collection site	No.*	Tritium units†		pCi/liter†		Ratio
				TWH	TBH	TWH	TBH	TBH/TWH
Fucus	Entire	Constantine Harbor	2	<35 ± 18	167 ± 14	<113 ± 58	539 ± 45	>4.8
Fucus	Entire	Square Bay	3	<26 ± 12	49 ± 12	<84 ± 39	158 ± 39	>1.9
Fucus	Entire	Sand Beach Cove	2	<21 ± 1	49 ± 12	<68 ± 3	158 ± 39	>2.3
Greenling	Muscle	Constantine Harbor	1	<14	52 ± 18	<45	168 ± 58	>3.7
Greenling	Muscle	Square Bay	4	<20 ± 2	63 ± 12	<65 ± 6	203 ± 39	>3.2
Greenling	Muscle	Sand Beach Cove	2	<20 ± 1	80 ± 19	<65 ± 3	258 ± 61	>4.0
Dolly Varden	Muscle	Bridge Creek‡	2	16 ± 2	73 ± 11	51 ± 6	235 ± 36	4.6
Dolly Varden	Muscle	Jones Lake	4	26 ± 16	81 ± 11	85 ± 52	261 ± 37	3.1
Dolly Varden	Muscle	Cannikin Lake	1	39 ± 12	92 ± 12	126 ± 39	297 ± 39	2.4
Fontinalis	Entire	White Alice Creek	2	39 ± 28	180 ± 13	126 ± 91	580 ± 40	4.6
Fontinalis	Entire	Long Shot drainage	2	85 ± 14	248 ± 20	275 ± 45	801 ± 65	2.9

*Number of free water samples from a single tissue sample.

†The error term for single samples (all bound samples plus free samples where n equals 1) is a one-sigma counting error, whereas the error for free samples where n is greater than 1 is one standard deviation of the mean.

‡Intertidal area at the mouth of the creek.

Table A.19—Strontium-90 in Bone from Rats and Ptarmigan and in Soil Collected at Amchitka Island

Collection date	Location	Sample type	pCi ^{90}Sr/g of dry weight*
October 1971†	Sand Beach Cove	Rat, bone	0.7 ± 0.2
October 1971†	Sand Beach Cove	Rat, bone	2.5 ± 0.2
December 1971	Sand Beach Cove	Rat, bone	10.1 ± 0.4
December 1971	Sand Beach Cove	Rat, bone	1.6 ± 0.2
April 1973	Sand Beach Cove	Rat, bone	1.9 ± 0.5
August 1973	Main dump	Rat, bone	1.8 ± 0.1
August 1974	Main dump	Rat, bone	0.8 ± 0.7
August 1974	Duck Cove	Rat, bone	2.3 ± 0.7
August 1975	Constantine Harbor	Rat, bone	1.6 ± 0.8
August 1975	Duck Cove	Rat, bone	1.2 ± 0.9
August 1975	Sand Beach Cove	Rat, bone	0.5 ± 0.1
November 1971†	Clevenger Creek	Ptarmigan, bone	27.0 ± 0.8
November 1971†	Baker Runway	Ptarmigan, bone	35.2 ± 1.0
December 1971	Base Camp	Ptarmigan, bone	18.3 ± 0.5
December 1971	C Site	Ptarmigan, bone	30.7 ± 0.9
August 1973	Silver Salmon Lake	Ptarmigan, bone	13.9 ± 0.2
September 1973	Clam Lake	Ptarmigan, bone	11.0 ± 0.2
August 1974	Mile Post 8	Ptarmigan, bone	16.1 ± 2.3
August 1975	Milrow Area	Ptarmigan, bone	13.8 ± 0.7
August 1975	Mile Post 8	Ptarmigan, bone	19.2 ± 1.4
August 1975	Cannikin Area	Ptarmigan, bone	12.5 ± 0.5
August 1975	Main Camp	Soil	0.03 ± 0.01
August 1975	Cannikin Area	Soil	<0.16

*Errors are one-sigma, propagated, counting errors for a single sample.
†Pre-Cannikin.

Table A.20—Plutonium-239,240 in *Fucus*, Greenling, Sand, and Soil Collected at Amchitka Island in August 1975

Sample type	Collection location	pCi/g of dry weight*	dpm/kg of wet weight
Fucus, entire	Sand Beach Cove	0.006 ± 0.001	3.0 ± 0.5
Fucus, entire	Constantine Harbor	0.002 ± 0.001	0.7 ± 0.4
Greenling, muscle	Sand Beach Cove	<0.002	<0.8
Greenling, muscle	Constantine Harbor	<0.003	<1.2
Sand, surface†	Sand Beach Cove	0.004 ± 0.001	
Sand, surface	Constantine Harbor	<0.002	
Soil, surface	Cannikin Area	0.015 ± 0.002	
Soil, surface	Main Camp	0.001 ± 0.001	

*Errors are one-sigma, propagated, counting errors for a single sample.
†Surface samples were the 0- to 2.5-cm layer.

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Polychlorinated Biphenyls in the Ecosystems

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Chemical residues in the form of DDE and polychlorinated biphenyls (PCB) from 21 species taken from Amchitka environs between 1970 and 1974 were identified and quantified. These samples were from birds, mammals, and fish and represented carnivores, herbivores, and omnivores, and both the aquatic and terrestrial ecosystems. The levels of DDE and PCB were then compared with ecological equivalents of the same or similar species in other parts of the Aleutians and Pacific Basin. The Amchitka samples generally had higher residue levels than ecological equivalents in the Southern Hemisphere, and carnivores were generally higher than other types. The sources of these pollutants found in the Amchitka region are discussed. Current levels of DDE and PCB are not high enough in the Amchitka ecosystem to be of prime concern or to impair reproduction. They are, however, higher than would be expected for the remoteness of the island from sources of pollutants and bear careful monitoring.

Polychlorinated biphenyls (PCB), a class of industrial synthetic chemicals, have become ubiquitous contaminants in marine environments (Jensen et al., 1969; Koeman et al., 1969; Risebrough et al., 1968; 1972; Risebrough and Carmignani, 1972; Risebrough and de Lappe, 1972; Harvey et al., 1974). The chemistry of the PCB has recently been reviewed by Hutzinger, Safe, and Zitko (1974); production and use data have been presented by Nisbet and Sarofim (1972), the Panel on Hazardous Trace Substances (1972), and Peakall (1975); Peakall (1975) has reviewed studies of the environmental effects of PCB. The amounts of PCB transferred to the environment and the rates of transfer have been estimated by Nisbet and Sarofim (1972) and by the Panel on Hazardous Trace Substances (1972).

This chapter examines the presence of PCB in ecosystems of Amchitka Island to (1) determine as far as possible their present levels in representative species; (2) determine whether the observed distribution of PCB suggests local input from human activities, atmospheric input from distant sources, or transport to Amchitka in ocean currents; (3) compare levels within Amchitka ecosystems with those of other ecosystems in the Pacific basin; and (4) assess potential impact on the local environment.

Waste-water outfalls and the dumping of sewage sludge in coastal areas introduce large quantities of PCB to the marine environment (Schmidt, Risebrough, and Gress, 1971; Holden, 1970; Young et al., in press). Rivers also constitute an input. In southern California, however, the amounts of PCB entering the sea from rivers have been small relative to the input from waste-water outfalls. Trichlorinated and tetrachlorinated biphenyls predominate in these waste waters (Young et al., in press). Many data also indicate that PCB enters the sea from the atmosphere. Bidleman and Olney (1974a; 1974b) and Harvey and Steinhauer (1974) have measured PCB in the atmosphere over the North Atlantic. The decrease in atmospheric concentration of PCB from near shore to open ocean was approximately exponential with distance (Harvey and Steinhauer, 1974). Trichloro- and tetrachlorobiphenyls predominate in these atmospheric samples (Bidleman and Olney, 1974a). Significant PCB levels in arctic fauna in areas where the atmosphere is the only plausible input source also indicate significant atmospheric transport of the polychlorinated biphenyls (Risebrough and Berger, 1971; Bowes and Jonkel, in press; Walker, in press).

Polychlorinated biphenyls consist of many different kinds of molecules that differ in the number of chlorine atoms and their positions on the parent biphenyl molecule. Commercial mixtures differ by their average chlorine content: commonly used preparations contain an average of 42%, 48%, 54%, or 60% chlorine by weight, consisting predominantly of trichloro-, tetrachloro-, pentachloro-, and hexachlorobiphenyls, respectively. An account of their principal indus-

trial applications and probable routes of environmental input has been given by Nisbet and Sarofim (1972). Japan, the Soviet Union, Canada, and the United States are, or have been, major users of PCB. The PCB in Amchitka ecosystems might therefore derive, via atmospheric or oceanic transport, from all these countries as well as from countries more remote. The major portion of the PCB that has been used consists of mixtures in which trichlorobiphenyls predominate (Nisbet and Sarofim, 1972). The Japanese product with this chlorine composition is marketed under the name Kanechlor-300 (Kuratsune and Masuda, 1972); the corresponding American preparation is Aroclor 1242. Among environmental samples, birds and mammals usually contain PCB of a somewhat higher chlorine content, consisting of pentachloro- and hexachlorobiphenyls.

MATERIALS AND METHODS

Samples were collected on Amchitka Island in the course of field studies carried out from 1969 through 1974. The majority of the samples were frozen until analysis; several were preserved in Formalin in glass jars. Tissues were ground with anhydrous sodium sulfate. Lipids were soxhlet-extracted with hexane : acetone (2 : 1). Cleanup was accomplished with sulfuric acid : fuming sulfuric acid : celite columns (Stanley and LeFavoure, 1965; Risebrough et al., 1970).

Both nonpolar OV-1 and polar QF-1 columns were used in the gas chromatographic analyses. Since several of the principal PCB peaks as well as several of the chlorinated hydrocarbons of insecticide origin emerge at different times from the two columns, identity is partially confirmed. In addition, many samples were saponified to remove interference with PCB determination by two of the principal DDT compounds, p,p′–DDT and p,p′–DDD (Risebrough, Reiche, and Olcott, 1969).

The predominant chlorobiphenyls in each sample were determined through comparison with standards of Aroclor 1242, 1248, 1254, and 1260. Polychlorinated biphenyl with profiles on the gas chromatograms most resembling that of Aroclor 1260 was quantified by averaging three determinations with the use of three of the most prominent peaks of Aroclor 1260. Similarly, PCB with a profile most resembling Aroclor 1254 was quantified by averaging three determinations based on the three principal peaks emerging after p,p′–DDE with the use of the OV-1 column.

A fishing float from the Japanese fleet, found on a beach on Amchitka, was soxhlet-extracted for 10 hr with 600 ml of hexane. The extract was found to have a gas chromatographic profile identical to either Aroclor 1248 or the equivalent Japanese preparation Kanechlor-400. The extract was quantified on the basis of one characteristic peak from the Aroclor 1248 standard. The PCB in samples containing predominantly trichlorobiphenyls was also quantified on the basis of one of the characteristic peaks.

The majority of the samples were analyzed at the Bodega Marine Laboratory with these methods. The remainder were analyzed by the Inter-Mountain Laboratory in Salt Lake City through the assistance of the Environmental Protection Agency and the Utah State Board of Health.

RESULTS AND DISCUSSION

Analytical results are given in Table 1. Selected data of DDE and PCB residue determinations in the same species or in closely related species that are biocoenetic equivalents from other areas of the Pacific basin or of the arctic are also included for purposes of comparison. To date comparatively few studies have been made of chlorinated hydrocarbon distributions in Pacific Ocean ecosystems. Sample sizes are therefore necessarily small. Nevertheless, sufficient data are now available to begin to put together a picture of the overall contamination patterns.

Peregrine Falcon (*Falco peregrinus*) tissue samples included four addled eggs and the liver, brain, and breast muscle of a fledgling killed by a Bald Eagle (*Haliaeetus leucocephalus*). These residue levels are compared with determinations of chlorinated hydrocarbons in eggs of peregrines from Amchitka by other investigators (Peakall et al., 1975), with DDE and PCB concentrations in two unhatched peregrine eggs from West Greenland (Walker, Mattox, and Risebrough 1973a), the yolk obtained from the oviduct of a female peregrine that died at Morro Rock, California, in 1969, the breast muscle of this bird (Risebrough, unpublished results), the carcass of an adult peregrine from coastal California obtained in 1966 (Risebrough et al., 1968), two samples of biopsy fat of peregrines from coastal Chile (Walker et al., 1973b), and an addled egg of a closely related species, the New Zealand Falcon (*Falco novaeseelandiae*), obtained on the Auckland Islands in subantarctic New Zealand in 1973 (Bennington et al., 1975). The latitude of the Auckland Islands in the southern hemisphere is the same as that of Amchitka in the northern hemisphere; samples from the two areas may therefore be used to compare contamination levels in the two hemi-

Table 1 Levels of PCB and DDE in Amchitka Habitat Systems; A Comparison with Biocoenetic Equivalents in the Pacific Basin

Food and habitat type	Locality	Species and date	Tissue	Lab.*	No.	Percent lipid	DDE,† ppm	PCB,† ppm		Dominant biphenyls	PCB/DDE	Ref.‡
Raptor, primarily avian carnivore	Amchitka	Peregrine Falcon, 1970	Addled egg	B	1	19	11 D	160 D	870 L	Pentachloro-	14.9	(1)
			Addled egg	B	1	29	56 D	190 D	660 L	Pentachloro-	3.3	(1)
			Addled egg	B	1	13	20 D	66 D	510 L	Pentachloro-	3.2	(1)
		Peregrine Falcon, 1972	Addled egg	IML	1	ND	1.7 W	2.1 W	ND	Pentachloro-	1.2	(1)
		Peregrine Falcon, 1971,	Pectoral muscle	B	1	5.5	1.2 W	10.7 W	202 L	Pentachloro-	8.8	(1)
		fledgling	Brain	B	1	4.4	0.2 W	2.1 W	49 L	Pentachloro-	10.5	(1)
		killed by eagle	Liver	B	1	2.3	0.3 W	3.4 W	146 L	Pentachloro-	10.8	(1)
		Peregrine Falcon, 1971	Egg		3		23 D	114 D		ND	5	(2)
		Peregrine Falcon, 1973	Egg		7		26 D	145 D		ND	6	(2)
	West Greenland	Peregrine, 1972	Addled egg		1	9.9	36 W	40 W	403 L	Hexachloro-	1.1	(3)
			Dead embryo		1	3.1	9 W	6.3 W	210 L	Hexachloro-	0.7	(3)
	California coast	Adult peregrine, 1969	Yolk—oviduct		1	19.3	93 W	55 W	280 L	Hexachloro-	0.6	(4)
			Breast muscle		1	5.6	39 W	20 W	350 L	Hexachloro-	0.5	(4)
		1966	Carcass		1	3.3	74 W	65 W	1980 L	ND	0.9	(5)
	Chilean coast	Adult peregrine, 1972	Biopsy fat		1	46	60 L		150 L	Hexachloro-	2.5	(6)
			Biopsy fat		1	71	120 L		170 L	Hexachloro-	1.4	(6)
	Auckland Islands, N.Z.	New Zealand Falcon, 1973	Addled egg		1	5.6	3.8 W	4.9 W	88 L	Hexachloro-	1.3	(7)
Raptor, primarily avian carnivore, terrestrial	Amchitka	Gyrfalcon, 1970	Pectoral muscle	B	1	3.1	7.5 L	0.58 W	19.5 L	Hexachloro-	2.7	(1)
			Brain	B	1	6.1	0.8 L	0.13 W	2.1 L	Hexachloro-	2.7	(1)
	Seward Peninsula, Alaska	Gyrfalcon, 1970, 1971	Biopsy fat		10	100	22 L		34 L	Hexachloro-	2.8	(8)
Raptor, feeding on birds, mammals, and fish	Amchitka	Bald Eagle, 1971	Addled egg	B	1	100	32 L		80 L	Hexachloro-	2.5	(1)
			Addled egg	B	1	100	36 L		134 L	Hexachloro-	3.7	(1)
			Pectoral muscle subcutaneous fat	B	1	14	3.4 W	9.9 W	63 L	Hexachloro-	2.9	(1)
		Bald Eagle, 1972	Addled egg	IML	1	ND	1.9 W	2.9 W§	ND	ND	1.6	(1)
			Addled egg	IML	1	ND	4.3 W	3.5 W§	ND	ND	0.8	(1)
Mammalian	Agattu	Harbor seal, 1974	Back muscle	B	1	7.9	0.021 W	0.033 W	0.42 L	Tetrachloro-		(1)
							(0.23 W, p,p′–DDT)	0.030 W	0.38 L	Hexachloro-		
		Steller's sea lion, 1974	Back muscle	B	1	22.3	0.24 W	0.47 W	2.1 L	Pentachloro-	2.0	(1)
	Auckland Islands	Hooker's sea lion, 1972	Subcutaneous fat	B	1	100	0.42 L		0.083 L	Hexachloro-	0.20	(7)
Mammalian	Agattu	Arctic fox, male, 1974	Leg muscle	B	1	6.5	0.03 W	1 W	20 L	Tetrachloro-, pentachloro-, hexachloro-	30	(1)
			Liver	B	1	9.7	<.2 W	2 W	20 L	Tetrachloro-, pentachloro-, hexachloro-	>10	(1)

(Table continues on page 618.)

Table 1—(Continued)

Food and habitat type	Locality	Species and date	Tissue	Lab.*	No.	Percent lipid	DDE,† ppm	PCB,† ppm		Dominant biphenyls	PCB/DDE	Ref.‡
		Arctic fox, female, 1974	Leg muscle	B	1	10.0	<.02 W	2 W	20 L	Tetrachloro-, pentachloro-, hexachloro-	>100	(1)
			Liver	B	1	8.7	<.02 W	2 W	30 L	Tetrachloro-, pentachloro-, hexachloro-	>100	(1)
Coastal herbivores and omnivores	Amchitka	Emperor Goose, 1971	Breast muscle, lipid	B	1	100	0.6 L		7.0 L	Pentachloro-	11	(1)
			Breast muscle	B	1	100	0.005 L		0.3 L	Pentachloro-	60	
		Norway rat, 1970 or 1971	Whole body	IML	1	ND	0.01 W	0.22 W		ND	22	(1)
			Whole body	IML	1	ND	<0.01 W	0.23 W		ND	>23	(1)
	Attu	Norway rat, 1974	Whole body	B	2	3.7	<0.04 W	6.0 W	160 L	Pentachloro-, hexachloro-	>150	(1)
	Amchitka	Norway rat, 1974	Whole body	B	1	12.3	<0.01 W	3 W	24 L	Tetrachloro-, pentachloro-, hexachloro-	>300	(1)
Terrestrial	Amchitka	Rock Ptarmigan, 1970	Carcass homogenate	B	10	2.8	0.0006 W	0.005 W	0.19 L	Pentachloro-	8	(1)
			Carcass homogenate	B	10	2.9	0.0012 W	0.005 W	0.16 L	Pentachloro-	4	(1)
	Seward Peninsula	Willow Ptarmigan, 1970, 1971	Carcass homogenate		6	1.9	0.009 W	0.016 W	0.84 L	Pentachloro-	1.8	(8)
		Rock Ptarmigan, 1970, 1971	Carcass homogenate		6	2.0	0.0016 W	0.005 W	0.24 L	Pentachloro-	3	(8)
	Attu Island	Rock Ptarmigan, 1974	Carcass homogenate	B	1	2.5	0.0011 W	0.0039 W	0.14 L	Pentachloro-	4	(1)
								0.0067 W	0.26 L	Trichloro-	8	(1)
Coastal fish	Amchitka	Rock Greenling, 1970	Body section	B	1	1.2	<0.0001 W	0.06 W	4.8 L	Tetrachloro-	600	(1)
			Whole-body homogenate: replicate 1	B	10	3.0	0.008 W (0.02, p,p′–DDT)	0.18 W	6.1 L	Pentachloro-	22	(1)
			Whole-body homogenate: replicate 2			2.8	0.009 W (0.021, p,p′–DDT)	0.20 W	7.0 L	Pentachloro-	22	(1)
		1974 (Pacific Ocean side)	Whole-body homogenate	B	3	1.9	0.002 W	0.02 W	1.2 L	Tetrachloro-	6	(1)
		1974 (Bering Sea side)	Whole-body homogenate	B	3	2.8	0.003 W (0.002, p,p′–DDT)	0.008 W	0.3 L	Tetrachloro-, pentachloro-	3	(1)
		Spotted snailfish, 1974	Whole-body homogenate	B	3	1.6	0.0013 W	0.015 W	0.6 L	Pentachloro-	5	(1)
								0.010 W	0.6 L	Trichloro-	8	(1)
		Pacific cod, 1974	Whole-body homogenate	B	1	0.8	0.005 W (0.002 W, p,p′–DDT)	0.016 W	2.0 L	Pentachloro-	3	(1)
		Dolly Varden trout, 1974	Whole-body homogenate	B	3	2.1	0.0018 W	0.01 W	0.5 L	Trichloro-	5	(1)
								0.01 W	0.7 L	Pentachloro-	5	(1)
		Smooth lumpsucker, 1974	Whole-body homogenate	B	1	1.4	0.0024 W (0.0025 W, p,p′–DDT)	0.004 W	0.3 L	Trichloro-	2	(1)
								0.008 W	0.6 L	Pentachloro-	4	(1)
Fishing float	Amchitka beach		Whole float	B	1		<0.1 D	21.8 D		Tetrachloro-		(1)

Fish eater	Amchitka	Red-faced Cormorant, 1971	Yolk	B	1	20	0.76 W	3.8 W	19 L	Hexachloro-	5.0	(1)
			Pectoral muscle	B	1	100	3.5 L		21 L	Hexachloro-	6	(1)
		Red-faced Cormorant, juvenile, 1974	Pectoral muscle	B	1	3.9	0.04 W	0.02 W	0.6 L	Tetrachloro-		(1)
								0.08 W	2 L	Hexachloro-		(1)
		Pelagic Cormorant, 1974	Pectoral muscle	B	1	4.0	0.03 W	0.3 W	8 L	Hexachloro-	10	(1)
	Agattu	Red-faced Cormorant, 1974	Pectoral muscle	B	1	3.8	0.09 W	0.2 W	4 L	Tetrachloro-	2	(1)
								0.4 W	10 L	Pentachloro-	4	(1)
	Peru	Guanay, 1969	Egg lipid	B	4	100	12.2 L (geometric mean)		15 L (geometric mean)	ND	1.2	(9)
	Auckland Islands	Auckland Island Shag	Egg lipid	B	4	100	0.9 L (geometric mean)		0.25 L (geometric mean)	Hexachloro-	0.3	(7)
	Southern California	Double-crested Cormorant, 1969	Egg lipid	B	7	100	754 L (arithmetic mean)		87 L (arithmetic mean)	Pentachloro-	0.1	(10)
	Northwestern Mexico	Double-crested Cormorant, 1969–1970	Egg lipid	B	6	100	574 L (arithmetic mean)		422 (arithmetic mean)	Pentachloro-	0.7	(10)
Alcids and pelagic species	Amchitka	Pomarine Jaeger, 1971	Carcass	B	1	6.7	1.1 W	0.25 W	3.4 L	Pentachloro-	0.23	(1)
	Agattu	Black-legged Kittiwake, 1974	Whole body	B	1	7.6	0.07 W	0.15 W	2 L	Tetrachloro-		(1)
								0.6 W	7 L	Hexachloro-	10	(1)
	Amchitka	Least Auklet, 1971	Whole body	B	1	6.9	0.03 W	0.13 W	1.9 L	Pentachloro-	5	(1)
		Parakeet Auklet, 1971	Whole body	IML	1	ND	0.02 W	0.4 W§		ND	20	(1)
			Whole body	IML	1	ND	0.01 W	0.3 W§		ND	30	(1)
		Parakeet Auklet, 1974	Carcass	B	1	4.5	0.07 W	0.1 W	3 L	Tetrachloro-	1	(1)
								0.1 W	3 L	Hexachloro-	1	(1)
		Tufted Puffin, 1974	Pectoral muscle	B	1	3.5	0.07 W	0.25 W	7 L	Pentachloro-	4	(1)
	Agattu	Thick-billed Murre, 1974	Carcass	B	1	4.0	0.08 W	0.09 W	2 L	Hexachloro-	1	(1)
	Snares Islands, N.Z.	New Zealand Diving Petrel, 1971	Whole body	B	3	10.6	0.009 W (geometric mean)	0.009 W	0.09 L	Pentachloro-	1	(7)
	Amchitka	Fulmar, 1970	Pectoral muscle	B	1	4.7	0.07 W	0.55 W	12 L	Hexachloro-	7	(1)
		Leach's Storm Petrel, 1970	Whole body	B	1	2.1	0.51 W	0.8 W	27 L	Hexachloro-	2	(1)
Migrants and Asiatic species	Shemya Island	Spinetail Swift, 1974	Carcass	B	1	2.1	3.8 W	0.4 W	28 L	Pentachloro-	0.14	(1)
	Amchitka	Bristle-thighed Curlew, 1974	Carcass	B	1	ND	0.16 W	0.03 W		Tetrachloro-		(1)
								0.04 W		Pentachloro-	0.25	(1)
		Bean Goose, 1974	Pectoral muscle	B	1	6.6	<0.0001 W (0.0006 W, p,p′–DDT)	0.004 W	0.06 L	Trichloro-		(1)
								0.009 W	0.14 L	Pentachloro-		(1)
			Liver	B	1	6.0	0.0003 W	0.01 W	0.18 L	Trichloro-		(1)
								0.003 W	0.08 L	Pentachloro-	10	(1)

*B, Bodega Marine Laboratory; IML, Inter Mountain Laboratory.

†W, wet weight; D, dry weight; L, lipid weight.

‡References: (1) This paper; (2) Peakall et al., 1975; (3) Walker et al., 1973a; (4) Risebrough, unpublished; (5) Risebrough et al., 1968; (6) Walker et al., 1973b; (7) Bennington et al., 1975; (8) Walker, in press; (9) Risebrough, Anderson, and McGahan, unpublished; (10) Gress et al., 1973; ND, not determined.

§Quantitated with Aroclor 1254.

spheres. The PCB values in the three eggs obtained on Amchitka in 1970 and the eggs subsequently obtained in 1971 and 1973 are among the highest of the recorded values, exceeded only by the residues in the body fat of an adult female in California. The latter value may be considered elevated because of depletion of body-fat reserves during illness of the bird (Risebrough et al., 1968). Ratios of PCB to DDE were also higher in the Amchitka samples. A local source of the contaminating PCB is therefore suggested; alternatively, these high PCB values may reflect high past input of PCB into the marine environment from Japanese sources.

Within an ecosystem, peregrines and other species of bird-eating raptors accumulate the highest residues of organochlorine pollutants (Ratcliffe, 1970; Risebrough et al., 1968). On Amchitka high levels of the DDT compound p,p′–DDE have been recorded in the peregrines, and shells of peregrine eggs on Amchitka have become significantly thinner than the shells in museum collections obtained before 1946 (White, Emison, and Williamson, 1973; Cade et al., 1971). Peregrines and other bird-eating raptors are also the first species in an ecosystem to show reproductive failures and population declines associated with organochlorine contamination (Hickey, 1969; Ratcliffe, 1970; Cade et al., 1971). Table 1 shows that the peregrines have the highest concentrations of DDE and PCB of all the species examined on Amchitka.

Between April and July 1968–1972, 548 food items of peregrines were obtained on Amchitka (White et al., 1973). Seventy percent consisted of alcids; of them, 24% were Crested Auklets (*Aethia cristatella*), 15% were Ancient Murrelets (*Synthliboramphus antiquus*), and 23% were Least (*Aethia pusilla*), Whiskered (*Aethia pygmaea*), and Parakeet (*Cyclorrhynchus psittacula*) Auklets. After mid-June falcons were seen more frequently on land than at sea. Prey items included the Green-winged Teal (*Anas crecca*), Lapland Longspur (*Calcarius lapponicus*), Gray-crowned Rosy Finch (*Leucosticte tephrocotis*), and Rock Ptarmigan (*Lagopus mutus*). Therefore during the breeding season the bulk of the peregrine prey was marine rather than terrestrial.

On a lipid basis (60 to 190 ppm lipid weight), DDE levels in the peregrine eggs from Amchitka are equivalent to the DDE levels in the fat, obtained by biopsy, of two adult peregrines examined in Chile in 1972. The addled egg of the New Zealand Falcon obtained in the Auckland Islands in 1973 contained 76 ppm DDE lipid basis. The DDE contamination at the latitude of the Auckland Islands appears therefore to be of the same order of magnitude as contamination levels at equivalent latitudes in the northern Pacific. The PCB concentration, however, in the New Zealand Falcon egg was an order of magnitude lower than that in the Amchitka peregrine eggs.

Gyrfalcon (*Falco rusticolus*) are frequent on Amchitka but apparently do not breed there (White, Emison, and Williamson, 1971). Prey items recovered on Amchitka and observations of feeding behavior indicate that approximately 80% of the diet of the Gyrfalcon consists of ptarmigan; ducks, Snow Buntings (*Plectrophenax nivalis*), rosy finches, and longspurs constitute the remainder. The single individual analyzed contained lower residues than 10 adults of the Seward Peninsula in western Alaska from which biopsy fat samples were obtained in 1970 and 1971 (Table 1) (Walker, in press). Geometric mean values of residues in the Seward Peninsula birds were two to three times higher, but the range was large: 0.7 to 290 ppm DDE; 6 to 210 ppm PCB. The higher concentrations, however, are associated with those Gyrfalcons preying on summer migrants, which have much higher residue burdens than do the resident ptarmigan (Walker, in press). The lower concentrations in the single bird from Amchitka do not therefore necessarily suggest that contamination levels differ in these regions, being 2.7 and 2.8 in the Amchitka and Seward Peninsula birds, respectively.

Bird material constitutes the major food of Bald Eagles (*Haliaeetus leucocephalus*). Among 639 food items collected, 61% consisted of birds, principally gulls, auklets, cormorants, and assorted ducks. Mammals constituted 23% of the items, of which more than half were sea otters (*Enhydra lutris*). Fish and marine invertebrates constituted the remaining 16% (Sherrod, 1975). Because of water loss, PCB levels in two eagle eggs were analyzed on a lipid basis and found to be 80 and 134 ppm. The DDE levels were lower by approximately a factor of 3 (Table 1). Residue levels have previously been reported for Bald Eagles from the Admiralty Island area in southeastern Alaska and from Kodiak (Wiemeyer et al., 1972). One eagle egg from South Midway Island near Admiralty Island contained 11 ppm DDE and 2.3 ppm PCB wet weight. Residues in four other eggs from the area were much lower, averaging 0.95 ppm DDE and 0.75 ppm PCB. To the west on Kodiak Island, seven eggs averaged 1.9 ppm DDE and 2.2 ppm PCB. If the percent lipid in Bald Eagle eggs is assumed to be 5%, our PCB values from Amchitka, considerably to the west and more oceanic, are somewhat higher than those closer to the North American continent.

Samples of back muscle were provided from two pinnipeds, the harbor seal (*Phoca vitulina*) and the Steller's sea lion (*Eumetopias jubata*), both found dead at the beach at Agattu Island in the Aleutian chain in 1974. In the harbor seal PCB consisted predominantly of a mixture of tetrachloro- and hexachlorobiphenyls; both were present in quantities slightly higher than levels of p,p′–DDE. Pentachlorobiphenyls in the Steller's sea lion sample were approximately twice as concentrated as p,p′–DDE. In contrast, PCB levels were lower in subcutaneous fat of a Hooker's sea lion (*Otaria hookeri*) at an equivalent latitude in the southern hemisphere in 1972; DDE values, however, were intermediate between those in the harbor seal and those in the Steller's sea lion (Table 1; Bennington et al., 1975). This comparison between the contamination levels in the two hemispheres is therefore comparable to that made above between the peregrine and the New Zealand Falcon.

The Arctic fox (*Alopex lagopus*) is a beach scavenger; two specimens were obtained from Agattu Island. Concentrations of p,p′–DDE were low but comparable, however, to those of the harbor seal from the same island. The PCB consisted of a mixture of tetrachloro-, pentachloro-, and hexachlorobiphenyls; the profile was similar in the four tissues examined but differed from the gas chromatographic profiles of standard mixtures in that a number of the PCB compounds had selectively accumulated whereas others had been excreted or metabolized. These substantially higher PCB concentrations in the fox tissues than those in the harbor seal and sea lion suggest a source of PCB that is not available to the food webs that support the pinnipeds; flotsam and beach refuse from ships possibly contain substantial amounts of PCB. The foxes were collected from an area uninhabited since the 1950s.

This hypothesis is supported by the comparatively high PCB concentrations in Norway rats (*Rattus norvegicus*), which live primarily on the beach and which feed on rotten kelp and a variety of animal and vegetable material. Two rats obtained from Attu Island in 1974 contained a mean value of 160 ppm PCB lipid weight consisting of a mixture of pentachloro- and hexachlorobiphenyls. A rat obtained on Amchitka in 1974 had somewhat lower PCB concentrations; these were, however, an order of magnitude higher than those in two rats obtained on Amchitka in 1970 or 1971. The PCB : DDE ratios were exceptionally high in all samples, again suggesting beach sources of PCB contamination.

Emperor Geese (*Philacte canagica*) are primarily intertidal, feeding principally on beach lettuce (*Ulva*), assorted grasses, and invertebrates. They spend about 6 months of the year on Amchitka. Two samples of breast muscle from birds obtained in 1971 were analyzed. Both contained predominantly pentachlorobiphenyls; PCB concentrations in the two samples differed by a factor of 20 lipid weight.

Two terrestrial plants [horsetail (*Equisetum arvense*) and crowberry (*Empetrum nigrum*)] are the principal foods of the Rock Ptarmigan (*Lagopus mutus*) and constitute in the order of 90% of the dry weight ingested (W. Emison, C. M. White, and F. S. L. Williamson, unpublished observations). The only plausible source of chlorinated hydrocarbons in tissues of these birds is atmospheric fallout onto land; ptarmigan are upland birds that do not generally approach the coast and therefore are not exposed to marine contamination. Twenty skinned carcasses of ptarmigan obtained in 1970 were divided into two portions and homogenates made of each. Residues were very low, on the order of 0.02 to 0.04 ppm DDE and 0.16 to 0.19 ppm PCB in the body lipids (Table 1). Residue levels and PCB : DDE ratios were very close to those found in a sample of six Rock Ptarmigan from the Seward Peninsula in western Alaska (Walker, in press). The level of atmospheric fallout in the two regions appears therefore to be comparable. The PCB in these Rock Ptarmigan and in Willow Ptarmigan (*Lagopus lagopus*) obtained on the Seward Peninsula in 1970 and 1971 consisted predominantly of pentachlorobiphenyls. A Rock Ptarmigan obtained on Attu Island in 1974 also contained pentachlorobiphenyls in the same ratio to DDE as those samples obtained earlier but contained, in addition, substantial quantities of trichlorobiphenyls at levels approximately twice those of the pentachlorobiphenyls (Table 1). The sample was collected within 4 miles of a Coast Guard loran station.

In the fish examined DDE concentrations were relatively constant, ranging between 1 and 5 ppb, except those in the rock greenling (*Hexagrammos lagocephalus*), a fish inhabiting coastal inshore waters which was obtained in 1970. Replicates of a homogenate of 10 fish obtained in 1970 contained 8 and 9 ppb, respectively, of p,p′–DDE; the body section of a larger fish contained less than 0.1 ppb on a wet-weight basis (Table 1).

Fish of all species obtained in 1974 did not diverge widely in PCB concentrations; values ranged from 0.3 to 2.0 ppm lipid weight but showed considerable variation in PCB composition. On a lipid-weight basis, the rock greenling obtained in 1970 contained substantially higher PCB concentrations. The homogenates of the small rock greenling obtained in 1970 contained predomi-

nantly pentachlorobiphenyls, whereas the body sections of larger fish contained principally tetrachlorobiphenyls. Tetrachlorobiphenyls were also present in rock greenling obtained in 1974; fish from the Pacific Ocean side of the island contained approximately three times the concentrations of tetrachlorobiphenyls as fish from the Bering Sea side of the island. The latter, however, also contained p,p′–DDT and pentachlorobiphenyls.

Three spotted snailfish (*Liparis callyodon*), small intertidal fish that do not leave the intertidal zone, contained predominantly trichlorobiphenyls. A Pacific cod (*Gadus macrocephalus*) obtained at an eagle's nest on Amchitka Island contained a very different chlorinated biphenyl composition, consisting predominantly of pentachlorobiphenyls. The PCB : DDE ratio of approximately 3 was similar to that recorded in earlier samples of eggs of the Bald Eagle on Amchitka (Table 1). Dolly Varden (*Salvelinus malma*), an anadromous species obtained in Jones Lake on Amchitka Island, contained DDE concentrations equivalent to those in other species but a mixture of both pentachloro- and trichlorobiphenyls. A smooth lumpsucker (*Aptocyclus ventricosus*) collected from an eagle's nest but an intertidal species like the greenling and snailfish contained a mixture of trichloro- and pentachlorobiphenyls.

All intertidal fish contained mixtures of trichloro- and tetrachlorobiphenyls with one or the other predominating. A fishing float found on an Amchitka beach contained trace quantities of tetrachlorobiphenyls equivalent to the American PCB preparation Aroclor 1248 and the Japanese preparation Kanechlor-400. We assume that the PCB was accumulated by the float from ambient water. The coastal zone and perhaps also the offshore waters are therefore contaminated with both trichloro- and tetrachlorobiphenyls. We assume also that the presence of p,p′–DDT in this area is an indication of atmospheric fallout; fish containing detectable quantities of p,p′–DDT also invariably contained pentachlorobiphenyls.

Tetrachlorobiphenyls were detected in pectoral muscle of Red-faced Cormorants (*Phalacrocorax urile*) from both Amchitka and Agattu. Thus some of the tetrachlorobiphenyls present in fish persist in this cormorant. Residues in the Red-faced Cormorant and in the pectoral muscle of a Pelagic Cormorant (*Phalacrocorax pelagicus*) are compared with those in the egg lipids of other species of cormorants from coastal California, northwestern Mexico, Peru, and the Auckland Islands. On Amchitka the Pacific sand lance (*Ammodytes hexapterus*) is most frequently found in the food regurgitated by the young. In the 1971 samples, PCB levels on a lipid basis w re approximately 20 ppm, comparable to the 15 ppm recorded in eggs of the Guanay (*Phalacrocorax bougainvillii*) from central Peru (R. W. Risebrough, D. W. Anderson, and J. McGahan, unpublished observations). These levels are much lower than residues in eggs of the Double-crested Cormorants (*Phalacrocorax auritus*) of southern California and northwestern Mexico, where average PCB residues in 1969 were found to be 87 and 422 ppm, respectively (Gress et al., 1973). These higher residues derive from industrial discharges in the Los Angeles area (Schmidt et al., 1971; Young et al., in press). On the Auckland Islands, in 1973 PCB residues in egg lipids of the Auckland Island Shag (*Phalacrocorax campbelli*) averaged less than a part per million (Bennington et al., 1975). Thus PCB levels at the same latitude in the northern and southern hemispheres appear to differ by an order of magnitude, whereas DDE levels in these closely related species are comparable; these cormorant data complement those obtained from seals and sea lions and from falcons, as discussed previously.

Among the alcids and pelagic species, tetrachlorobiphenyls were detected in a Black-legged Kittiwake (*Rissa tridactyla*) from Agattu and a Parakeet Auklet from Amchitka. In the North Atlantic, kittiwake specimens analyzed have shown consistently PCB : DDE ratios that are higher than those in other marine birds examined (Bourne and Bogan, 1972). The ratio of 10, hexachlorobiphenyl : DDE, in the Agattu kittiwake is noticeably higher than the ratio found in the Thick-billed Murre (*Uria lomvia*), also obtained on Agattu Island in 1974, but is not different from ratios found in other species of the area. High PCB : DDE ratios were found in the two Parakeet Auklets obtained in 1971, but lower ratios were found in a Least Auklet obtained in that year and in a Parakeet Auklet and a Tufted Puffin (*Lunda cirrhata*) obtained in 1974. Least and Parakeet Auklets are primarily subsurface feeders on zooplankton, principally a euphausid of the genus *Thysanoessa*, and mysids of the genera *Acanthomysis* and *Stilomysis*. In Table 1 residues in these birds are compared with those recorded in the Diving Petrel (*Pelecanoides urinatrix*) from the Snares Islands (Bennington et al., 1975). The DDE levels in the New Zealand Diving Petrel are comparable to those in the Least and Parakeet Auklets obtained in 1971; DDE residues in the Parakeet Auklet, the Thick-billed Murre, and the Tufted Puffin obtained in 1974 appear to be somewhat higher.

Among the pelagic species, the Pomarine Jaeger (*Stercorarius pomarinus*) had a PCB : DDE ratio of 0.23, a ratio characteristic of California coastal waters, where DDE concentrations are generally

higher than those of PCB (Risebrough et al., 1968). Most of the residue burden of this bird may therefore have been acquired during migration. Concentrations and ratios in the Fulmar (*Fulmarus glacialis*) and in the Leach's Storm Petrel (*Oceanodroma leucorhoa*) are comparable to those in other species of the area. The DDE levels in these species were substantially lower than those in Fulmars and petrels taken off California (Risebrough et al., 1968); the PCB level in the Fulmar (0.55 ppm wet weight) may be compared to the three values of 0.08, 0.34, and 6.5 ppm wet weight in whole bodies of Fulmars taken off California (Risebrough et al., 1968). Trichlorobiphenyls were detected in a Bean Goose (*Anser fabalis*), a vagrant from Asia, collected on Amchitka in 1974. The DDE levels were very low in tissues of this bird. In contrast, a Spinetail Swift (*Hirundapus caudacatus*) collected on Shemya Island in 1974 and the first North American record of the species (C. M. White, unpublished observation) had exceptionally high DDE (3.8 ppm wet weight) and comparatively low PCB. A Bristle-thighed Curlew (*Numenius tahitiensis*) collected in May 1974 on Amchitka was the first Aleutian record; this species migrates to islands of the South Pacific from its Alaskan breeding grounds. This bird contained comparatively low levels of both DDE and PCB with DDE predominating.

The wide divergence in PCB composition among the specimens examined provides at best an imperfect comparison of PCB levels; this is particularly true in the comparisons of samples that consist predominantly of trichlorobiphenyls with those containing principally hexachlorobiphenyls. Pentachloro- and hexachlorobiphenyls are present, however, in the commercial mixtures of Aroclor 1242 and 1248. Thus samples containing principally pentachloro- and hexachlorobiphenyls do not necessarily reflect environmental exposure to these PCB mixtures. Rather, compounds of higher water solubility that are more readily metabolized may have been selectively excreted (Lincer and Peakall, 1973).

SOURCES OF PCB CONTAMINATION

Present and Past Human Activities

In 1943 the U. S. military established a base on Amchitka for a staging area from which to launch attacks on Japanese-occupied Attu and Kiska to protect the North American coastline. Up to 15,000 troops were based on the island during World War II; the base was abandoned in 1951. In 1959 the Western Electric Company constructed a site for the White Alice communications network in the interior of the island. In 1964 Amchitka began to be used as a site for underground nuclear tests by the United States. The average population between 1968 and 1972 was between 300 and 500, with up to 750 present at peak times. Some of these activities may be assumed to have contributed PCB to the local environment. Moreover, waste materials were frequently burned; injection into the atmosphere and fallout back onto the land was therefore possible.

Hundreds of kilograms of plastic objects wash up on the beaches of Amchitka each year. These include bottles, fishing nets, polyethylene sheets, ropes, and other assorted plastic objects used by the Soviet and Japanese fishing fleets (T. R. Merrell, personal communication). Refuse from ships may therefore be the source of PCB in the intertidal organisms and animals foraging along the beach.

Storm tracks based on data available from 1899 to 1954 lie in a southwest-northeast direction during all seasons of the year. Summer winds tend to blow from the southwest, and west-northwesterly winds are frequent in fall and winter; at other times there is no prevailing wind direction (Armstrong, 1971, and Chap. 4, this volume). Prevailing surface winds immediately southward of the Aleutian chain in the vicinity of Amchitka are westerly at all seasons of the year (U. S. Weather Bureau and U.S. Hydrographic Office records).

The pattern of surface currents is considerably more complex. To the south the current carries water eastward to enter the Alaskan gyre. Near Amchitka surface currents are to the west, bringing, in part, water from the Alaskan gyre to the east (McAlister and Favorite, Fig. 1, Chap. 16, this volume).

Among polar ecosystems, organochlorine contamination of food webs has been studied on the Seward Peninsula in western Alaska (W. Walker, in press) and on the Antarctic Peninsula (Risebrough and Carmignani, 1972). The highest concentrations are found either in birds migrating into the area or in species that prey on them. Most of the species examined on Amchitka, however, are dependent on the local marine ecosystem, and the proportion of migratory birds is relatively small.

Airborne PCB from Japan can be expected to show the same exponential decrease with distance from its source as does PCB originating in the eastern United States and deposited in the North Atlantic (Harvey and Steinhauer, 1974). These residues are most likely carried farther east by the prevailing currents. Bidleman and Olney (1974a) have reported that PCB in atmospheric samples obtained over the North Atlantic consisted pre-

dominantly of trichloro- and tetrachlorobiphenyls; in seawater, however, pentachlorobiphenyls predominated, suggesting that the lower chlorinated compounds had been degraded, perhaps by ultraviolet light or by metabolism. These observations are inconsistent with the hypothesis that the trichloro- and tetrachlorobiphenyls found in the vicinity of Amchitka had traveled by atmospheric or ocean currents from Japan. Local sources of contamination, including the disposal of PCB-containing refuse on beaches, appear more plausible.

Sublethal effects of PCB that might be expected to impair reproductive capacity of birds have been reviewed by Vos (1972) and Peakall (1975). The species most vulnerable to organochlorine contamination on Amchitka is clearly the Peregrine Falcon. The DDE residues in this population are associated with some thinning of eggshells (White et al., 1973; Cade et al., 1971). Available data indicate that the present residue burdens are not impairing the reproductive capacity of this species, but increases in levels of either PCB or DDE could be expected to have deleterious effects. Fortunately the high levels of PCB in many ecosystems have prompted restrictions on PCB use on an international level; this should decrease the environmental input of these pollutants (World Health Organization, 1973).

ACKNOWLEDGMENTS

Research was supported by the Atomic Energy Commission contract AT(26-1)-171 to Battelle Columbus Laboratories, F. S. L. Williamson, principal investigator; Brigham Young University Research Division; the International Decade of Ocean Exploration Program of the National Science Foundation, grant GX-32885; the Toxic Chemicals Section of the Canadian Wildlife Service; and the Environmental Division of the Utah State Board of Health. We thank the U. S. Fish and Wildlife Service and the Alaska Department of Fish and Game for arranging for the collection of specimens or providing samples. We also thank J. T. Mendola and T. T. Schmidt for their assistance.

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