UNIVERSITY OF WASHINGTON'S RADIOECOLOGICAL STUDIES IN THE MARSHALL ISLANDS, 1946–1977

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Abstract—**Since 1946, personnel from the School of Fisheries, University of Washington (Applied Fisheries Laboratory, 1943–1958; Laboratory of Radiation Biology, 1958–1967; and Laboratory of Radiation Ecology, since 1967), have studied the effects of nuclear detonations and the ensuing radioactivity on the marine and terrestrial environments throughout the Central Pacific. A collection of reports and publications about these activities plus a collection of several thousand samples from these periods are kept at the School of Fisheries. General findings from the surveys show that (1) fission products were prevalent in organisms of the terrestrial environment whereas activation products were prevalent in marine organisms; (2) the best biological indicators of fallout radionuclides by environments were (a) terrestrial—coconuts, land crabs; (b) reef—algae, invertebrates; and (c) marine—plankton, fish. Studies of plutonium and americium in Bikini Atoll showed that during 1971–1977 the highest concentrations of ^{241}Am, 2.85 Bq g^{-1} (77 pCi g^{-1}) and ^{239,240}Pu, 4.44 Bq g^{-1} (120 pCi g^{-1}), in surface sediments were found in the northwest part of the lagoon. The concentrations in the bomb craters were substantially lower than these values. Concentrations of soluble and particulate plutonium and americium in surface and deep water samples showed distributions similar to the sediment samples. That is, the highest concentration of these radionuclides in the water column were at locations with highest sediment concentration. Continuous circulation of water in the lagoon and exchange of water with open ocean resulted in removal of 111 G Bq y^{-1} (3 Ci y^{-1}) ^{241}Am and 222 G Bq y^{-1} (6 Ci y^{-1}) ^{239,240}Pu into the North Equatorial Current. A summary of the surveys, findings, and the historical role of the Laboratory in radioecological studies of the Marshall Islands are presented.**

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LABORATORY HISTORY

THE LABORATORY was established at the University of Washington, College of Fisheries, in late 1943. Its first mission was to obtain information about the effects of ionizing radiation upon fish and other aquatic organisms. In July 1946, the Laboratory participated in the first series of nuclear tests in the Marshall Islands, Operation Crossroads, at Bikini Atoll and in the 1947 extensive resurvey. In the 1950's, the Marshall Island studies became the principal focus of the Laboratory's research efforts. The last test of the 66 nuclear detonations in the Marshall Islands was 18 August 1958, at Eniwetok. Since that time there have been a few other resurveys and surveys with other missions.

The name assigned to the Laboratory in 1943 by the U.S. Army Corps of Engineers, Manhattan Project, was "Applied Fisheries Laboratory," and bibliographically identified as UWFL (University of Washington Fisheries Laboratory). In 1957 the name was changed to Laboratory of Radiation Biology (LRB) and in 1966 changed again to Laboratory of Radiation Ecology (LRE). To avoid confusion, the simple term "Laboratory" will be used in this report.

In the planning stages for the Hanford plutonium production plant, there was concern about potential impact of the discharge of reactor cooling water into the Columbia River and its effects upon the plants and animals in the river, especially the very valuable salmon resource. A study of this potential problem was favored by Leslie Groves and Stafford Warren of the U.S. Army Corps of Engineers, the agency responsible for development of the Hanford Project. It was then suggested "that the program be set up outside of the Manhattan District by persons experienced in aquatic biology" (Hines 1962). Lauren R. Donaldson, College of Fisheries, accepted the leadership role for this research study in late summer 1943, about 3 mo after the beginning of construction of the first pile at Hanford. He served as Laboratory Director for 24 y. As a Manhattan District sponsored project, the program was classified until it was transferred to the Atomic Energy Commission in 1947.

Marshall Islands, 1946–1961

The sources of the fallout radionuclides in Marshall Islands samples were from one or more of 66 nuclear detonations: 23 at Bikini and 43 at Eniwetok. The schedule of detonations is given in Table 1.

A detailed and excellent account of the Laboratory's involvement in the Marshall Islands testing program is provided in Hines (1962). He participated in the field programs and was well acquainted with the Laboratory

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Table 1. Schedule of nuclear detonations at Bikini and Eniwetok Atolls 1946–1958[a]

Atoll	Operation code name	Date	No. of detonations B[b]	No. of detonations E[b]	Comments
Bikini	Crossroads	1946 July	2		1 air drop; 1 underwater; yields : 23 KT each
Eniwetok	Sandstone	1948 April–May		3	3-tower yield: 37, 49 & 18 KT
Eniwetok	Greenhouse	1951 April–May		4	4-tower yields: 3–?, 1–47 KT
Eniwetok	Joy	1952 Nov		2	first thermonuclear (MIKE)); surface; 10 MT also, 1 air drop, 500 KT
	Castle	1954			second thermonuclear; surface; 15 MT;
Bikini		March–May	5		also 3 barge, 1 surface at 110 KT; 3–?
Eniwetok		May		1	barge; yield,?
	Redwing	1956			first U.S. airdrop of a thermonuclear; also
Bikini		May–July	6		4 barge, 1 surface; yields (total) 10
Eniwetok		May–July		11	1 airdrop; 2 barge; 2 surface; 2 tower; 4–? yields: 1–40 KT; 10–?
	Hardtack	1958			
Bikini		May–July	10		1; barge; yields: 10–?
Eniwetok		April–August		22	1 balloon NE of Eniwetok; 15 barge; 2 surface, 2 underwater, 3 (?) yields 3–29 MT, total: 18–?
			23	43	
			TOTAL B[b] + E[b]	66	

[a] Selected information form Schultz and Schultz (1994).
[b] B = Bikini Atoll and E = Eniwetok Atoll.

and its people. For this period, he recognized four phases: 1946–1949; 1952; 1954; and 1958.

1946–1949. Operation Crossroads, pre and post test surveys, was the starting point where almost everything was new. Survey and analytical procedures needed to be tested and adapted to the task at hand. The instrument first used for detection and measurement of radiation in the field and in samples brought to the field or home laboratories was a simple Geiger-Mueller counter. The counting rates provided estimates of the relative radioactivity of the samples but no qualitative information. There were pre-Crossroads studies and collections for use in comparison with the post-Crossroads resurveys of 1946 and 1947. For operations Sandstone (1948) and Greenhouse (1951) there were no plans for environmental surveys. A plan for the Laboratory to return to Eniwetok for a post-Sandstone, pre-Greenhouse survey was canceled because of the Korean war.

1952. The first thermonuclear detonation (MIKE) was on 1 November 1952, at Eniwetok Atoll. This much more powerful detonation brought a new dimension to fallout studies. [The islet on which the detonation occurred became a hole in the reef more than 1.85 km (one nautical mile) wide and 60 m (200 feet) deep (Hines 1962).] With thermonuclear detonations, much greater quantities of fallout radionuclides were produced per detonation, and a relatively greater proportion was injected into the stratosphere.

1954. A 15-megaton thermonuclear detonation (BRAVO) at Bikini Atoll on 1 March 1954, had grave consequences. The prevailing wind in this area is the NE trade wind, but at the time of BRAVO the tropospheric fallout was carried to the NE and E of Bikini. There was a heavy fallout of Bravo-produced radionuclides onto a Japanese fishing boat that was 150 km (80 miles) NE of Bikini at the time of the detonation and this incident became of great national concern to the Japanese people. Also, Bravo fallout was carried to Rongelap Atoll, a populated atoll, 185 km (100 miles) east of Bikini. The mean external dose to individuals at Rongelap was calculated to be 1.75 Gy (175 R); they were in the SE corner of the atoll, but had they been in the northern area their calculated dose would have been as great as 8 Gy (800 R). The radioisotope of greatest concern was ^{131}I, which was primarily inhaled by the residents and accumulated in the thyroids. Children were affected most seriously because as they became adults thyroid nodules developed. The Brookhaven National Laboratory had the responsibility for caring for the health of Rongelap people. An account of radiation doses to the people are given by Conard (1992). Our Laboratory began intensive ecological studies at Rongelap soon after the arrival of the 1954 Bravo fallout. The terrestrial ecosystems studies are reported by Walker, Gessel, and Held in another section of this volume.

1954 was also the year of the first ocean survey, the voyage of the Japanese oceanography research vessel "Shunkotsu Maru," and this was followed by six U.S.

surveys—the Taney in 1955, the Walton and Marsh in 1956, and the Rehoboth, Collett and Silverstein in 1958 (Palumbo et al. 1959).

1958. By international agreement, the United States ended the program of nuclear testing in the Marshall Islands in August, 1958.

As the Laboratory's Marshall Island survey studies became less frequent, the knowledge gained from these experiences prepared the staff for expanding the scope of their radioecological studies to Fern Lake, Washington; the Washington State Coast; Amchitka, Alaska; Cape Thompson, Alaska; and elsewhere.

1962–1977. In 1964, six years after the last test series, the Laboratory carried out a survey of Bikini and Eniwetok Atolls to obtain information on the long-term effects of nuclear detonations. The major objectives for the 1964 study were documentation of biological and physical conditions at the atolls; a comparison, wherever possible, of the biological and physical conditions with those existing before and during the testing period; and documentation of the radiological conditions of the atolls. Specifically, during this expedition, the Laboratory had documented the kinds, numbers, and condition of organisms present in 1964, described the physical environment of the lagoon and land areas, identified the radionuclides present, and determined the amount of radioactivity in the biota and in the physical environment. An extensive photographic documentation of plants and the environment in general accompanies the 1964 survey report (Welander 1964).

A study of the concentrations of two long-lived radionuclides ^{239}Pu ($t_{1/2}$ = 24,000 y) and ^{241}Am ($t_{1/2}$ = 458 y) in biota and sediments at Bikini and Eniwetok Atolls was initiated in 1970. The survey for this study, later named the Biogeochemistry of the Transuranic Elements in Bikini and Eniwetok Atolls, was a joint effort of our Laboratory, the Lawrence Livermore National Laboratory, and the Puerto Rico Nuclear Center in 1972. The Laboratory conducted additional field surveys in 1976 and 1977. The purpose of this study was to investigate the concentration and redistribution processes of the long-lived radionuclides ^{239}Pu and ^{241}Am in Bikini Atoll lagoon.

In 1974, the Laboratory's program to determine the concentration of radionuclides in foods, plants, animals, and soils was extended to the Central Pacific atolls and islands. The purpose was to furnish data to other agencies so that they might make an assessment of the dose of fallout radiation received by the people living throughout the Central Pacific. Areas sampled from April 1974 to August 1975 were, in addition to the Marshall Islands, Truk and Ponape in the Caroline Islands, Guam in the Marianas Islands, Christmas Island in the Line Islands, and Koror and Babelthaup in the Palau Islands.

SURVEY FINDINGS

Introduction

The basic field program was the collection of terrestrial, lagoon, and ocean samples that represented the major components of the ecosystem. Initially, a broad spectrum of sample types was collected but later most attention for biological samples was focused on specific radionuclide indicators. With regard to identification and measurement of the radionuclides in the samples, some of this work was done in the field, either in temporary accommodations aboard ships or at the Eniwetok Marine Biology Laboratory. The purpose of the field measurements was to provide guidance to the on-going field program. However, most of the samples were counted in the home laboratory where there were facilities for more sensitive detection and measurement of radionuclides and longer sample counting times could be accommodated.

Both Bikini and Eniwetok atolls were prime collection sites, and Rongelap Atoll became a major study area after the arrival of Bravo fallout from the 1 March 1954 detonation at Bikini Atoll. At the Bikini and Eniwetok sample collection sites, the nuclear detonation impact included thermal, over pressure, prompt radiation and local fallout factors, factors not present at Rongelap Atoll.

The discussions of the "findings" will be grouped by major environments: terrestrial, lagoon, ocean. Greater emphasis will be placed on general findings than on quantitative values for specific radioisotopes that change constantly with time, except when these values may be of relative significance. If more detailed information is sought, see the Archives section of this report for the location and availability of the Laboratory's publications and reports, especially Hines (1962).

Terrestrial

What happens to fallout after it arrives on island soils? Horizontal distribution will be largely by wind, precipitation, run-off and wash-overs; and vertically by percolation and sorption. Biological uptake also will play some role in fallout distribution—for example, the transfer of radionuclides from the ocean to seabirds to island nesting areas.

Bikini and Eniwetok are in the "local" fallout area where "the effects of blast and fire may be of even greater importance than the effects due to ionizing radiation . . ." (Eisenbud 1963). The specific cause of observed effects may be difficult to identify. The estimated relative yields of a nuclear explosion at "ground zero" are as follows: "Approximately 50% of the energy from a nuclear explosion is released in the form of blast effects, 35% as thermal radiation and the remaining 15% as ionizing radiation . . ." " . . .Of the ionizing radiation one third is prompt radiation . . . and the remainder is produced by decaying fission products and induced radionuclides" (Eisenbud 1963). Hence, the "cause-effect" relationship in a "local" fallout area is clouded by uncertainty about the cause(s).

The first thermonuclear detonation was the Mike shot of 1 March 1952 at the northern reef of Eniwetok Atoll. The estimated energy release was 10 MT. The Laboratory conducted both pre-shot and post-shot surveys. For the pre-shot survey, the most radioactive sample types (the residual radioactivity from previous detonations) were algae, aquatic invertebrates, plankton, fish, land plants and land invertebrates. The post-shot collection schedule in terms of days after Mike and of distance from ground zero were as follows: +2 to +4 d, 26–37 km (14–20 miles); +5 to +6 d, 13–22 km (7–12 miles); and +7 d, 3.7–5.6 km (2–3 miles). The order of radioactivity for sample type was the same as for pre-test samples except that post-test land plants ranked third. The ratio of post-shot to pre-shot radioactivity values was about 300 for the aquatic organisms and 1,000 for the land plants and vertebrates (Donaldson 1953).

For the 1959 Rongelap samples, information about what radionuclides were present in what samples was presented in an ecosystem type of chart. See Fig. 1 (Hines 1962). The distribution of fallout isotopes at Bikini and Eniwetok in comparable samples would be expected to be similar to Fig. 1. Although Bikini and Eniwetok were in the "close-in" fallout zone, there was no close-in fallout at Rongelap.

In 1964, a radiobiological study of the islands and reefs of Bikini and Eniwetok atolls was conducted by Welander et al. (1964). They observed that principal damage to the islands was the loss of topsoil on or near the test islands, apparently as a result of blast and heat effects. Similarly, blast and heat damaged the reefs and added greatly to fine silt and turbidity of the reefs and lagoons. ^{60}Co was the dominant radionuclide in the marine samples, whereas ^{137}Cs and ^{90}Sr were dominant in the land environment (Welander et al. 1964).

An extensive radiological survey of plants, animals, and soil at five atolls in the Marshall Islands was reported by Nelson (1979). The results of this survey indicated that ^{90}Sr and ^{137}Cs were dominant in the terrestrial environment and, in addition, ^{241}Am and ^{239,240}Pu were also important long-lived radionuclides in the soil samples from Bikini and Rongelap atolls. ^{60}Co and ^{55}Fe were dominant in the marine environment together with naturally occurring ^{40}K.

The amounts of radioactivity varied between atolls and between islands within an atoll in relation to the distance from the test sites. In the 1974–1975 survey, Bikini Atoll had the greatest amount of fallout radioactivity (^{90}Sr, ^{137}Cs, and ^{239,240}Pu), but the northern islands of Rongelap Atoll had only slightly lower amounts. Rongerik and Ailinginae Atolls and the southern island of Rongelap Atoll had similar amounts of radioisotopes, but were less than similar values for Bikini by factors of 5 to 10 or more. Values at Utirik Atoll were lower still, but were higher than amounts at Wotho and Kwajalein Atolls. Christmas Island in the Line Islands had the least amount of radioactivity of the areas surveyed. It was concluded that radioactivity on Bikini and Rongelap atolls had declined significantly with time and should continue to do so because of physical and biological processes (Nelson 1979).

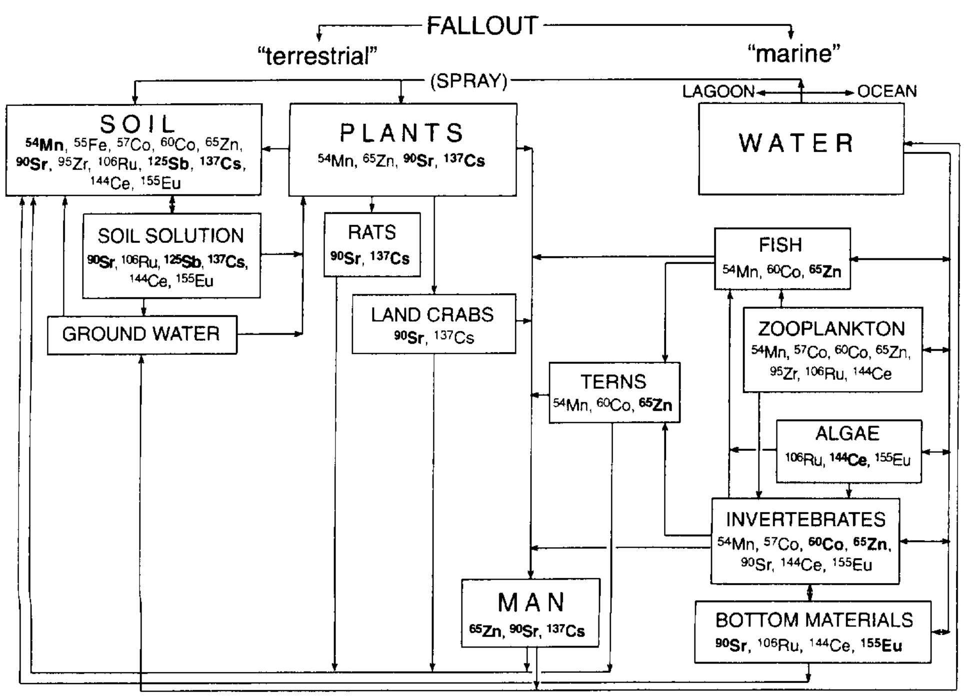

Fig. 1. Distribution of fallout radioisotopes at Rongelap Atoll, 1959, the dominant isotopes indicated in bold-faced type (Hines 1962).

The soils of the Marshall Islands consist of calcareous materials and a thin layer of organic matter that has produced a shallow, organic-rich horizon suitable for certain plant growth. Plutonium and americium measurements of surface soil samples collected on 6 of the 26 islands of Bikini Atoll in 1975 showed that $^{239,240}Pu$ values ranged from 0.02 to 13.3 Bq g^{-1} (0.5 to 360 pCi g^{-1}) and ^{241}Am values ranged from 0.04 to 1.7 Bq g^{-1} (1.2 to 45 pCi g^{-1}). The vertical distribution of plutonium in soil varied with soil types. Although about 98% of plutonium was retained in the top 25 cm in undisturbed soil, the remaining 2% was detectable as deep as 100 cm. The suspension and resuspension of plutonium and plutonium-bearing particles in the soil column by rain water (150–175 cm y^{-1}) seemed to be the principal mode of plutonium transport in the soil. Plutonium was found to be associated with the algal crust of the atoll soils. A comparison of ^{90}Sr and plutonium showed a similar pattern of vertical distribution in both disturbed and undisturbed areas, although the values for ^{90}Sr, 13.7 Bq g^{-1} (371 pCi g^{-1}), were much greater than for $^{239,240}Pu$, 0.3 Bq g^{-1} (9.3 pCi g^{-1}) (Nevissi et al. 1976).

General findings from the terrestrial surveys are as follows:

1. Fission products are present in organisms of the terrestrial environment whereas activation products are prevalent in marine organisms.
2. The best biological indicators of fallout radionuclides are:
   a. terrestrial—coconuts, land crabs
   b. reef—algae, invertebrates
   c. marine—plankton, fish
3. The deficiency of potassium in Marshall Island soils enhances the uptake of ^{137}Cs by plants and animals.
4. Potassium fertilizers can diminish ^{137}Cs uptake.
5. In areas devastated by nuclear detonations signs of plant regrowth were seen within a week, and "greening" of the area within a month.
6. Rats living in underground tunnels and nests survived in areas close to large detonations.
7. The geographical, environmental, and biological distributions of fallout radionuclides were well established.

Lagoon

Generally, what happens to fallout after it arrives on the lagoon surface is similar to what occurs in the ocean, except that the basin is smaller and the circulation pattern is more restricted. The northeast trade winds move the surface waters from the east to the west side of the lagoon and in so doing there is upwelling on the east side of the lagoon to replace the westward flowing surface water. Hence, a circulation pattern is established in which surface water moves westward and sinks, and the bottom waters move eastward and upwell. The average depths of the lagoons are about 60 m (200 ft). The flushing time for Bikini lagoon, in term of half-time is about 1 mo (Van Arx 1954). Therefore, nearly complete flushing would occur in 7 mo—i.e., more than 99% of water present in the lagoon on day one would have been flushed into the ocean.

Plankton samples were collected in the lagoon as well as in the ocean. Following is an account of a representative lagoon plankton survey. In the 1949 surveys of Bikini, Eniwetok and Likiep, plankton collections were a part of each survey. (There were no nuclear detonations in 1949, but in 1946 there were two at Bikini and in 1948 three at Eniwetok). Likiep Atoll was a control area, i.e., outside of the fallout pattern but 280 miles SE of Bikini.

Forty-six samples were obtained by filtering water through nets of various mesh sizes. The nets were either towed or water was pumped from specific depths through them. The ratios of the radioactivity for test sites versus control were as follows: Bikini, (Island area)/Likiep, 1; Bikini, (target area)/Likiep, 3; and Eniwetok, (test site)/ Likiep, 8.

The plankton samples from the fine-meshed nets were the most radioactive both in 1948 and 1949. For comparable samples at Bikini and Eniwetok the 1949 radioactivity values were about one-half the 1948 values.

The radioecology of plutonium and americium in Bikini Atoll lagoon was studied during 1971–1977. The largest source of radionuclides available for transport as indicated by ^{241}Am and $^{239,240}Pu$ in sediments and water samples resided in the deep water in the northwestern quadrant of Bikini Lagoon approximately 6 km south of the second thermonuclear detonation, Shot Bravo. The highest concentrations of ^{241}Am and $^{239,249}Pu$ were 2.9 Bq g^{-1} (77 pCi g^{-1}) and 4.4 Bq g^{-1} (120 pCi g^{-1}), respectively. The concentrations in the bomb craters were substantially lower than these values probably due to two processes: (1) dilution by eroding crater wall material and (2) loss of the fine particles containing the largest concentration of radionuclides by fluvial transport away from the crater (Nevissi and Schell 1975a).

Concentrations of soluble and particulate americium and plutonium in surface and deep water samples showed distributions similar to the sediment samples—that is, the highest concentration of these radionuclides in the water column were at locations with highest sediment concentration. Sixteen years after the last nuclear test on the atoll, the radionuclides were neither totally buried in the lagoon sediments, nor had they been completely transported to the ocean. Continuous circulation of water in the lagoon and the exchange of water with the open ocean resulted in removal rate of ^{241}Am, 111 GBq y^{-1} (3 Ci y^{-1}) and $^{239,240}Pu$, 222 GBq y^{-1} (6 Ci y^{-1}) into the North Equatorial Current (Nevissi and Schell 1975a).

Measurements of radioactivity in water and biological samples from Bikini and Eniwetok lagoons in 1972 indicated that the values of naturally produced ^{210}Po were usually greater than the values of $^{239,240}Pu$ that were produced by nuclear detonations, by factors as great as 100 (Nevissi and Schell 1975b).

Ocean

What happens to fallout after it arrives at the ocean's surface? It will enter the surface water circulation systems, begin a downward descent and some will be absorbed or adsorbed by organisms in the water. Before the fallout radionuclides enter the deep waters of the ocean (average depth, 3,800 m), they move through a transitional zone where there are steep gradients for both temperature (thermocline) and salinity (pycnocline). This zone may temporarily delay the descent of the fallout radionuclides into the deep water, which is characterized by stratification and very slow movement.

In the Bikini-Eniwetok area, the surface waters are in the major gyre of the North Pacific Equatorial Circulation system, which rotates in a clockwise direction that moves westward to near the Philippine Islands. Here, the major portion of the stream turns northward in the direction of Japan and is known as the Kuroshio Current. The lesser portion flows southward and then eastward near the equator and is known as the North Equatorial Counter Current. In the surface current there is constant and vigorous mixing, which rapidly dilutes the concentration of the fallout radionuclides. Horizontal distribution of radionuclides is principally by surface water currents and to some degree by plankton and larger organisms. Plankton movement is passive except for some diurnal movement in surface waters; for larger organisms, their movement may be multidirectional.

There have been ocean surveys in search of radionuclides produced by the Bravo (Bikini Atoll) detonation of 1 March 1954, by both Japan and the United States. The general objectives have been to locate the fallout "foot print," determine its rate of advance, predict arrival time at specific locations and determine the kinds, amounts, and distribution of the radionuclides in the water and biota.

The Japanese oceanographers were the first to search for fallout radionuclides in the ocean from nuclear detonation at the Pacific Proving Grounds. There was great national concern in Japan about the consequences of Bravo fallout in the North Pacific Ocean. This concern was conditioned by the Hiroshima-Nagasaki experience, the illness that befell the fishermen who were aboard the Japanese fishing vessel near Bikini at the hour of the Bravo detonation, the contamination of the tuna caught by and sold to the Japanese, and the prediction that the Bravo "foot print" would reach Japan by early 1955, all of which contributed to the vast "unknown" about the hazards from ionizing radiation. As a consequence, the Japanese conducted a full-scale oceanographic survey from 15 May to 4 July 1954, with the research vessel "Shunkotsu Maru," in search of the Bravo "foot print." Also, between October 1954 and February 1955, two Japanese training ships made incidental collections of water and fish for radiological analyses while in transit through areas in the vicinity of the test site.

The first U.S. ocean survey to scope the Bravo fallout "foot print" was in March and April, 1955, in the area of the test site and westward, then northward, to Japan. One of the objectives was to answer the question, "Would it be safe to swim in Japanese coastal waters in 1955?" Otherwise, the objectives were similar to those for the "Shunkotsu Maru." The U.S. operation was known as "Troll" and the U.S. Coast Guard cutter "Roger B. Taney" was the platform for the survey (Harley 1956). The radioactivity in the surface water was constantly monitored by a specially built probe towed behind the ship; also, samples of deeper water, plankton and fish were obtained for radiological analyses. Direction of the Troll Operation was assigned to AEC's Health and Safety Laboratory, New York; the survey team members were from several laboratories, including one from the University of Washington.

After Troll, there were two ocean surveys in 1956, and three in 1958. Four of these surveys were Laboratory programs and the other (in 1958) was a joint effort of three teams, of which the Laboratory was one. All of these surveys were supported by ships from the U.S. Navy. The general objectives for study of the fallout "foot print" remained the same, and, in a sense, the later surveys were considered to be sequels to preceding surveys. Principal findings are as follows:

1. The Bravo (March 1954) radionuclide footprint was identified in water samples below the thermocline near the Philippine Islands in March 1955. The identification was by radioisotopes of nuclear detonation origin and the quantity was less than the abundance of naturally occurring radionuclides. (Significance—the coastal Japanese waters would be safe for swimming in 1955.)
2. The rate of advance of radioactivity in surface waters was estimated to be approximately 13–18 km (7–10 miles) per day and was reasonably close to previous predictions.
3. The U.S. surveys generally confirmed the results of the original survey by the Japanese.
4. After the underwater detonation in the ocean 3.7 km (2 miles) SW of Eniwetok Atoll, Test Wahoo on 16 May 1958, the distribution of the radioactivity in surface waters was as follows:
   - +6 h; major concentration, top 25 m; thermocline, little;
   - +28 h; major concentration, top 50 m; thermocline, little; and
   - +48 h; major concentration at thermocline (100 m); some to 300 m.
5. Immediately after detonation the short-lived fission products—^{99}Mo, ^{99}Tc; ^{132}Te, ^{132}I; ^{140}Ba—were dominant in plankton. The radioisotopes ^{90}Sr and ^{137}Cs accumulated slightly in marine organisms; in fish, radioisotopes of iron, zinc, and manganese prevailed. Some weeks after the detonation, the principal radionuclides in plankton were radioisotopes of zinc, cobalt and iron. Note: The principal factor in radionuclide accumulation by plankton could be adsorption (Lowman 1960).
6. To indirectly monitor the arrival of fallout radionuclides "downstream" from the test sites, collections of plankton, fish, invertebrates and algae were obtained from Guam, Palau and the Gulf of Siam from July 1958 to October 1959. Their distances from the test

sites were approximately 2,200, 3,600, and 7,900 km (1,200, 1,950, and 4,250 miles), respectively. Guam and Palau are in the North Pacific Equatorial Current System, the Gulf of Siam is not. In terms of gross beta activity of the plankton samples, the Guam samples were very much greater than the other two and Palau greater than the Gulf of Siam. Radioactivity of the Gulf of Siam samples was no greater than would be expected from naturally occurring radioisotopes. There was a major peak at Guam in January 1959 and a minor peak at Palau in August 1958. Conclusion: the feasibility of using biota for this indirect measure of identifying the presence of fallout radionuclides transported by water is demonstrated; however, a reliable prediction of the date of radionuclide origin (the date of nuclear detonation) cannot be made from the available data.

7. Plankton are the best indicators of radioactive contaminants in ocean waters. Collection and analyses are relatively simple. Concentration factors, plankton/water, are of the order of 104 shortly after the detonation but decrease rapidly with time, due to decay of short-lived radionuclides and dilution.
8. The probe used for constant monitoring of radioactivity in surface water provided data that compared favorably with data obtained by conventional water sample analyses.
9. Conclusion: In consideration of the hazards to man and biota from fallout radionuclides, the consequence would be less for fallout into the ocean than onto land for two principal reasons—the much greater dilution in the ocean and the very long residence time in the deep waters of the ocean.

Other observations in seawater and fish

^{55}Fe in seawater and fish. ^{55}Fe is a neutron-induced radionuclide produced in large quantities from ferrous materials in the immediate vicinity of a nuclear detonation. Usually this radioisotope was the most abundant fallout radionuclide in marine organisms at the time of, and a few months after, some of the detonations. In Bikini Atoll lagoon, concentrations of ^{55}Fe found in water were 4.4–25.2 Bq m^{-3} (120–680 pCi m^{-3}) in 1972 and were estimated to be partitioned into 45% particulate (>0.3 mm), 45% colloidal and 10% soluble (Schell 1976).

Samples of light and dark muscle from tuna obtained in 1968 and 1969 from the Japanese tuna fishery in the Pacific and at Bikini Atoll showed no significant trend in the data when ^{55}Fe-specific activities were compared by species, month of catch, location of catch, or size of fish (Held 1973). Tuna from the southern hemisphere tended to have lower concentrations and specific activities than tuna from the northern hemisphere. There was a close correlation of ^{55}Fe-specific activity in light muscle, dark muscle, and liver, and of ^{55}Fe concentration between dark muscle and liver. Yellowfin tuna caught near Bikini Atoll contained ^{60}Co believed to be derived from the atoll (Held 1973). ^{55}Fe in Rongelap people, fish, and soils were reported by Beasely et al. (1972). They reported that the ^{55}Fe body burdens for 60 residents of Rongelap Atoll were approximately three times higher than those of a similar number of residents from Tokai-mura, Japan, which in turn had substantial ^{55}Fe body burdens.

Biological accumulations of radionuclides from the ocean. Three factors appeared to control the selective uptake of radionuclides from sea water by the plankton, omnivorous fish, and carnivorous fish studied by Lowman (1963). These were isotope dilution (by the corresponding stable element or chemical analogue element) in the sea water, the tendency of divalent cations to complex strongly with biological substrates, and the biological requirements for specific elements in metabolic processes. The uptake patterns in the three trophic levels were as follows.

During the first 48 h after fallout, the plankton in the contaminated area accumulated radionuclides (the mechanism of this accumulation, whether by adsorption or by active metabolic uptake, was not known) in approximately the same ratio as they occurred in sea water. After 1 wk the radioisotopes of the three elements cobalt, iron, and zinc were actively taken up by the plankton. Omnivorous fish, which feed on plankton, almost completely excluded the fission products and concentrated ^{65}Zn and ^{55,59}Fe but discriminated against ^{57,58,60}Co. Carnivorous tunas, which feed primarily on omnivorous fishes, discriminated against zinc and manganese but concentrated iron and cobalt (Lowman 1963).

Aberrant growth forms. Instinctively, where radioactivity is present in an area that has been exposed to high levels of radiation some time in the past, one looks for aberrant growth forms and if these are seen, one is inclined to ascribe the abnormality to the radiation exposure; however, at a nuclear test site, establishment of a meaningful radiation exposure-effect relationship is nigh impossible. Biddulph and Biddulph (1950) observed ten or more plant species with morphological abnormalities, but some of the same abnormalities were found in non-fallout areas. Some were caused by insects, some by bird droppings, and some by chemicals. However, a rough estimate of the radiation-dose effect relationship can be obtained from the results of controlled field experiments by Gunckle and Sparrow (1954). They observed that chronic dose rates of gamma radiation of 0.13–0.37 Gy d^{-1} (13–37 R d^{-1}) for 2–4 mo [total dose, 7.8 to 55 Gy (780 to 5,500 R)] can cause plant abnormalities of various kinds similar to those found at Eniewetok Atoll (Palumbo 1962).

Certainly exposures equal to or greater than those of the Gunckel-Sparrow experiments were present at Bikini-Eniewetok. Apparently there is no aberrant growth form that is uniquely related to ionizing radiation exposure. The plant with the most obvious morphological abnormality was the morning glory. Instead of being a trailing vine, on occasion it grew upright as a foot-and-a-half-high stalk with regenerated, rudimentary leaves and many tumors (Hines 1962). Tumorous morning glories on Engebi Island (Eniewetok Atoll), first observed in 1949, were also present in 1957 (Palumbo 1962).

No morphologically changed fish or invertebrates were seen. However, there was one interesting nuclear-detonation fish-related observation. In 1954, in a shallow reef area near a detonation site, Eniewetok Atoll, a few mullet about 37 cm (15 inches) in length were caught that had a band of green algae growing on one side of their bodies near the top of the fish. One guess of what had occurred was that the fish had been near the surface in an area near ground zero and had received a thermal burn, and that omnipresent algae had successfully invaded the injured flesh. The collection was made only 1 wk after nuclear detonation at a nearby site. Since the injured flesh occurred on only one side of the fish, the injured side suggested the orientation of the fish to the heat source at the instant of the detonation.

In a non-Laboratory related program, a study of *Drosophila* (a fruit fly) mutation rates of natural colonies were made at Bikini and control atolls by W. E. Stone. Stone et al. (1957) have concluded from studies of the *Drosophila* populations at Bikini that, while there is evidence of genetic changes caused by radiation, other factors mask the radiation effects.

In regard to the number of aberrant growth forms in the near detonation site areas, perhaps the organisms with significant potential to produce morphological abnormalities did not survive the initial impact of the detonation, or if they did survive, they were lost by predation.

Survival of the Polynesian Rat at Engebi Island, Eniewetok Atoll

This 250 acre island has a population of rats that survived heavy bombardment by the U.S. Navy in 1944, and heavy construction and earth movement during the nuclear testing program, and was near ground zero for four nuclear detonations in 1952–1954, including a wash-over. The rats live underground in nests and pathways 15 to 60 cm (6 inches to 2 feet) below the surface but feed at the surface principally on seeds and vegetation. Apparently they survived because they were underground at the time of the detonations, but post-detonation survivors were exposed to significant external radiation plus some internal exposure from foodstuff. In 1955, both the number of rats and the size of their habitat were increasing. In 1964, populations appeared to be in equilibrium with the available food supply.

Resiliency

During the years of observations of the environmental damage in areas near ground zero for nuclear detonation, a subjective opinion developed that recovery by plants was more rapid than might be expected. To provide some objectivity to this opinion a program was planned to make both pre- and post-detonation observation of plants in an area near ground zero of a nuclear detonation.

The area selected was Belle Island, 5 km (2.7 miles) from ground zero for the Nectar detonation of 14 May 1954, at Eniewetok Atoll. Belle was far enough away that the plants were not expected to be uprooted, but heat, overpressure and ionizing radiation were expected to produce significant effects. Previously, Belle had been scathed by the November 1952 Mike detonation but the damage to plants and loss of topsoil was not documented.

Before the Nectar detonation, specific plants and shrubs were staked, labeled, measured and photographed (Palumbo 1962). After the detonation, observations were made for comparison with the pre-event plant conditions and gamma survey meter readings were obtained. The calculated dose rate at +1 min was ~0.01 Gy h^{-1} (1 R h^{-1}); the accumulated dose at 200 d was calculated to be ~4 Gy (400 R). The first post-event observation was +8 d, and from the air Belle looked scorched, i.e., brown and desolate with most of the surviving shrubs prostrate, but closer observation on ground showed signs of new growth. An abbreviated account of the observations follows:

+8 d	green buds were observed (there was a heavy rain 3 d post detonation)
+35 d	new shoots, leaves and flowers
+3 mo	some shrubs near pre-Nectar size
+6 mo	most shrubs near pre-Nectar size
+10 mo	generally, all vegetation back to pre-Nectar status

At Bikini Atoll in 1985, Fosberg observed the revegetation of the atoll and concluded, "The simple, quantitative effects of previous nuclear testing, construction and resettlement activities on vegetation have perhaps been minimal. The islands are all practically completely vegetated at present except at places where disturbance has been very recent . . . The total biomass may be as great or greater than at the time when the people were first removed" (Schultz and Schultz 1994).

The recovery of plants at Eniewetok in a general way is similar to plant recovery now seen following the 1980 Mt. St. Helens eruption and the 1988 Yellowstone Park Fire.

Archive samples

Over the years, personnel from the Laboratory have collected terrestrial and marine samples from various locations throughout the Central Pacific. In general, the collection trips and analytical programs were conducted to survey radiation at selected sites or to maintain a post-testing monitoring program. There have been few attempts to compare data from different sampling programs or to examine the results for long-term trends in radionuclide concentrations. Many of these samples have been analyzed for total radiation or for selected radionuclides, and the results have been forwarded to the granting agencies (AEC, ERDA, DOE). Many surplus samples have been stored for additional analyses at a later date.

Currently, there are several thousand samples stored at the School of Fisheries, and a few hundred have been transferred to the Nevada Test Site for storage. No similar collection of samples is known to exist elsewhere. Therefore, these samples represent a unique source of information for describing the initial uptake, accumulation, and subsequent loss of long-lived radionuclides by both terrestrial and aquatic biota. Furthermore, additional radiological analyses of some samples may be useful for calculating the dose that native populations were exposed to during the testing.

Availability of the laboratory reports

Some of the Laboratory reports of the early years of the Marshall Island studies bore military and/or AEC classification originally but later were declassified, and some were in the "gray literature" area and may remain difficult to find, but many were published in the open literature. After the Laboratory closed its doors in early 1980's, one set of the Laboratory's copies of their research reports was transferred to the Publications Office, School of Fisheries, University of Washington, and a duplicate set of early publications was retained at the University of Washington's Fisheries/Oceanography Library.

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