410384

Conference on Nuclear Detonations and Marine Radioactivity
Kjeller, Norway
September 16 - 21, 1963

EVALUATION OF RADIOACTIVITY IN THE MARINE ENVIRONMENT OF THE PACIFIC PROVING GROUND

by

Lauren R. Donaldson

Laboratory of Radiation Biology
University of Washington
Seattle, Washington

EVALUATION OF RADIOACTIVITY IN THE MARINE ENVIRONMENT OF THE PACIFIC PROVING GROUND

During the years 1946 to 1962 a number of atomic detonations were carried out under water, over water, or on land near the water of the central Pacific. Most of these experiments took place at tropical Bikini and Eniwetok Atolls in the Marshall Islands, and at Johnston, Christmas, and Malden Islands farther east. While these experiments were conducted primarily to measure physical forces, they also contributed in a marked degree to a better understanding of the distribution of the radionuclides produced.

Biologists have been a part of the scientific team activity since the detonation of the first test device over the sea at Bikini Atoll, July 1, 1946. Thus, it has been possible to study the radioactive materials produced from the weapon tests and deposited in the sea and on the islands. Even where the radionuclides become diluted to infinitesimal quantities by ordinary standards, it has been possible to follow the distribution and biological cycling of these materials. Hines (1962) has summarized the general problem of evaluating this research.

Radioactive waste products in the the sea are of interest to man insofar as they constitute a potential hazard in his food derived from the sea. Aquatic forms may be destroyed by atomic detonations from external sources of ionizing radiation. The radioactive material that is absorbed or ingested with the food and retained in the organism as an internal emitter is, however, of much more concern.

The effects of ionizing radiation upon aquatic forms are most difficult to measure directly in field situations such as those that prevail at or near the test sites. Donaldson and Foster (1957) have reviewed the literature from laboratory-type experiments:

> A broad review of the results obtained with the organisms of different phyla indicates that the lower or more primitive forms are generally more resistant to ionizing radiation than are the more complex vertebrate forms[*] Welander (unpublished data) has summarized much of the data for which some approximation of dose can be made. Table 1 is a further condensation of these data which were obtained in experiments where whole body doses (usually X-rays) were administered. Owing to the great variety of circumstances under which the experiments were conducted, these data represent only orders of magnitude of effects.
>
> The algae and protozoa are most resistant with LD_{50} values in the order of many thousands of roentgens. The molluscs and crustaceans are somewhat more sensitive, with LD_{50} values of a few thousand roentgens

---

[*] See Figure 1.

Relative sensitivity of various organisms

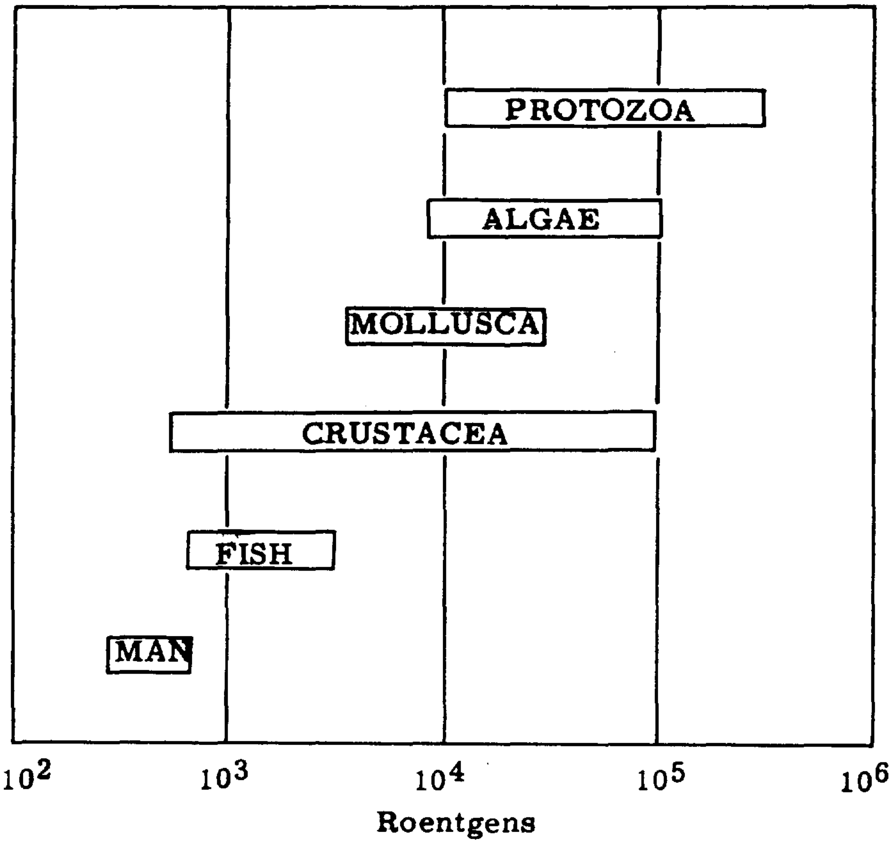

Fig. 1. X-rays or gamma rays required to kill 50 per cent of organisms. (Data from Donaldson and Foster, 1957).

Table 1. Relative Sensitivity of Different Groups of Organisms to Radiation

	(r) Dose which caused			
Group	50% mortality	100% mortality	"Latent" period	Investigators
Algae	8,000-100,000	25,000- 600,000	45 days	Bonham and Palumbo (1951); Crowther (1926) Bonham, et al. (1947).
Protozoa	10,000-300,000	18,000-1,250,000	45 min.-40 days	Ralston (1939); Back (1939); Back and Halberstaedter (1945); Halberstaedter and Back (1943); Powers and Shefner (1950); Feldman-Muhsam and Halberstaedter (1946).
Molluscs	5,000- 20,000	10,000- 50,000	3 weeks-2 years	Bonham and Palumbo (1951).
Crustaceans	500- 90,000	5,000- 80,000	5 days-80 days	Bonham and Palumbo (1951).
Fish	600- 3,000	370- 20,000	14-460 days	Corbella (1930); Welander et al. (1948); Foster et al. (1949); Ellinger (1939) (1940); Ssamokhvalova (1938) Solberg (1938).
Insects*				

*No data except for _Culex_ and non-aquatic forms.

Table 2. Relative Sensitivity of Different Life Stages of Salmonoids

Stage irradiated	Species	Approximate median effective dose (LD_{50})	Investigator
Gametes*	rainbow trout	50- 100 r	Foster, et al. (1949)
Eyed eggs	chinook salmon	1000 r	Welander, et al. (1948)
Fingerlings	chinook salmon	1250-2500 r	Bonham, et al. (1948)
Adult	rainbow trout	1500 r	Welander, et al. (1949)

*In parent fish.

> (aquatic insects probably also fall in this category) and the fish are most sensitive with an LD_{50} of about one thousand roentgens--in the same order of magnitude as that of other cold-blooded vertebrates.
>
> ....It must be recognized in any consideration of the relative sensitivity to radiation of different groups of organisms that considerable variability exists between similar species. In comparing the sensitivity of two species of snails, Bonham and Palumbo (1951) found that 'at 10 kr, approximately one month elapsed before 50 per cent of the *Radix* died, while in the case of the *Thais* it was approximately one-half of a year.' Consideration must also be given to the different developmental stages of the same species. Since many investigators (Evans, 1936, Rugh, 1949) have correlated radiosensitivity with metabolic rate of the dividing cell, it is not surprising that dormant eggs of aquatic invertebrates should be especially resistant. Bonham and Palumbo (1951) found that the two-week LD_{50} for dry *Artemia* eggs was about 50,000 roentgens, but after soaking the eggs for a short time in water, so that embryonic development was resumed, the radiosensitivity increased more than twofold.

The Bikini-Eniwetok test site in the Pacific, where the United States has tested its largest nuclear devices, provides the best study areas of the fate of radionuclides in the sea and their effect upon the biota. Because the levels of radioactivity are considerably greater in the Bikini-Eniwetok area than elsewhere in the ocean, the effects would be likely to be more evident.

> ...Dead fish have been observed in the vicinity of the detonation of nuclear devices at Bikini-Eniwetok, and although the cause of death was not known for sure, it is reasonable to believe the cause was more likely to have been from blast effects or radiation released at the instant of the detonation than from the radioisotopes in water. In the absence of the effects of blast and heat, death to fish from ionizing radiations could be expected in the immediate vicinity of the detonation of a large device. However, if death resulted solely from radioactivity in water, mortalities would be expected to occur over an extended period of time and area, but this condition has not been observed. Although it is recognized that observations of dying fish may not be apparent because of the removal by predators of fish in a weakened condition, it is believed that the amount of radioactivity in water necessary to kill fish directly would have to be greater than the amount of radioactivity that has occurred in the water in the vicinity of Bikini-Eniwetok.
>
> If fish survive exposure to ionizing radiations there still may be non-lethal effects in the form of pathological or genetic damage from either external or internal emitters. Again referring to the Bikini-Eniwetok area, thousands of fish have been examined for gross pathological and morphological changes but no

obvious changes have been observed (Welander 1959). However, Gorbman and James (1959) found upon examining microscopically the thyroids of reef fish from an area close to a test site that the damage to the thyroid ranged from zero to 100 per cent. In those fish in which the thyroid was damaged, the fish otherwise appeared to be normal. The cause of damage to the thyroids was undoubtedly radioisotopes of iodine, as internal emitters, that are present in relatively great abundance immediately after the detonation of a nuclear device. As the half life of these radioisotopes of iodine is short (range from 2 hours to 8 days), the damage to the thyroids would be expected to occur soon after exposure.

Because the genetic effects of ionizing radiation occur in the progeny of the exposed individuals and may be subtle, it cannot be said that mutations have not occurred in fish in the Bikini-Eniwetok area, although it can be said that there have been no recognizable mutations in the thousands of fish that have been observed. If mutations have occurred they are not the type that manifest themselves as morphological abnormalities. Laboratory experiments rather than field observations are needed to determine the genetic effects of low, chronic doses of ionizing radiation. (Seymour, 1960).

Operation Crossroads during the summer of 1946 provided the first real opportunity to evaluate the over-all impact of the energy release from atomic devices. This, unquestionably, was the most thoroughly documented, reported and publicized peace-time military exercise in history. The tests were necessary, it was explained, to determine the effects of atomic blasts on naval vessels. The tests at Bikini Atoll brought to bear virtually the entire range of scientific disciplines.

Bikini Atoll is in the classic atoll configuration. The outer rim of islets surrounds a lagoon about twenty-six miles long from east to west, and fifteen miles wide from north to south. In area the lagoon covers about two hundred and forty-three square miles. The land area totals about 3.4 square miles. The islands are low, only eight to twelve feet high, except for a few domes that are slightly higher. The lagoon of Bikini Atoll and, subsequently, the lagoon of Eniwetok Atoll provided excellent partially-enclosed basins in which the cycling, biological uptake, and decline of the radionuclides produced by the blasts might be studied.

Donaldson (1959) summarized the radiobiological studies.

> Little or no time is lost between steps in the biological cycling of materials for there is not only an abundance of organisms but also a wide variety of species--some 700 among the fishes alone (Schultz et al. (1953))--so that whatever is not utilized by one is

quickly taken by another. There is here a perfect economy of use of substances essential to life.

Available substances are rapidly taken up by the biota, never remaining long in the water to be diluted and washed away. This is dramatically demonstrated following an atomic test in which radioactive materials are deposited in the water. Within hours, the great bulk of these materials to is to be found in the living organisms. Plankton and some of the algae, which are the key organisms in the food chain, may concentrate within themselves more than a thousand times the amount of radioactive substances found in the sea water. The herbivorous fish and invertebrates have lower concentrations of radionuclides at any given time than do the plants on which they feed, and progressing along the food chain to the carnivores the concentrations become lower and lower. Within each organism there is a differential concentration from tissue to tissue, the digestive organs having a higher concentration than the other tissues, where a more selective deposition as to specific isotopes has taken place.

More specifically, plankton, the oceanic plants and animals that drift about passively with little or no resistance to water movements, may influence greatly the distribution of radioactive materials in the sea. These forms include many groups of organisms from the simple one-celled plants to the larval forms of vertebrates.

Plankton acquire radioisotopes by absorption, adsorption, or both. Plankton, especially phytoplankton, present a greater absorptive surface to the environment than any other group of marine organisms. Thus, the major initial concentration of radioactive isotopes probably occurs in the phytoplankton--the same organisms which comprise the foundation of the food chain in the sea. The isotopes especially concentrated by these forms are, for the most part, representatives of those elements which tend to form strong complexes with organic material. They include most of the anionic radioisotopes,with the exception of iodine, and the cationic radioisotopes produced by neutron induction including radioactive zinc, cobalt, iron and manganese. All of the cationic radioisotopes concentrated in the plankton are biologically important elements comprising the essential parts of enzyme systems and, in one case at least, an essential vitamin.

The levels of radioisotopes present in the plankton vary with time after release of the radioactive materials, mainly because of the variation in availability due to physical decay of the individual radioisotopes (UWFL-53). In general, however, plankton contain the three radioactive isotopes of cobalt. Co^{57}, Co^{58} and Co^{60}, at a level of 11 to 50 percent of the total radioactivity. Zn^{65} is present at a level of 12 to 47 percent; Fe^{55-59} at a level of 1 to 40 percent; Mn^{54} in trace amounts, and the fission products Zr^{95}-Nb^{95} at levels of 3 to 44 percent; Ru^{106}-Rh^{106} from 0 to 7 percent; Ce^{144}-Pr^{144}, 0 to 13 percent; and Cs^{137} in trace amounts, if present at all (UWFL-54). Sr^{90}-Y^{90} has not been found in plankton.

Once the radioactive materials have been absorbed or adsorbed by the plankton, their distribution is likely to be greater both vertically and horizontally than if distribution were solely dependent upon the surface currents. One reason for a greater distribution would be that absorption by plankton makes the radionuclides available to larger organisms which can move beyond the current's boundaries. Similarly these materials also become available to the local resident populations and, as they are recycled through the food chain, the effect is a delay in their distribution away from the original area of contamination. Another factor influencing the distribution of radioactive materials by plankton is their diurnal vertical migration. If this migration were great enough to take the plankton below the current stream, it would extend the vertical distribution and also slow down the horizontal distribution, because the plankton would be moving horizontally more slowly than the water.

Plankton may carry radioactive materials from the deeper waters of the lagoons to the surface or even up onto the reefs and eventually to the islands by vertical migration. At Bikini it has been observed, for example, that these materials were picked up by the plankton in the deeper waters of the lagoon during the daytime. The concentrated radionuclides in the plankton were then transported to the surface by the diurnal vertical migration of these minute forms. At the surface, their presence at night caused the surface radiation content to increase measurably over the daylight readings. The fouling organisms on the bottoms of the ships and the plankton feeders on the reef became increasingly radioactive at night as the transport of the radioactive products continued.

It can be said then that plankton may cause the distribution of radionuclides in the sea to be different from that which would be expected from the distribution by currents alone in the following respects: (1) a delay in the movement from the area of original contamination, (2) a slower down-current movement, (3) a limited dispersion up-current or beyond the currents' boundaries, (4) a greater vertical distribution, and (5) an over-all greater dispersion of relatively lower concentrations.

Aquatic plants or algae may be free-floating (as are the phytoplankton), attached to the reefs, or growing in the shallow water. Just as do land plants, the algae contribute to the food supply of animal populations. Minerals as well as organic materials, concentrated and incorporated into the algae, are passed on in the food chain to the animals that feed upon them. Thus the radioactive materials pass through the algae to the animals in the normal course of food gathering.

The affinity of algae for some of the radioisotopes is well known. For example, Asparagopsis, a marine alga found on the reefs at Bikini and Eniwetok, has a great affinity for iodine (UWFL-44). In the presence of I^{131} Asparagopsis becomes radioactive. This alga is a succulent morsel sought by fishes; thus the I^{131} passes to the fish and along the food chain...

The invertebrates, or animals without backbones, make up the great bulk of the animal life of an atoll. The role of these animals in the cycling of radioactive materials in an atoll is as varied as the invertebrate forms. Sea cucumbers have been compared with earth worms in their ceaseless turning of the gravel and sand as they obtain their nutriment from bacteria and algae. Corals and clams remove microorganisms and particulate matter from the water and also are host to the unicellular algae, Zooxanthellae, which are found in their tissues. The Zooxanthellae may be thought of as a vast reservoir of trapped plankton. Their relationship to their host is not completely understood but it is probable that they play an important part in the removal of phosphate wastes. Corals and clams are eroded by algae and sponges, which bore holes in the skeleton or shell, thus contributing to a return of carbonates to the water. Crabs, sipunculid worms and others also attack the skeleton of the corals. Some of the land crabs contribute to the deposition of radioisotopes from the sea onto the islands by dragging fish and algae ashore when feeding. In short, within the invertebrates and their symbionts alone complete biological cycles occur from land to sea and back again, from inorganic substances to organic and back again.

The fishes of the waters in and about the Marshall Islands have received a major share of the attention in the study of the biological cycling of radioactive materials (AECD-3446, UWFL-46, UWFL-47, UWFL-49, UWFL-51, UWFL-55). Despite detailed study, the great variety of fishes with a correspondingly great variation in feeding habit make this a very difficult area in which to summarize results.

In general, the fishes may be divided by feeding habit into three groups: the herbivores, omnivores and carnivores. Since the herbivores feed directly on the algae, the radioisotopes concentrated from the water by the algae are passed on directly to the fish, and from the fish to the animal eating the fish. The herbivores, represented by such fishes as the surgeonfish and parrotfish, have the greatest amount of radioactivity of the three major groups.

Omnivorous fish such as the damselfish have less contamination than have the herbivorous fish, for they feed on more complex organisms.

The herbivorous and omnivorous fish tend to concentrate the same isotopes found in the plankton except for the radioisotopes which are taken up only in trace amounts by these animals. Zn^{65} usually accounts for 50 percent or more of the total radioactivity in the organs of these fish and Fe^{55-59} comprises a major part of the remaining activity. The radioactive isotopes of cobalt account for 7 to 20 percent of the radioactivity and Mn^{54} 2 to 6 percent.

The minimum concentrations of radioactive material are found in the carnivores, for these fishes, like the reef-dwelling groupers, or the roaming carnivores, like the tuna and barracuda, obtain their "tag" of radioactive material only after it has been passed through a number of living forms which select, retain, or reject various radioisotopes. With the passage of time

> longer-term studies indicate that several years after a single contamination of an area the carnivorous fish contain the greatest amount of radioactivity.
>
> The carnivorous fish such as tuna and bonito, caught in the open ocean, contain Zn^{65} at the highest levels of any of the three groups of fish. In these animals Zn^{65} accounts for 75 to 92 percent of the total radioactivity; Fe^{55-59}, 6 to 25 percent; the cobalt radioisotopes, 1 to 3 percent; and Mn^{54}, less than 1 percent.
>
> In all species of fish, the greatest amount of radioactivity is found in the alimentary tract, with liver, skin, bone and muscle having lesser amounts in descending order. Skin and bone are quite similar in the amounts present, and usually the radioactivity averages about twice that found in the muscle. The liver may have two to nine times as much radioactivity as the bone or skin, and the alimentary tract contains two to four times as much as the liver.

During the spring of 1954 a series of experiments at Bikini and Eniwetok Atolls produced radiation that really initiated full-fledged oceanographic studies. Hines (1962) describes the events that led to the radiological evaluations over much of the western Pacific.

> The Operation Castle test series was opened at Bikini on March 1, 1954. The first detonation in the proving ground was Bravo. Its yield in energy release was placed at about fifteen megatons. At such a level

the device was 750 times more powerful than the nominal atomic bombs used at Crossroads eight years before and very much more powerful than the Mike shot of 1952.

Bravo was a surface shot, detonated at 6:45 A.M. The test may have been of greater yield than had been calculated, but the effect would have been only the production of an explosion proportionately greater than that of Test Mike, either in immediate physical terms or in the release of radiation products, except that the shot took place at a moment at which circumstances were combining to produce mishap and human suffering, the first such results attributable to a test program. Because Bravo was detonated on a coral island, its energy and heat carried upward--its cloud reached an altitude of 100,000 feet--a great volume of radioactive particles which would fall down rather quickly to the earth's surface when the turmoil of the nuclear fire had been dissipated. And on that morning there was blowing across the Pacific an upper wind which would carry the Bravo fallout not to the north, as had been expected, but eastward toward the inhabited atolls of Rongelap, Ailinginae, and Rongerik, the last the atoll on which the Bikini people had spent a brief and difficult interlude. In the area of the eastward fallout, some eighty miles from Bikini, there also was a Japanese long-line fishing vessel, the small (100-ton) Fukuryu Maru No. 5.

The Japanese organized a survey of the currents flowing westward of Bikini,and during May and June of 1954 the survey ship Shunkotsu-Maru determined the amounts of radioactivity in the sea water and marine life.

> The maximum sea water activity* found during the Japanese expedition was about 91,000 d/min/liter, 450 km west of Bikini on June 21, 1954. Over 1000 d/min/liter was found as far as 2000 km WNW of Bikini. According to the Japanese scientists, this activity was in solution, since it passed through a fine filter paper. In addition, samples taken in depth showed activity was present at some locations down several hundred meters. (NYO-4656)

After consulting the Japanese data it was decided to attempt to measure the residual activity remaining in the Pacific Ocean a year after its deposition. Operation Troll on the U.S. Coast Guard Cutter Taney covered a course of 17,419 miles between February 25 and May 3, 1955.

The conclusions drawn from the data gathered and edited by Harley (NYO-4656) are summarized as follows:

> 1. Sea water and plankton samples show the existence of widespread low-level activity in the Pacific Ocean. Water activity ranged from 0-570 d/min/liter and plankton from 3-140 d/min/g wet weight.
> 2. There is some concentration of the activity in the main current streams, such as the North Equatorial Current. The highest activity was off the coast of Luzon, averaging 190 d/min/liter down to 600 m (April 1, 1955).
> 3. Analyses of fish indicate no activity approaching

---

* Measurements were made by coprecipitation with ferric hydroxide and barium sulfate. This procedure eliminates the natural K^{40} activity and loses certain fission products, such as Cs and some of the Ru and Nb.

the maximum permissible level for foods. The highest activity in tuna fish was 3.5 d/min/g ash, less than 1 percent of the permissible level.

4. Measurements of plankton activity offer a sensitive indication of activity in the ocean.

5. Similar operations would be valuable in assessing the activity from future tests and in gathering valuable data for oceanographic studies.

In the planning for the 1956 series of tests at Bikini and Eniwetok (Operation Redwing) it was decided to carry on oceanographic cruises during and following the tests to determine, if possible, the levels of ocean-borne contamination. Two cruises were planned, one during the test period to outline the area of contamination, and a second after the completion of the tests to determine the spread over the ocean of contaminated water and to trace the farthest drift of the fallout after it had been dispersed and diluted in the ocean.

A destroyer escort, the U.S.S. Walton, was used as the first survey ship. The cruise plan covered an area 400 miles in length and 200 miles in width. Samples of sea water and plankton were collected from fifty-three stations over a 78,000 square-mile area. Hines (1962) summarizes the survey results.

> Analysis of the Walton's samples disclosed that radioactive contamination was present in relatively heavy concentrations in identifiable locations within

the survey area, which finally covered 78,000 square miles. Radioactivity diminished in value around the edges of the sampling area, indicating that the survey had, in fact, encompassed the waters in which the heaviest contamination would be found. Counts of activity in the surface waters were considerably higher than those down to 100 meters, for the fallout deposited on the surface during the tests had not yet penetrated the stirred layer. The surface water samples had an average value, for the 3,300-mile run, of 10,000 disintegrations per minute per liter of total beta radioactivity, whereas water sampled from the 100-meter depth had the lowest average content, about 3,900 disintegrations per minute. It was noted that, while measurable amounts of activity were found in the waters of each station sampled, the lowest values were found in the northwest part of the survey area, in that part where the survey had started, while the highest readings were found immediately north and west of Bikini, where maximum readings of 120,000 disintegrations per minute were recorded.

The pattern of plankton contamination was a magnification, many times over, of the contamination in the water. The average value of radioactivity in plankton was 71,000 disintegrations of total beta activity per minute per gram, the highest value, found in a sample taken north of Bikini, being 1,200,000 disintegrations per minute. On a weight-for-weight basis, the average value of plankton radiation was 7,000 times that of the surface water. The minimum

> level, of 1,300 disintegrations per minute, was almost as high as the maximum level recorded by the Taney survey of 1955, so that it was assumed that the entire area covered by the Walton was contaminated to some extent. The levels of plankton contamination, highest north of Bikini, diminished rapidly to the south and trailed off gradually to the northwest, except that there was a long stream of plankton contamination extending from Eniwetok to Bikini and on to the southwest corner of the survey area, a stream identifiable for more than 300 miles. Examination of the measurements by the probe showed that the curves checked closely with those produced by the surface water samplings on most of the fifty-three stations.

After completion of the 1956 test series the second oceanographic cruise ship, the U.S.S. Marsh (DE 699) made two zigzag passages, one east to west and one west to east from Eniwetok Atoll to Guam and return. The cruise lasted twenty days during which samples of sea water and plankton were collected at seventy-four stations. The spread of the contaminated water during the six-week interval between the Walton and Marsh surveys and the decrease in radiation as determined by the water and plankton samples may be summarized as follows:

> The Marsh brought back the answer to the question of how far and at what levels of activity contamination had moved westward. At Guam, samples of water showed very low levels of radioactivity, yet the values at the

surface were four to twenty times the lowest values (48 counts per minute per liter of gross beta) found northeast of Bikini, where test contamination was virtually absent. Thus it appeared that the westward fringe of the drift had reached, in September, the vicinity of Guam, but at levels so low that they were significant only for the purposes of identification. Furthermore, the maximum value for water, regardless of place or depth of the sample, was 19,000 disintegrations per minute of total beta, and this single sample was taken from the surface at Station 2, southwest of Eniwetok toward Ujelang Atoll, as the cruise began. Levels of radioactivity diminished sharply thereafter, trailing off to the lower values, while the samplings down to 150 meters were variable in content and seemed, as the report later stated, to fall into regional patterns. As all of the earlier surveys had discovered, the Marsh also found that plankton were the most sensitive indicators of the presence of radioactivity. The highest value of total beta activity in plankton, 21,000 disintegrations per minute per gram, was found in samples taken eighty miles north of Eniwetok, and the lowest, 27, near Guam. The average of ratios of plankton activity to sea water activity was 2,500 to 1, much lower than the ratio of 7,000 to 1 reported by the Walton three months earlier.

The Marsh survey between September 1 and 20, 1956, completed the second phase of a two-stage study of a radiation-tagged water mass. It had found radioactivity

> from Redwing at lower levels, as had been expected. It also confirmed the general accuracy of the Japanese in their original analysis of the ocean contamination problem, even though the levels again were below those that could cause concern. (Hines, 1960)

The 1958 series of tests, Operation Hardtack, brought more oceanographic studies of a more sophisticated nature. In addition to the tests over water or on the small islands near the water, tests were conducted under water in the open sea and in the lagoon. Three vessels were made available for oceanographic surveys, the U.S.S. Rehoboth, a seaplane tender converted by the navy for oceanographic work, the U.S.S. Collett (DE 730), and the U.S.S. Silverstein (DE 534). The Rehoboth was used to follow the contaminated water mass subsequent to the underwater detonations. The data collected provide some of the most detailed information on short-lived radioisotopes in the sea.

> The data developed aboard the Rehoboth and later, particularly in analysis of radioisotopic content of specimens, revealed certain striking differences in radioactive composition immediately following nuclear detonation. The short-lived fission products were dominant. The gamma-emitting radioisotopes in plankton collected between May 16 and May 20 included molybdenum 99-technetium 99, with a half-life of sixty-six hours; and tellurium 132-iodine 132, with a half-life of seventy-seven hours. The larger plankton were found to have ingested larger proportions of

> barium 140, with a half-life of 12.8 days, while smaller plankton contained higher percentages of molybdenum 99-technetium 99, but otherwise the radioisotopic compositions were similar. (Hines, 1962)

The Collett, following a tract over somewhat the same general area west of the test site as covered by the Walton two years earlier, collected samples of water and plankton that indicated the distribution of the fallout from a number of tests conducted at various points in time. The highest concentrations of radioactivity came from above the thermocline. The variations were such, however, that it was obvious the radioactivity was not evenly distributed throughout the mixed layer. An unexpected radioelement, tungsten-185, was found in some of the Collett samples. Both plankton and water samples contained this radioisotope which apparently had been incorporated into some of the devices being tested as a means of tracing and indentifying the fallout.

> The Silverstein, leaving Eniwetok on September 3, followed a zigzag track similar to that of the Marsh two years before. In the interval between the August and September surveys the center of ocean radioactivity that had been noted 170 miles northwest of Eniwetok had moved west-southwest some 250 miles. Because the Silverstein cruise pattern permitted observations over a much wider area of ocean, four

> major concentrations of waterborne radioactivity were found--one 270 miles due north of Eniwetok, another 330 miles to the northwest, and two to the west-northwest at distances of 390 and 570 miles. The leading edge of the contaminated area extended in September almost to Guam. In one plankton sample taken 110 miles northeast of Guam on September 7 the gross beta radioactivity was 39,000 disintegrations per minute per gram (dry weight), and in a sample taken 80 miles southeast of the island on September 9 the level was at 28,000 disintegrations per minute. Water taken at the same stations produced readings of 6,200 and 3,000 disintegrations per minute for 5-liter amounts. Plankton taken north of Guam, toward the island of Rota, contained activity producing only 3,200 disintegrations per minute, and no activity was detectable in the water there. (Hines, 1962)

During the summer of 1962 a series of high altitude tests were held at Christmas and Johnston Islands. The fallout from the tests was measured in the sea from samples of sea water, plankton, and fish. The Japanese used the oceanographic vessel Shoyo Maru and the United States used the Charles H. Gilbert, a research vessel of the United States Department of Interior, Bureau of Commercial Fisheries. The fallout was evaluated over a large portion of the central Pacific, and samples of sea water, plankton, and fish were collected before, during, and after the tests. Foodstuffs were also sampled from ten islands located in an area extending from 5°N to 22°S latitude and from 173°E to 155°W longitude.

Pre-Dominic samples were expected to contain fallout radionuclides from previous British, United States, or U.S.S.R. tests. In the pre-Dominic samples zinc-65, a non-fission product, was predominant (Palumbo, 1963). The values in the fish ranged from 0.78 to 4.4 pc/g wet weight.

> Postshot samples of fish from seven islands contained radionuclides which indicate the presence of fallout from the Dominic series. I^{131} was found in fish from Canton and Christmas, and Washington, Ba^{140}-La^{140} in fish from Canton and Christmas, and Zr^{95}-Nb^{95}, Ru^{103} and $Ce^{141,144}$ from Samoa, Canton, Fiji, Malden, Penrhyn, Christmas, and Washington. The highest values generally were found in samples from Christmas, Canton and Fiji, and the lowest in samples from Penrhyn, Rarotonga, and Tongatapu. The highest value for any of the nuclides was 25 picocuries of I^{131} per gram of wet pigfish liver from Canton Island. The majority of the values were below 1 pc/g wet. K^{40}, a naturally occurring nuclide, was present in most samples, averaging 3.8 pc/g wet for fish from all islands, and was the greatest single contributor to the total radioactivity of the samples. (Palumbo, 1963)

Studies of the material collected during the 1962 program continue. Additional sampling and improved techniques and equipment will provide a more complete understanding of the fate of radionuclides released under, on, and over the ocean.

LITERATURE CITED

Bonham, Kelshaw and Ralph F. Palumbo. 1951. Effects of X-rays on snails, crustacea and algae. Growth, Vol. XV, p. 155-188.

Donaldson, Lauren R. 1959. Radiobiological studies at the Eniwetok Test Site and adjacent areas of the western Pacific. Transactions Second Seminar on Biological Problems in Water Pollution, April 20-24, 1959. U.S. Public Health Service, Robert A. Taft Sanitary Engineering Center (Cincinnati). 7 p.

Donaldson, Lauren R. and Richard F. Foster. 1957. "Effects of radiation on aquatic organisms." In The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences-National Research Council (Washington, D.C.) Publ. No. 551. p. 96-97.

Harley, John H. (ed.). 1956. Operation Troll. U.S. Atomic Energy Commission report NYO-4656. Office of Technical Services, U.S. Department of Commerce (Washington, D.C.). p. 1, 13.

Hines, Neal O. 1962. Proving Ground. An Account of the Radiobiological Studies in the Pacific, 1946-1961. University of Washington Press (Seattle). p. 165, 226-229, 230-232, 281, 290.

Palumbo, Ralph F. 1963. Radionuclide content of foodstuffs collected at Christmas Island and at other islands of the central Pacific during Operation Dominic, 1962. U.S. Atomic Energy Commission report UWFL-87. Laboratory of Radiation Biology, University of Washington (Seattle). p. 8-9.

Seymour, Allyn H. 1960. Fish and radioactivity. Laboratory of Radiation Biology, University of Washington (Seattle). p. 4-6.

Welander, Arthur D. (Unpublished data).